研究報告

世界の偏極 $^3He^{2+}$ イオン源に関するレビュートーク

田中　正義

Review Talk on the Polarized $^3He^{2+}$ Ion Sources in the World[1]

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SUMMARY

Abstract. A brief review of the polarized ^3He ion sources so far developed in the world community is described emphasizing the physics behind the methods of polarization.

In the latter part of this report, the long history of the polarized ^3He ion source developed at RCNP (Research Center for Nuclear Physics), Osaka University over the decade is presented. Lastly, an emphasis is placed upon the description of the latest development on the SEPIS (Spin Exchange Polarized Ion Source).

偏極方法の背後にある物理を特に強調して現在までに世界で開発されてきた偏極^3Heイオン源の簡単なレビューを行う。この報告書の後半では、10年以上にわたって大阪大学核物理研究センターで開発されてきた偏極^3Heイオン源の歴史を紹介する。最後に最新のSEPIS (Spin Exchange Polarized Ion Source) の開発を重点的に述べる。

1. INTRODUCTION

The mid 80th in the last century was the golden age when the development of polarized ^3He ion sources was progressed actively. In these days, polarized ^3He beams with a sizable polarization from the accelerators (mainly cyclotrons, or Van de Graaffs) were actually used for nuclear physics research. In addition to enormous efforts to improve the polarization degree and beam intensity, a variety of new ideas to create the polarization were also born. [1]

[1] Presented at the International workshop on polarized ions, targets, and polarimetry (PSTP2007), Sept 2007, Brookhaven, New York, U.S.A.

However, thereafter, such a proud history disappeared from the front stage possibly due to the shut down of many accelerator institutes and loss of physical interest. On the contrary, the polarized ^{3}He gases received much attention in association with its application to medical use as well as particle physics research, and have achieved remarkable advances until now. [2, 3]

Nevertheless, an effort to develop polarized ^{3}He ion sources toward the high intensity and high polarization has been continued at limited institutes such as RCNP (Research Center for Nuclear Physics, Osaka University), Dubna, INR (Institute for Nuclear Research, Moscow), and BNL (Brookhaven National Laboratory, New York).

In RCNP, the successive directors and the Japanese minister of education and sciences continuously supported our development understanding importance of the polarized ^{3}He beam as a probe of nuclear physics research for study of nuclear synthesis in the super novae [4], pion condensation in nuclei, and so on.

Fortunately, there has been an earnest demand to develop the polarized ^{3}He ion sources in recent years from the high energy physics associated with the NUCLOTRON in Dubna [5], and the e-RHIC proposal at BNL. [6] This would be a hopeful sign of our common goal to obtain ^{3}He beams at an intermediate and high energy region. It is timely and necessary to review a brief history on the development of the polarized ^{3}He ion sources.

I will touch, in the next section, basic outlines of the methods employed to polarize ^{3}He by emphasizing physics behind them for each type of polarized ^{3}He ion sources. A long history of progress in the RCNP polarized ^{3}He ion source will, then, be presented.

2. A REVIEW OF POLARIZED ^{3}HE ION SOURCES

To make a comprehensive review of the polarized ^{3}He ion sources is beyond my ability. Therefore, I will confine myself only on the description of principles used so far for polarizing ^{3}He offered or put to practical use. Though attainable polarization, beam intensity, emittance, energy spread, transport and acceleration of the polarized ^{3}He beam are, of course, an equally important subject, I do not touch them because they are beyond my scope.

2.1. Lamb shift of $^3He^+$ ion

A somewhat comprehensive summary of the polarized $^3He^{2+}$ ion source based on a variety of methods including Lamb shift type is presented by Oh. [7, 8, 9] In 1974, the first polarized $^3He^{2+}$ beam was successfully extracted from the Birmingham cyclotron in England after a long development over the decade, and actually used for nuclear physics research. The method of polarization was basically to use Lamb shift of a $^3He^+$ ion ($\tau \sim 2$ ms). It was, in the first place, necessary to generate an unpolarized $^3He^+$ in the $2^2S_{1/2}$ metastable state. This was done by an electron capture process of 30-keV $^3He^{2+}$ ion by N_2 gas. It was experimentally confirmed that about 5% of the outgoing $^3He^+$ ions was the metastable state. On the other hand, later at the Van de Graaff accelerator facility in Laval/ Quebec, Slobodrian et al. succeeded in more conveniently

