Method for production of a ^{3}He beam with high polarization and high intensity

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We describe a concept in the production of a highly polarized $^3He^+$ beam using multiple-electron capture and stripping collisions between a fast incident $^3He^{2+}$ ion and a polarized alkali-metal atom at a strong magnetic field of 1–2 T. The yield and polarization of the outgoing $^3He^+$ ion are calculated by solving the rate equations. The yield shows a characteristic pattern as a function of the alkali-metal-atom vapor thickness as a result of the multiple-electron capture and stripping collisions. The polarization shows a gradual decrease at low vapor thicknesses and a steep increase up to unity at about 2×10^{15} atoms/cm^2. By using 30-keV/amu $^3He^+$ as a primary beam, a fully polarized $^3He^+$ beam of about 0.5 mA may be possible. It is also suggested that not only polarized ^{3}He ions but a polarized fast atomic ^{3}He beam can be produced by the present method, where the expected polarization and beam intensity are ~0.8 and $\sim6\times10^{15}$ atoms/sec, respectively.

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I. INTRODUCTION

Since the suggestion [1] of a polarized proton ion source based on polarized electron captures in an alkali-metal-atom vapor, much effort has been devoted to the realization of the optical pumping polarized ion source (OPPIS). As a result, polarized proton beams with a polarization higher than 0.8 and a beam intensity current higher than 0.4 mA have become available in a pulsed mode [2–5] and greater than 0.1 mA in a cw mode [6].

The prospect for producing polarized heavy ions by means of the OPPIS technique has been discussed [7]. A success in polarizing heavy ions by this method was accomplished for production of $^3He^+$ [8] and N^{4+} [9]. However, through the above studies it has been found that heavy-ion nuclear polarizations obtained by the use of OPPIS are restricted to lower values than the proton polarization. For example, the maximum ^{3}He polarization obtainable by this method is only about 0.3 [10].

The origin of this polarization reduction for heavier ions is explained as follows: A polarized electron is transferred from an alkali-metal atom to an incident highly stripped heavy ion by an electron-capture collision. Since the captured electron is usually in an excited level of the ion, the ion disintegrates to the ground or metastable levels by photon emission. A considerable amount of the electron polarization is carried away by the photons because the LS coupling allows a spin-flip transition.

An external magnetic field to decouple L and S, the so-called "decoupling field," is usually applied to avoid the spin-flip transition. The required decoupling field B_{LS} for a hydrogenlike atom with a nuclear charge Z [11] is proportional to

$$B_{LS} \propto \frac{Z^4}{n^3 l(l+1)} , \tag{1}$$

where $n(\neq1)$ and $l(\neq0)$ are, respectively, the principal and the orbital angular-momentum quantum numbers for the electron orbital formed by the polarized electron capture. This result shows that the necessary B_{LS} is a maximum, when the excited level with $n=2$ and $l=1$ is populated after photon emissions from the higher excited levels. The maximum B_{LS} required for a proton is only 1–2 T, whereas a huge B_{LS} is needed for heavier ions due to a term proportional to Z^4 in Eq. (1); a field of about 30 T is necessary even for the lightest heavy ion such as ^{3}He. The depolarization due to an insufficient LS decoupling field is unavoidable for heavier ions.

This high decoupling field is a serious drawback for the OPPIS method when it is applied to polarize heavier nuclei. Therefore a method to avoid the electron depolarization due to an insufficient LS decoupling field is required. Recently, evidence for a sequential double electron-capture process was suggested from the analysis of the experimental data of the $^3He^+$ yield versus sodium vapor thicknesses for $^3He^{2+}$ incident on Na [10]. This interesting phenomenon motivated us to examine an idea for polarizing ^{3}He nuclei beyond the polarization limit due to an insufficient LS decoupling field. As is discussed in the following section, our idea is to obtain electron polarization by sequential electron capture and stripping between incident $^3He^+$ ions and polarized alkali-metal atoms. Through the multiple collision processes, the relevant charge states of the ^{3}He ions are mainly neutral and singly ionized if the incident energy of the ^{3}He ions is a few keV/amu. This means that the strength of the LS decoupling field required for these processes is comparable to the decoupling field required for protons (1–2 T). Our idea is in striking contrast to the OPPIS for which a single electron-capture process dominates and which requires a decoupling field more than 30 T.

A concept of the polarization deposition by successive collisions was previously examined by Anderson *et al.* [12] to provide highly polarized intense hydrogen or deuterium beams for the fusion research. They called the method collisional pumping. An advantage of this idea is that no strong decoupling field is necessary. In recent years, the use of multiple spin-exchange collisions has been experimentally examined by Zelenski and Kokhanovksi [13] at Institute of Nuclear Research, Moscow, and TRI University Meson Facility, Vancouver, in pursuit of an alternative type of a polarized proton ion source. We call an ion source based on our method a multiple-electron capture and stripping ion source (MECSIS).

Application of the MECSIS method is not restricted to technology used in the polarized ion sources. Since the effect of multiple collisions in an ion-atom system has not been well studied, our method may shed light on plasma physics and astrophysics as well as atomic physics.

II. OUTLINE OF MULTIPLE-ELECTRON CAPTURE AND STRIPPING COLLISIONS

A. Intuitive explanation of the principle

In our previous work [10], we found that with $^3He^{2+}$ incident as the sodium vapor thickness increases, the $^3He^+$ yield increases in proportion to the vapor thickness for low values of the target thickness. Beyond a vapor thickness of $\sim 3\times 10^{13}$ atoms/cm^2 the yield shows a decrease. The initial increase of the $^3He^+$ yield is a consequence of the electron-capture process, while decrease of the yield of $^3He^+$ ions is due to predominance of sequential double electron-capture processes expressed by

$$^3He^{2+}\rightarrow {}^3He^+\rightarrow {}^3He^0 , \tag{2}$$

at higher vapor thickness. It is expected that as the alkali-metal-atom vapor thickness increases, the charge state distribution for an incident $^3He^{2+}$ ion is equilibrated. The equilibrated charge distribution is mainly determined by the incident $^3He^{2+}$ energy. When the incident $^3He^{2+}$ energy is 5–6 keV/amu, the percentage yield ratio of the outgoing ion is given [14] in Table I. Though the yield ratio for higher charged states becomes significant at higher incident energy, the yield ratio for the $^3He^{2+}$ ion is still less than 2% as long as the incident energy is less than $\sim$30 keV/amu. In the equilibrated condition, the following electron pickup and stripping collisions repeatedly occur in the alkali-metal-atom vapor:

$$^3He^0\rightarrow {}^3He^+ \quad \text{(electron stripping)} ,$$
$$^3He^+\rightarrow {}^3He^0 \quad \text{(electron capture)} . \tag{3}$$

Here, the electron stripping of a $^3He^+$ ion to form a $^3He^{2+}$ ion can be neglected at these incident energies.

An intuitive scenario of the polarization deposition is shown in Fig. 1. An incident $^3He^{2+}$ captures a fully polarized electron from an alkali-metal atom and the electron polarization is reduced to about 0.3 (a short arrow in

TABLE I. Charge distribution of outgoing ^{3}He ions at 6.7 and 30 keV/amu impact energies referred from Ref. [14].

Outgoing ion	Yield ratio (%) at 5 keV/amu	Yield ratio (%) at 30 keV/amu
$^3He^{2+}$	0	2
$^3He^+$	11	47
$^3He^0$	89	51

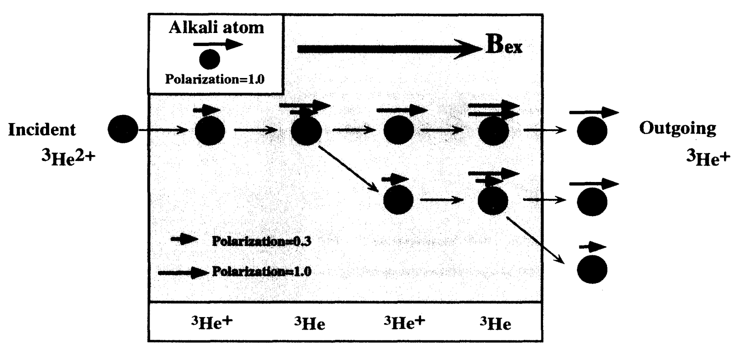

FIG. 1. Illustration showing a principle of the polarization deposition assuming that an alkali-metal atom is completely polarized and an external magnetic field (1–2 T) necessary to decouple L and S for $Z=1$ is applied. A $^3He^{2+}$ ion incident on an alkali-metal vapor cell captures a completely polarized electron. The captured electron polarization reduces to 0.3 (a short arrow) due to the insufficient decoupling field. An additional electron capture occurs keeping the polarization of the captured electron 1.0 (a long arrow). An electron stripping, then, occurs, where the stripping probability for a completely polarized electron is approximately equal to that for an electron with the polarization of 0.3. A repeated sequence of the capture and stripping collisions makes the electron polarization for the $^3He^+$ ion increase.