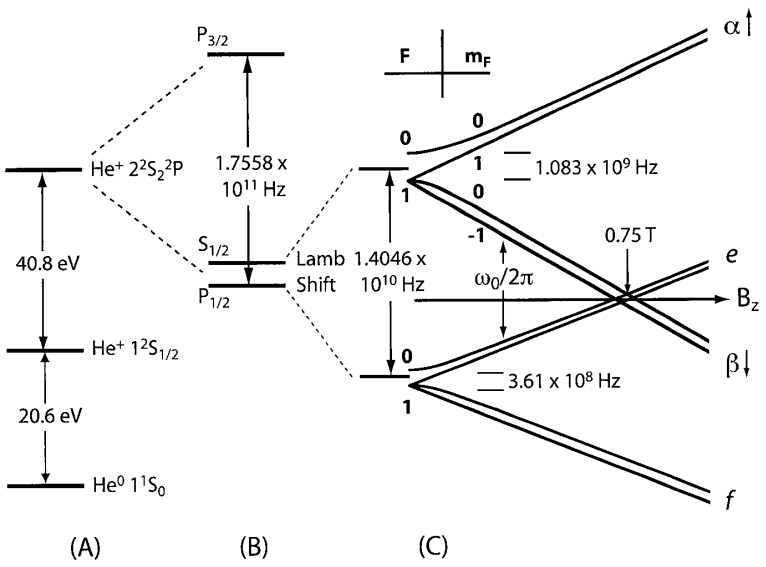

FIGURE 1. Energy level of He atom and ion

producing a similar ratio (~5%) of $^3He^+$ ($2^2S_{1/2}$) ion extracted from an rf ion source operated at a low voltage. [10] As shown in Fig. 1, Stark quenching at the β-e crossing point at $\mathbf{B}_{ex}$ = 0.75 T with a transverse static electric field for the $^3He^+$ ($2^2S_{1/2}$) is used.

The difficulty consisting in this method as compared with polarizing a proton was that the Lamb shift for $^3He^+$ ion is an order of magnitude larger than that for hydrogen, and subsequently $\mathbf{B}_{ex}$ at the β-e crossing point was an order of magnitude larger than hydrogen case. Because of strong magnetic field, an induced electric field caused by $\mathbf{v}\times\mathbf{B}$ would overcompensate the Stark quenching, and as a result, the final polarization becomes unexpectedly small. They, instead, used an rf transition (10GHz) with $\mathbf{B}_{ex}$ = 0.25T to overcome this difficulty.

Another difficulty in the Lamb shift type was how to separate the polarized metastable $^3He^+$ ions from a large amount of unpolarized ground state $^3He^+$ ions. This problem was solved by the discovery that the stripping cross sections for a $^3He^+$ ($2^2S_{1/2}$) ion forming a $^3He^{2+}$ ion is two orders of magnitudes larger than $^3He^+$ (ground state) ion in case of stripping gas such as N_2 or Helium, i.e., a selective ionization of polarized $^3He^{2+}$ ion was expected. [11]

2.2. Atomic beam method

Polarized proton ion sources based on the atomic beam method have shown a remarkable success in practical use for nuclear and particle physics. On the contrary, since a ^3He atom in the ground state (1^1S_0) has no electron spin, it is very difficult to directly employ Stern-Gerlach splitting. To overcome this difficulty, the metastable state of the ^3He excited state (2^3S_1) has been usually used, since the ^3He metastable state has an electron spin, S = 1. However, there was an exceptional trial with the ground state ^3He as shown in the following subsection.

2.2.1 Super cooled atomic beam method

The first observation of ^3He polarized ^3He ion source based on the atomic beam type was done for the ground state of ^3He (1^1S_0). [12] Their idea was to directly polarize ^3He nucleus by using a hexapole magnet. A supersonic nozzle cooled to liquid helium temperatures was used to produce intense slow ^3He beams in order to enhance the Stern-Gerlach splitting, and then nuclearly polarized ^3He was ionized by electron bombardment. With a hexapole magnet 50 cm long having an entrance diameter of 0.3cm the polarized $^3He^+$ beam current of 10 nA was expected. However,

so far a tiny evidence of polarization was only detected by comparing the beam currents with an exciting current of the hexapole magnet switched on and off.

2.2.2. Atomic beam method for 2^3S_1 metastable state

A successful polarized ^{3}He ion source based on the atomic beam method was developed by the Laval group [13, 14, 15, 16]. They used the metastable state ^{3}He atom (2^3S_1, τ = 4166 s) instead of the ground state ^{3}He atom. They created the metastable ^{3}He atom at thermal temperature by a ^{3}He gas in a cold cathode electron bombardment, and polarized it by using a sextupole magnet. Finally, they ionized it and a $^3He^+$ ion was extracted from an ionizer. The ionizer used was a strong field (0.2 T) electron bombardment ionizer with ionization efficiency better than 35 %. Since their performance was excellent, i.e., polarization of 95 %, beam current of 100 nA, beam emittance of 25 mm.mr, their method was inherited to Princeton, Saclay, and so on. However, I have not heard of the development after that.

2.3. 2^3S_1 metastability-and charge-exchange collisions

A very strange but important phenomenon later called "metastability-exchange collisions" was discovered in 1963 through the development of polarized ^{3}He ion source using an optical pumping. [17] The principle of the method is shown in Fig. 2. Firstly, an unpolarized ^{3}He atom in the 2^3S_1 metastable state is produced by applying an rf field, and then polarized by optical pumping with a 1.083 μ light (see Fig. 2-a). When ^{3}He gas thickness is low, polarized ^{3}He in the 2^3S_1 metastable state (both electrons coupled to S = 1 and ^{3}He nucleus are polarized) collides with another ^{3}He atom in the ground state. In this collision, only the electron spins of metastable ^{3}He atom exchanges with the ground state spin of ^{3}He atom, while the nuclear spin does not change (see Fig. 2-b). The Rice group in collaboration with the cyclotron group from Texas A & M succeeded in accelerating a polarized $^3He^+$ beam with a beam energy in a range of 18.4 -49.0 MeV by this method [18].

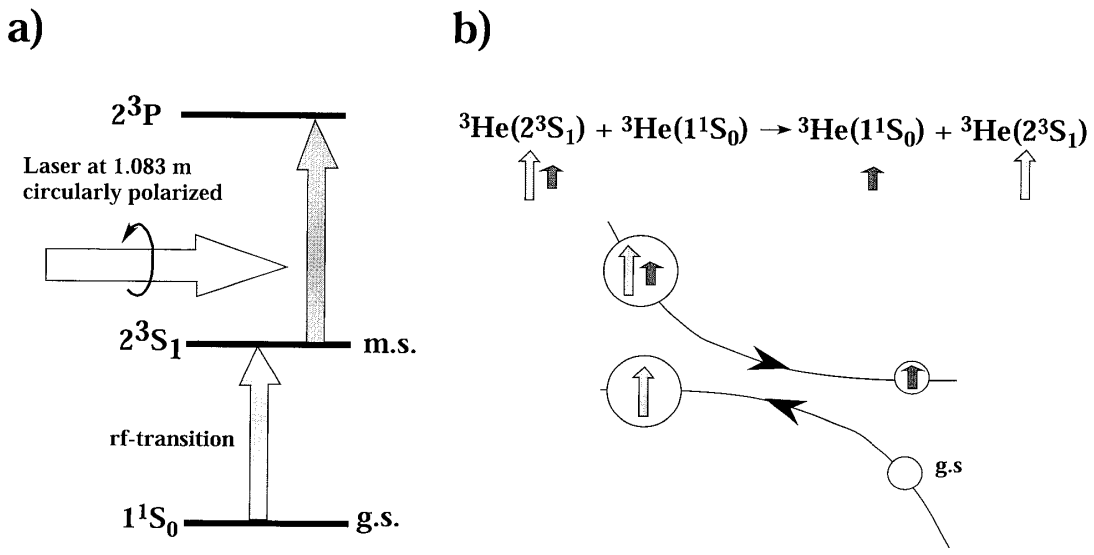

FIGURE 2. Principle of metastability-exchange collision

2.4. $^3He^-((1s2s2p)\,^4P_{5/2})$ metastable negative ion

^{3}He nuclear polarization using negative ^{3}He ion in the $^3He^-$ ($(1s2s2p)\ ^4P_{5/2}$) state was proposed, and tested by the group from Columbia University. A negative metastable Helium ion having a configuration, $(1s2s2p)\,^4P_J$ was discovered in 1939. It was produced from $^3He^+$ by a two-step process in which ^{3}He $(1s2s)\,^3S_1$ was first produced by a nearly resonant charge transfer and then $^3He^-$ was produced by capture of a 2p electron. [19] The zero-field lifetimes obtained are 11 ± 5 μs for J = 1/2, 3/2, and 345 ± 90 μs for J=5 / 2. The former two components are easily removed from the beam line because of their short life times. Under the presence of an external magnetic field, magnetic substate M of the J = 5/2 state will mix with that of J = 3/2 through the Zeeman mixing, whereas $M=\pm 5/2$ substates never mix up due to the angular momentum conservation. In other words, only the $M=\pm 5/2$ substates survive [20], and therefore, $^3He^-$ nucleus is polarizable by the hyperfine interaction, where the decay due to the Zeeman mixing is formulated as shown below. The decay rate Γ_M of the substate M is given by