Fig. 1) due to the emission of photons in a magnetic field less than B_{LS} as was discussed in the preceding section. The $^3He^+$ formed by the capture process, then, captures another fully polarized electron (a long arrow in Fig. 1). The second electron capture results in a fast neutral atom. The necessary decoupling field is similar to the value for the proton OPPIS. As a result, the polarization of the second electron can be kept 1.0 during the cascade decay to the $2\,^3S$ metastable level. Following this capture, the stripping collision occurs. The averaged electron polarization for the $^3He^+$ ion thus formed is

$$\frac{0.3+1.0}{2}=0.65 , \tag{4}$$

assuming stripping of a completely polarized electron is approximately equal to that of an electron with a polarization of 0.3. Further additional electron-capture and stripping collisions are repeated before a $^3He^+$ ion comes out of the alkali-metal-atom vapor cell. Every capture and stripping collision makes the average electron polarization increase. After many capture and stripping collisions, the electron polarization for the $^3He^+$ ion outgoing from the alkali-metal vapor cell tends to 1.0. In this simple model, the polarization deposition due to repeated spin-exchange collisions [12] between $^3He^+$ ions or atoms and polarized alkali-metal atoms is not considered although it may be important [13].

B. Quantitative evaluation of the polarization

In this section, we make a quantitative calculation of yields and electron polarizations of $^3He^+$ ions produced by the MECSIS method by solving the appropriate rate equations. The $^3He^{2+}$ incident energy is chosen as 5 keV/amu. Our calculation includes formation of both triplet ($2\,^3S$) and singlet ($2\,^1S$) levels of $^3He^0$ by the electron-capture process. We also consider the effect of spin-exchange collisions between a $^3He^+$ ion or $^3He^0$ atom and an alkali-metal atom.

The rate equations are given by

$$\frac{dH^{2+}}{d\pi}=-\sigma_{21}H^{2+} , \tag{5a}$$

$$\frac{dH^{+}_{1/2}}{d\pi}=+\frac{1+P_0}{2}\sigma_{21}H^{2+}-\sigma_{+t}H^{+}_{1/2}+\sigma_{t+}(H_{t1}+\tfrac{1}{2}H_{t0}) +\sigma_{\mathrm{SEI}}H^{+}_{-1/2} , \tag{5b}$$

$$\frac{dH^{+}_{-1/2}}{d\pi}=+\frac{1-P_0}{2}\sigma_{21}H^{2+}-\tfrac{1}{2}(\sigma_{+t}+\sigma_{+s})H^{+}_{-1/2} +\tfrac{1}{2}\sigma_{t+}H_{t0}+\sigma_{\mathrm{SEI}}H^{+}_{-1/2} , \tag{5c}$$

$$\frac{dH_{t1}}{d\pi}=\sigma_{+t}H^{+}_{1/2}-\sigma_{t+}H_{t1}+\sigma_{\mathrm{SEA}}H_{t0} , \tag{5d}$$

$$\frac{dH_{t0}}{d\pi}=\tfrac{1}{2}\sigma_{+t}H^{+}_{-1/2}-\sigma_{t+}H_{t0}-\sigma_{\mathrm{SEA}}H_{t0} , \tag{5e}$$

$$\frac{dH_{t-1}}{d\pi}=0 , \tag{5f}$$

$$\frac{dH_{s0}}{d\pi}=\tfrac{1}{2}\sigma_{+s}H^{+}_{-1/2} , \tag{5g}$$

where π is an alkali-metal-atom vapor thickness in atoms/cm^2, P_0 is the $^3He^+$ polarization produced through a capture of a fully polarized electron from an alkali-metal atom by an incident $^3He^{2+}$ ion ($P\sim0.3$ [10]), H^{2+} is the $^3He^{2+}$ intensity in ions/s, $H^{+}_{1/2}$ and $H^{+}_{-1/2}$ are $^3He^+$ intensities for the $m_z=\frac{1}{2}$ and $-\frac{1}{2}$ levels, $H_{t1,}$ H_{t0} H_{t-1} are ^3He $2\,^3S$ intensities for the $m_z=1$, 0, and -1 levels, H_{s0} is the ^3He $2\,^1S$ intensity, σ_{21} is the capture cross section from the doubly to singly charged state, σ_{+t}, σ_{t+} are the capture cross sections from the singly ionized to the $2\,^3S$ level and the reverse process, σ_{+s} is the capture cross section from the singly ionized to the $2\,^1S$ level, and σ_{SEI} and σ_{SEA} are the spin-exchange cross sections for an ion and atom, respectively. In the derivation of the equations, we assume the following.

(1) Alkali-metal polarization is unity.