$$\Gamma_M = \cos^2\theta_M \gamma_{5/2} + \sin^2\theta_M \gamma_{3/2} \qquad (1)$$

where the mixing angle θ_M is a function of $\frac{\mu_0 H}{\Delta_{5/2\text{-}3/2}}$. Here, $\gamma_{5/2}$ and $\gamma_{3/2}$ are the zero-field decay rates for I=5/2, and 3/2 state, and $\Delta_{5/2\text{-}3/2}$ is the fine structure splitting between J=5/2 and 3/2 state, respectively.

Though unpolarized $^3He^-$ ions have been accelerated by tandem Van de Graafs, acceleration by cyclotrons may be very difficult because of a serious loss due electric dissociation caused by the $\mathbf{v} \times \mathbf{B}$ field.

2.5. Polarized liquid and solid ^{3}He

2.5.1. Polarized liquid ^{3}He

Polarized liquid and solid ^{3}He have been developed not as a polarized ^{3}He ion source but as a polarized ^{3}He target. An advantage of this method relative to directly produce a polarized ^{3}He gas is that ^{3}He atomic density is much more larger than that in the gas phase. As far as it is concerned with polarization of liquid ^{3}He, there is almost no hope of a sizable polarization even if a brute force, i.e., a strong magnetic field and low temperature is employed because of a temperature-independent Pauli spin susceptibility. [21] To realize a large ^{3}He polarization in the liquid phase, Castaing et al. [22], proposed to quickly (shorter than a spin relaxation time) melt a highly polarized solid ^{3}He , and experimentally demonstrated its validity. [23, 24] Here, a solid ^{3}He could be polarized with ease as shown in the next subsection.

Another promising method to polarize a liquid ^{3}He is to use DNP (Dynamic Nuclear Polarization); a nuclear spin flip accompanied with an electron spin flip by application of the resonant μ-wave and a short relaxation time of the electron relative to that of the nucleus under a strong magnetic field. To create the nuclear polarization by the DNP, materials with a paramagnetic center such

as teflon and charcoal were examined. [25, 26] The produced nuclear polarization propagates to surrounding ^{3}He nuclei. An enhancement of the NMR signals compared with the thermal equilibrium values were found for both cases.

Later, a more systematic study for a polyethylene, teflon, zeolite doped with a TEMPO (2, 2, 6, 6-tetramenthyl-piperidinyl-1-oxyle) free radical with a few successes. [27] Amazingly, there was a report in this workshop that a 2.34 times enhanced ^{3}He NMR signal relative to the thermal equilibrium value was observed for a zeolite doped with TEMPO with a relaxation time unexpectedly longer than 330 s at T = 1.48 K and B=2.5 T. [28] This result would be a promising means to obtain a polarized liquid ^{3}He in near future, though the current record on the ^{3}He nuclear polarization was only around 0.1% .

2.5.2. Polarized solid ^{3}He

A polarized solid ^{3}He employs a solidification of a liquid ^{3}He by means of a Pomeranchuk cooling [29], and a subsequent brute force method, i.e., a strong field and low temperature, where solidification of a liquid ^{3}He and cooling are realized by compressing a liquid ^{3}He at a temperature lower than 320 mK, where an Entropy of liquid phase is less that of solid phase. In fact, with a magnetic field of 15T and temperature of 4 mK, the observed ^{3}He polarization was 0.95. [30]

Once the highly polarized solid ^{3}He is created, it is possible to make a liquid or gas ^{3}He without loss of polarization. The available maximum production rate of polarized ^{3}He gas could be over 1000 ℓ/day. This is an order of magnitude larger than that available at Mainz, Germany. This huge amount of production rate will almost satisfy a requirement not only for nuclear physics research and medical application (MRI), but also for a 1 GW-power station based on neutron-lean nuclear fusion using a polarized D_2 -^{3}He as considered at RCNP in collaboration with Leiden /The Netherlands and Orsay/France. [31]

2.6. Miscellaneous Methods

A few ideas to create the polarized ^{3}He ions are mentioned. Murnick proposed polarization by using a collinear laser beam method for the ^{3}He metastable 2^3S_1 state using a 1.083 μ pumping laser. This method uses a predominant population of the ^{3}He metastable state by an incidence of low energy ($\leq$1 keV) $^3He^+$ ion on a sodium vapor [32], and subsequent polarization by optical pumping in flight. The merit of this method is that a large efficiency due to the Doppler free pumping, short accumulation time of polarization because of no use of the metastability-exchange collisions, and no relaxation due to atomic collisions. In fact, the BNL group is considering this method as a polarized ^{3}He ion source for the e-RHIC project.

A scheme for a polarized $^3He^{2+}$ ion source based on resonant charge-exchange between polarized ^{3}He atoms and unpolarized $^4He^{2+}$ ions was proposed by Belov [33] as a polarized $^3He^{2+}$ source with a high intensity and high polarization. Polarized ^{3}He atoms are produced by optical

pumping, and stored in a storage cell. Unpolarized $^4He^{2+}$ ions are produced in a separate unpolarized plasma source and are injected into a charge-exchange region in which the polarized $^3He^{2+}$ ions are produced by the resonant charge-exchange of the polarized ^3He atoms with the unpolarized $^4He^{2+}$ ions.

Belov (INR/Moscow) and later Agapov et al. (JINR/Dubna) proposes to create a polarized $^3He^{2+}$ beam by using a polarized ^3He gas produced by optical pumping, and subsequent ionization with an EBIS (Electron Beam Ion Source) ionizer [5]. An advantage of this method is that a production section of polarized ^3He gas is separated from an ionization section connected to the accelerator. Transportation of the polarized ^3He gas is done only by carrying a gas container carefully constructed to avoid depolarization. Therefore, a versatile application of polarized ^3He gas for other purpose such as MRI can be possible.

3. ^{3}HE OPPIS DEVELOPED AT RCNP

I have developed a polarized ^3He ion source for a long time at RCNP and Dept. of Physics, Osaka University. Over the decades ago, I started constructing a ^3He OPPIS (Optical Pumping Polarized Ion Source) which uses capture of a polarized electron. The idea was firstly proposed by Zavoiskii [34] in 1957, developed by Anderson [35], and finally its validity was proven for proton [36]. However, in spite of an enormous effort, I could not obtain a satisfactory performance as a practical device. [37, 38, 39, 40, 41, 42, 43] To overcome above difficulties, I finally invented a new idea of polarized ^3He ion source named, "SEPIS", i.e., Spin Exchange Polarized Ion Source. [44]

3.1. Principle of polarization

The concept of SEPIS was born from a detailed analysis of our previous data on the EPPIS (Electron Pumping Polarized Ion Source). [41, 42] An extremely large spin-exchange cross section, σ_{se} exceeding 10^{-14} cm^2 was theoretically predicted for a $^3He^+$ + Rb system at a low $^3He^+$ incident energy ($\leq$1 keV/A) by the semiclassical close-coupling calculations based on the molecular orbital expansion. [42]

Further, it was known that electron capture cross section for a $^4He^+$ ion incident on an alkali atom, Cs decreases as decreasing a $^4He^+$ kinetic energy. [45] If these aspects, i.e., a large spin-exchange cross section and a small electron capture cross section, are true, this must be used for polarizing a $^3He^+$ ion and subsequently a ^3He nucleus.

3.2. Current status of SEPIS development

To check validity of SEPIS, I constructed a bench test device allowing a measurement of both electron capture cross sections, σ_{ec} and spin exchange cross sections, σ_{se} (see Fig. 3-a). An unpolarized $^3He^+$ ion beam extracted from a 2.45 GHz ECR ion source is incident on a Rb cell located under an axial magnetic field with ~0.3 T. The Rb cell was insulated and applied a high