(2) The $2\,^1S$ level is mostly quenched to the $1\,^1S$ level and therefore stripping from any singlet level of the $^3He^0$ atom to the $^3He^+$ ion is neglected.

(3) Direct double electron capture from the $^3He^{2+}$ ion to the $^3He^0$ atom is small enough to neglect.

(4) Stripping from the $^3He^+$ ion to the $^3He^{2+}$ ion is small enough to neglect.

(5) Electron capture from the $^3He^0$ atom to negative ions is small enough to neglect.

(6) Electron capture from the $^3He^{2+}$ ion to the $2\,^2S$ metastable level of the $^3He^+$ ion is neglected.

The rate equations (5a)–(5g) are numerically solved by means of the Runge-Kutta method under the initial condition that $H^{2+}=1.0$, $H^{+}_{1/2}=H^{+}_{-1/2}=H_{t1}=H_{t0}=H_{t-1}=H_{s0}=0.0$ at $\pi=0$ with appropriate values of the capture, stripping, and spin-exchange cross sections: The capture cross sections, σ_{21} and σ_{10} ($=\sigma_{+t}+\sigma_{+}s$) are measured in an incident energy range from 0.025 to 0.38 keV/amu for Na, K, Rb, and Cs [15] and in an incident energy range from 0.5 to 50 keV/amu for lithium and sodium [16]. We employ $\sigma_{21}=1.41\times10^{-14}$, and $\sigma_{10}=1.15\times10^{-14}$ cm^2 which are the observed results for the sodium target at the incident energy of 5 keV/amu. Assuming that $\sigma_{+t}=\frac{3}{4}\sigma_{10}$ and $\sigma_{+s}=\frac{1}{4}\sigma_{10}$, we obtain $\sigma_{+t}=0.863\times10^{-14}$, and $\sigma_{+s}=0.288\times10^{-14}$ cm^2, respectively. Since the information on the spin-exchange cross sections for an ion and atom, σ_{SEA} and σ_{SEI}, are lacking, we assume that $\sigma_{\mathrm{SEA}}=\sigma_{\mathrm{SEI}}=0.1\times10^{-14}$ cm^2 using a value similar to that for the hydrogen atom [17]. The data on the stripping cross sections, σ_{t+} at the incident energy of present interest, are also not well known. Therefore we determine σ_{t+} so that the calculated $^3He^+$ yield ratio at the large alkali-metal vapor thickness, where the charge distribution is equilibrated for the $^3He^+$ ions passing through the alkali-metal-atom vapor, may reproduce the values in Table I. The result thus obtained is $\sigma_{t+}=0.123\times10^{-14}$ cm^2.

III. DISCUSSION AND FUTURE DIRECTIONS

A. $^3He^+$ yield ratio

According to the procedure in Sec. II, we calculate the outgoing $^3He^+$ yield ratio, $Y_{^3He^+}$, which is defined as

$$Y_{^3\mathrm{He}^+}=\frac{H^{+}_{1/2}+H^{+}_{-1/2}}{H^{2+}(\pi=0)}\ , \tag{6}$$

assuming the 5-keV/amu $^3He^{2+}$ ions with an intensity of 1 are incident on the alkali-metal-atom vapor. The calculated result is plotted in Fig. 2(a) as a function of the alkali-metal-atom vapor thickness.

We mentioned in Sec. II that the peak of the $Y_{^3\mathrm{He}^+}$ yield ratio [10] is a consequence of the sequential double electron capture. As shown in the solid curve in Fig. 2(a), the calculated result reproduces this behavior. At the vapor thicknesses above 10^{15} atoms/cm^2, the yield ratio is close to the saturated value of $\sim 11\%$. This indicates that the equilibrium is achieved due to the multiple-electron capture and stripping collisions.

B. $^3He^+$ polarization

The calculated $^3He^+$ polarization (solid curve), $P_{^3\mathrm{He}^+}$, defined by

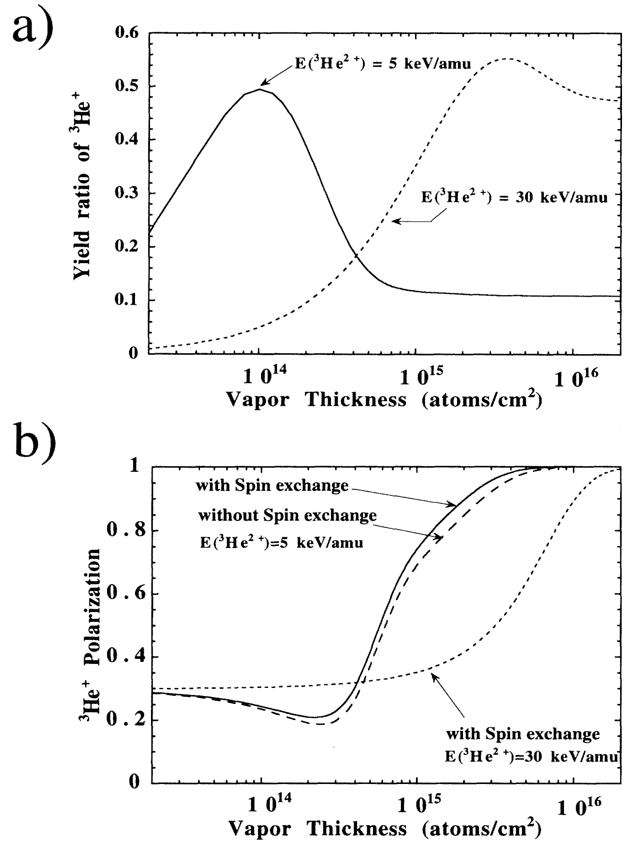

FIG. 2. The yield ratio and electronic polarization of the outgoing $^3He^+$ ions calculated by the Runge-Kutta method as a function of the alkali-metal-atom vapor thickness. (a) The solid (dotted) curve is the calculated result for the $^3He^{2+}$ incident energy of 5 keV (30 keV/amu). (b) The curves denoted by "with spin exchange" (solid curve) and "without spin exchange" (dashed curve) are the calculated results with the appropriate spin-exchange cross section and with the spin-exchange cross section set exactly to zero, respectively, where the incident $^3He^{2+}$ energy is 5 keV/amu. The dotted curve is obtained for the $^3He^{2+}$ incident energy of 30 keV/amu.

$$P_{^3\mathrm{He}^+}=\frac{H^{+}_{1/2}-H^{+}_{-1/2}}{H^{+}_{1/2}+H^{+}_{-1/2}}\ , \tag{7}$$

is plotted in Fig. 2(b) as a function of the alkali-metal-atom vapor thickness. The polarization gradually decreases from 0.3 to less than 0.2, and then begins to increase. As the alkali-metal vapor thickness increases further, the $^3He^+$ polarization rises to unity at the vapor thickness of $\sim 10^{16}$ atoms/cm^2. The unexpected falloff of $P_{^3\mathrm{He}^+}$ at low vapor thicknesses is commonly seen for both calculated results with and without the spin-exchange collisions.

The above overall behavior is simply understood in terms of sequential double electron-capture and stripping processes. After the polarized $^3He^+$ ions are formed, they are converted into fast neutral atoms by successive electron capture. Since the capture cross section σ_{+t} is larger than σ_{+s}, the loss of $^3\mathrm{He}_{+1/2}$ is larger than the loss of $^3\mathrm{He}^{+}_{-1/2}$ by electron capture. This results in a decrease in the $^3He^+$ polarization at low alkali-metal target thickness. The increase in the $^3He^+$ polarization begins at the vapor thickness corresponding to $1/\sigma_{t+}\sim 10^{15}$ atoms/cm^2, where the stripping process becomes significant.

To see the effect of the spin-exchange collisions we have plotted the calculated result without the spin-exchange cross sections σ_{SEI}, and σ_{SEA}. There is only a minor polarization difference between the calculated results with and without the spin-exchange collisions, from which the spin-exchange collisions are less important in our method. This result is in striking contrast to the collisional pumping method of Ref. [12] in which the spin-exchange collisions are the primary driving force to produce the polarization.

Another important difference between the MECSIS and the collisional pumping method of Ref. [12] is the difference of the required vapor thickness; the vapor thicknesses required for obtaining the polarization larger than 0.9 are estimated to be 1.8×10^{15} for the MECSIS, and 50×10^{15} atoms/cm^2 for the collisional pumping, respectively. This clearly indicates that the MECSIS needs less vapor thickness than the collisional pumping of Ref. [12] by more than an order of magnitude. This is a great advantage because realization of completely polarized alkali-metal vapor is difficult for large vapor thickness [13].