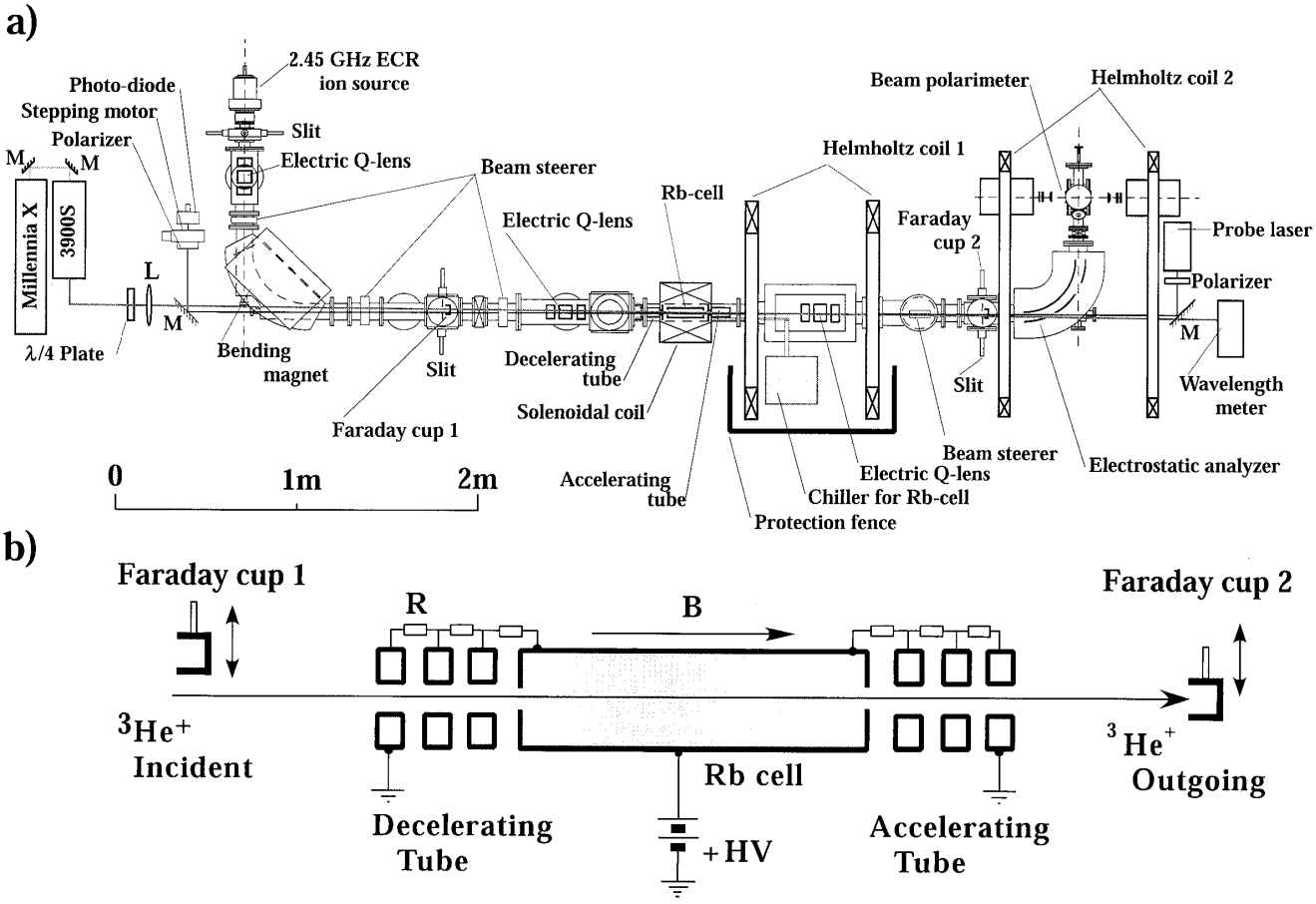

FIGURE 3. Experimental equipment constructed to prove the principle of SEPIS

voltage (see Fig. 3-b) so as to conveniently change the $^3He^+$ kinetic energy in a way free from tuning the other parts of the ion optics. The measurement of σ_{ec} for the $^3He^+$ + Rb system was done by varying a $^3He^+$ energy down to 1.7 keV/A. Observed σ_{ec} was simply extracted by comparing the $^3He^+$ beam intensity before and after the Rb cell. The experimental energy dependence of deduced σ_{ec} were roughly reproduced by the theory. [46]