C. Increase of $^3He^+$ polarized beam intensity

So far, we have restricted our discussion to the yield ratio and polarization of $^3He^+$ for a $^3He^{2+}$ incident energy of 5 keV/amu. The achievable $^3He^+$ beam intensity is determined by the $^3He^+$ yield ratio at saturation thickness. One way of increasing the outcoming $^3He^+$ beam intensity is to increase the $^3He^+$ yield ratio by increasing the incident energy since the charge distribution is expected to shift toward higher charged states. As a matter of fact, the yield ratio will increase up to almost 50% at the incident energy of 30 keV/amu as shown in Table I. To see the behavior of the polarization at such a higher incident energy, we solved Eqs. (5a)–(5g) by changing capture and stripping cross sections to fit those at the higher incident energy. Referring to the observed values for the electron-capture cross sections of the sodium target [16], we employ the following values: $\sigma_{21} = 0.052\times10^{-14}$, $\sigma_{+t} = 0.032\times10^{-14}$, and $\sigma_{+s} = 0.011\times10^{-14}$. The unknown stripping cross section σ_{t+} is determined so that the calculated $^3He^+$ yield ratio at the large vapor thickness may reproduce the value given in Table I. The obtained result is $\sigma_{t+} = 0.032\times10^{-14}$.

The results of the calculation are shown by the dotted curves in Figs. 2(a) and 2(b). As shown in Fig. 2(a), the peak yield shifts to higher vapor thickness. The saturated value of the $^3He^+$ yield ratio is 47%. The polarization shows a characteristic behavior in a similar way to the low incident energy case. However, there seems to be a big difference regarding the saturation vapor thickness at which the polarization exceeds 0.9. The saturation vapor thickness for 5 keV/amu incidence is 2×10^{15} atom/cm^2, while that for 30 keV/amu is 10×10^{15} atoms/cm^2. The increase of the saturation thickness at the higher incident energy is simply a consequence of the reduction of the electron-capture and stripping cross sections. The increase of the saturation vapor thickness is disadvantageous. However, it is very significant that the $^3He^+$ beam intensity can be increased by increasing the incident $^3He^{2+}$ energy keeping the polarization at 1.0.

However, one should remind oneself that our calculations assume that the formation of $^3He^{2+}$ ions by stripping is neglected. If the stripping to $^3He^{2+}$ is included, the expected polarization will be reduced because the electronic polarization formed through the electron capture by the $^3He^{2+}$ ions is 0.3 again. As shown in Table I, the $^3He^{2+}$ yield at 30 keV/amu is only 2%, which indicates that even at this incident energy our calculations are appropriate.

D. $^3He^+$ ion as an incident beam

We discuss here the possibility of using 30-keV/amu $^3He^+$ ions instead of $^3He^{2+}$ ions as the incident beam. For this purpose, we solved the rate equations (5a)–(5g) using the initial condition of $H^+{}_{+1/2} = H^+{}_{-1/2} = \frac{1}{2}$. The calculated results are shown in Fig. 3. The $^3He^+$ yield (the solid curve) smoothly decreases and reaches the saturation value, 0.46. In a similar way, the $^3He^+$ polarization (the dashed curve) shows a gentle increase toward the full polarization. The saturation vapor thickness is not so different from the case for incidence of the $^3He^{2+}$ ions. This result indicates that the $^3He^+$ ions can be used for a primary beam instead of the $^3He^{2+}$ ions. In addition, the use of $^3He^+$ ions is more advantageous because of the following crucial reasons.

(1) The $^3He^+$ ion current is much higher than the $^3He^{2+}$ ion current for available ion sources.

(2) A serious emittance growth induced by the charge changing collisions in the strong solenoidal magnetic field [1ɔ] can be completely eliminated.

E. Expected polarized $^3He^{2+}$ beam current

We evaluate here the expected $^3He^{2+}$ beam current based on the MECSIS in which $^3He^+$ ions with 30 keV/amu are used as an incident beam. As mentioned in Ref. [10], we are constructing a polarized ^3He ion source based on the OPPIS in combination with the electron cyclotron resonance ion source, Neomafios–10 GHz. This setup can also be used for our polarized ion source if one improves the assembly of the solenoidal coil and the sodium vapor cell.

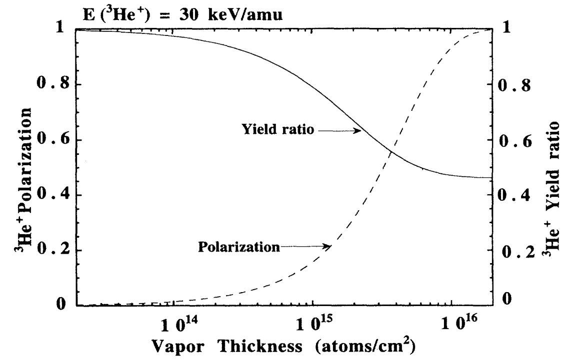

FIG. 3. The yield ratio (the solid curve) and electronic polarization (the dashed curve) of the outgoing $^3He^+$ ion calculated by the Runge-Kutta method are plotted as a function of the alkali-metal-atom vapor thickness. Here, $^3He^+$ ions are used as an incident beam.

According to the recent record on the performance of the Neomafios–10 GHz, more than 1-mA $^3He^+$ beam can be successfully extracted [19]. Using this value and the $^3He^+$ yield ratio tabulated in Table I, the outgoing polarized $^3He^+$ beam is estimated to be 0.47 mA. Before the injection into the cyclotron, the polarized $^3He^+$ beam should be stripped to the $^3He^{2+}$ beam and simultaneously the electron polarization should be converted to nuclear polarization by means of the Sona transition [20]. For this purpose, a stripping gas or foil is inserted between the Sona field. Since the stripping efficiency to make the $^3He^{2+}$ ions is 2% at 30 keV/amu as shown in Table I, the expected polarized $^3He^{2+}$ beam is estimated to be 19 μA. To improve the stripping efficiency stripping after acceleration of the polarized $^3He^+$ beam seems to be preferable. For example, if the polarized ion source assembly is mounted on a 300-kV high-voltage platform, one can expect $^3He^{2+}$ beam current of approximately 0.3 mA. This expectation value is more than orders of magnitude larger than our previous estimation based on the OPPIS [10].

F. Production of polarized fast ^3He atoms

By using the MECSIS one can expect not only polarized $^3He^+$ ions but polarized fast ^3He atoms. Because the charge states of these fast atoms are neutral, these components might be used as a polarized target as well. At the $^3He^+$ incident energy of 5 keV/amu, 89% of the outgoing ^3He ions are neutral as shown in Table I. We solve the rate equations (5a)–(5g) assuming $^3He^+$ ions are incident on the alkali-metal-atom vapor. In Fig. 4 the ^3He atomic polarization defined by

$$P_{^3\mathrm{He}} = \frac{H_{t1}}{H_{t1}+H_{t0}+H_{s0}} , \tag{8}$$

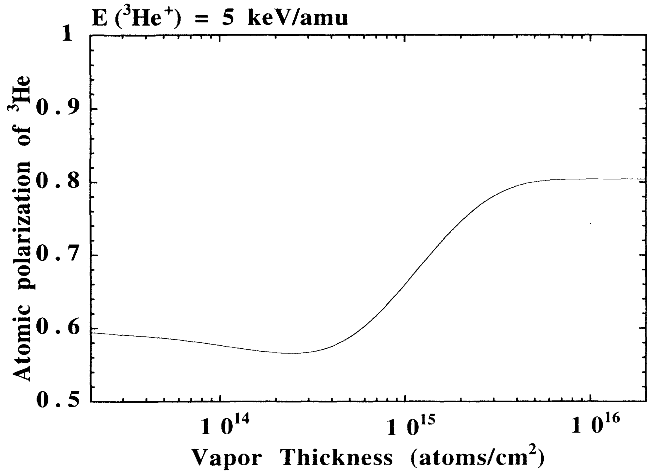

FIG. 4. The polarization of the ^{3}He atoms calculated by the Runge-Kutta method, where the incident $^3He^+$ energy is 5 keV/amu.

is plotted as a function of the alkali-metal vapor thickness. As the vapor thickness is increased, $P_{^3\mathrm{He}}$ decreases at first and then rises to the saturation value of ~ 0.8. This behavior is similar to that for the $^3He^+$ ions. The reduction of the saturation value from unity is due to the coexistence of the unpolarized $2\,^1S$ component. The expected beam intensity is 5.6×10^{15} atoms/sec.

IV. SUMMARY AND CONCLUSION

We present in this paper an outline of our method called MECSIS to increase both the nuclear polarization and beam current. The principle of the MECSIS is based on multiple-electron capture and stripping collisions between incident ions and polarized alkali-metal atoms. The MECSIS wil provide a completely polarized $^3He^+$ with a strong beam intensity. In particular, the use of the $^3He^+$ ions with 30 keV/amu as a primary beam will enable us to produce almost a half mA polarized $^3He^+$ beam without an emittance growth due to the solenoidal magnetic field. This expected performance ranks with the polarized proton ion sources based on the OPPIS. One of the promising applications of the MECSIS is the polarized ^{3}He target. This may be used for atomic physics, plasma physics, and high-energy physics as well as nuclear physics. Feasibility of the MECSIS will be experimentally examined by using optical pumping of alkali-metal-atom vapor with high power lasers.