Next, the measurement of σ_{se} was done as follows. The Rb vapor was polarized by means of optical pumping with a 795-nm pumping laser provided by a Ti:Sapphire laser pumped by a 10-W solid state green laser (see Fig. 3-a). The thickness and polarization of the Rb vapor were determined by observing a Faraday rotation angle for a 782-nm line from a probe laser. An unpolarized $^3He^+$ ion was incident on the Rb cell, the $^3He^+$ ion coming out of the Rb cell was electronically polarized by the spin-exchange collisions with polarized Rb atoms, and then nuclearly polarized via the hyperfine interactions. The nuclearly polarized $^3He^+$ beam was, then, introduced to a polarimeter after analyzed by an electro-static analyzer. Two sets of Helmholtz coils served as a polarization keeper against an unwanted stray magnetic field. A principle of the polarimeter is based on a beam foil spectroscopy with which a circular polarization was measured for photons emitted from a neutral ^3He in flight formed after penetrating a thin carbon foil. [37, 38] Thus, the $^3He^+$ nuclear polarization was determined as a function of the $^3He^+$ kinetic energy keeping the Rb vapor thickness fixed at ~1×1014 atoms/cm^2. The preliminary experimental

results are summarized in Fig. 4. Here, an ordinate is a polarization transfer coefficient defined by $2\times P_{^3He^+}/P_{Rb}$, where $P_{^3He^+}$ is a $^3He^+$ nuclear polarization and P_{Rb} is a Rb polarization, respectively. The solid curve in Fig. 4 is the calculated result assuming the theoretical values for σ_{se}. [44]

In conclusion, the present experimental data are qualitatively reproduced by the theory. This suggests, with the discussion previously given for σ_{ec}, that the SEPIS may be promising as a practical polarized ^3He ion source. [46]

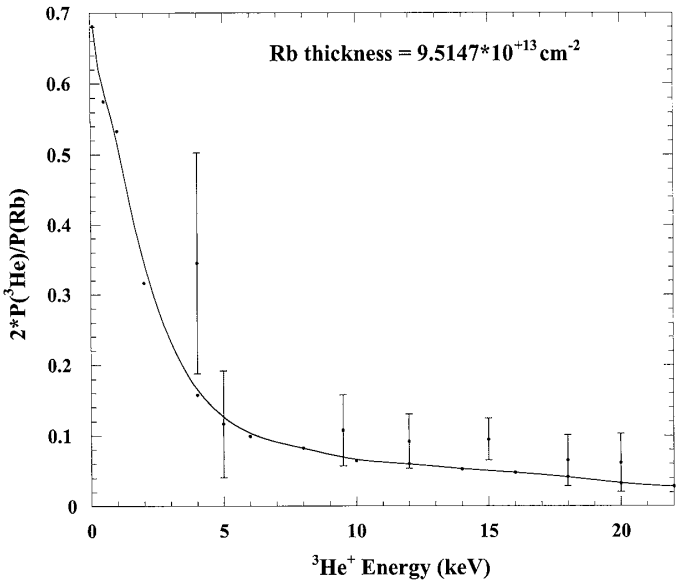

FIGURE 4. Observed and theoretical polarization transfer coefficients are plotted as a function of the incident $^3He^+$ energy.

TABLE 1. A table of performance for the polarized ^3He ion sources so far tested or put to practical use.

Lab.	Current(pnA)	Pol.(%)	Emittance (mm.mr)	En.(keV)	En. spr.(eV)	Ion
Birmingham	50	55-65	70	29	100	$^3He^{2+}$
Laval	100	95	25	12	-	$^3He^+$
Rice/Texas	8 pμA	11	10 mm.mr.eV$^{1/2}$	16	10-50	$^3He^+$
RCNP	10 pμA	5	$40\pi\times10^{-8}$ m.rad*	4	-	$^3He^+$

*Estimation by Yu. A. Plis [47]. This value was obtained assuming a SONA transition and production of a $^3He^{2+}$ ion by ionizing a polarized $^3He^+$ ion with a gas or foil stripper

4. CONCLUSION

I will show a table of performance for the polarized ^3He ion sources tested or put to practical use so far. Except ours, the table listed above sounds rather old; most of the data were taken more than 20 years ago. Therefore, when I consider a polarized ^3He ion source with high performance as a future plan, I must keep it in mind that this table would not be a starting point. Rather, the above table should be regarded as only the past mile stone.

Compared with the situation 20 years ago, our modern technologies including the laser, computer, ion sources, and so on have been far more developed. In addition, I have gained much invaluable experiences. I believe that it is quite timely now to start considering a polarized ^3He ion source with high performance, i.e., high polarization, high beam intensity, and small beam emittance.

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