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[1] L. W. Anderson, Nucl. Instrum. Methods **167**, 363 (1979).
[2] Y. Mori, A. Takagi, K. Ikegami, S. Fukumoto, and A. Ueno, J. Phys. Soc. Jpn. Suppl. **55**, 453 (1986).
[3] C. D. P. Levy, A. N. Zelenski, K. Jayamanna, M. McDonald, R. Ruegg, P. W. Schmor, and G. Wight, *Polarized Ion Sources and Polarized Gas Targets,* edited by L. W. Anderson and W. Haeberli, AIP Conf. Proc. No. 293 (AIP, New York, 1994), p. 179.
[4] R. L. York, D. Tupa, D. R. Swenson, M. W. McNaughton, and O. B. van Dyck, in Ref. [3], p. 196.
[5] Y. Mori, in Ref. [3], p. 151.
[6] P. W. Schmor (private communication).
[7] M. Tanaka, T. Ohshima, K. Katori, M. Fujiwara, T. Itahashi, H. Ogata, M. Kondo, and L. W. Anderson, Nucl. Instrum. Methods A **302**, 460 (1991).
[8] T. Ohshima, K. Abe, K. Katori, M. Fujiwara, T. Itahashi, H. Ogata, M. Kondo, and M. Tanaka, Phys. Lett. B **274**, 163 (1992).
[9] C.-J. Liu, N. B. Mansour, Y. Azuma, H. G. Berry, D. A. Church, and R. W. Dunford, Phys. Rev. Lett. **64**, 1354 (1990).
[10] M. Tanaka, N. Shimakura, T. Ohshima, K. Katori, M. Fujiwara, H. Ogata, and M. Kondo, Phys. Rev. A **50**, 1184 (1994).
[11] B. H. Bransden and C. J. Joachain, *Physics of Atoms and Molecules* (Wiley, New York, 1983).
[12] L. W. Anderson, S. N. Kaplan, R. V. Pyle, L. Ruby, A. S. Schlachter, and J. W. Stearns, Phys. Rev. Lett. **52**, 609 (1984).
[13] A. N. Zelenski and S. A. Kokhanovski, in *Polarized Ion Sources and Polarized Gas Targets,* edited by L. W. Anderson and W. Haeberli, AIP Conf. Proc. No. 293 (AIP, New York, 1994), p. 164.
[14] J. B. Marion and F. C. Young, *Nuclear Reaction Analysis* (North-Holland, Amsterdam, 1968).
[15] C. Reynaud, J. Pommier, Vu Ngoc Tuan, and M. Barat, Phys. Rev. Lett. **43**, 579 (1979).
[16] R. D. DuBois and L. H. Toburen, Phys. Rev. A **31**, 3603 (1985).
[17] D. R. Swenson, D. Tupa, and L. W. Anderson, Helv. Phys. Acta **59**, 662 (1986).
[18] G. G. Ohlsen, J. L. McKibben, R. R. Stevens, Jr., and G. P. Lawrence, Nucl. Instrum. Methods **73**, 45 (1969).
[19] K. Hatanaka, K. Takahisa, and I. Miura (private communication).
[20] P. Sona, Energ. Nucl. (Milan) **14**, 295 (1967).

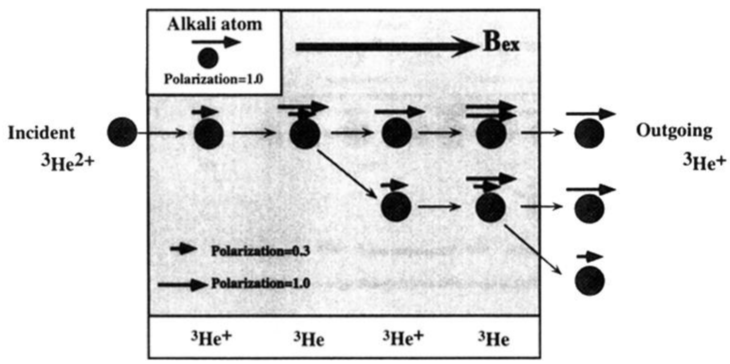

FIG. 1. Illustration showing a principle of the polarization deposition assuming that an alkali-metal atom is completely polarized and an external magnetic field (1–2 T) necessary to decouple L and S for $Z=1$ is applied. A $^3He^{2+}$ ion incident on an alkali-metal vapor cell captures a completely polarized electron. The captured electron polarization reduces to 0.3 (a short arrow) due to the insufficient decoupling field. An additional electron capture occurs keeping the polarization of the captured electron 1.0 (a long arrow). An electron stripping, then, occurs, where the stripping probability for a completely polarized electron is approximately equal to that for an electron with the polarization of 0.3. A repeated sequence of the capture and stripping collisions makes the electron polarization for the $^3He^+$ ion increase.