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# Monte Carlo Simulation of Ion Optics Involved Multiple Charge Exchange Interaction under a Solenoidal Magnetic Field

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## Abstract

Ion optics of a $^3$He ion involved multiple charge exchange interaction under a solenoidal magnetic field was investigated by means of Monte Carlo simulation. It was found that (1) beam emittance growth results not from an angular broadening but from a beam size enlargement, (2) the phenomena under the magnetic field B are simplified by a no charge exchange phenomenon under a weaker magnetic field (effective magnetic field), $B_{eff}$ defined by

$$B_{eff} \simeq \frac{\lambda_{+0}}{\lambda_{+0} + \lambda_{0+}} B,$$

where $\lambda_{+0}$ and $\lambda_{0+}$ are mean free paths for $^3He^+$ ion and $^3He^0$ atom, which undergo the charge exchange interactions traveling in the alkali vapor.

## 1 Introduction

A new type of a polarized $^3$He ion source based on a principle, so called " electron pumping ", was recently proposed [1]. The polarized ion source under this principle requires multiple electron capture and stripping collisions (hereafter, we use an abbreviated word, multiple collisions) of a $^3He^+$ ion with polarized alkali atoms under a strong magnetic field ( ~ 3T ). Since, no one has ever attempted to solve a problems induced by the multiple collisions under a strong magnetic field, a beam emittance growth and reduction of polarized beam intensity are considered to be one of the serious problems of this new ion source.

In the present work, the Monte Carlo simulation were performed paying a special attention on the emittance growth and reduction of the beam intensity due to the multiple collisions under a strong magnetic field. The calculated results were somehow in more detail discussed, from which a new concept of an "effective field" has been deduced. The effective field will provide a convenient tool in simply calculating the beam optics with a solenoid field in which charge changing collisions are allowed.

## 2 Monte Carlo simulation

We assume an idealized geometry in the Monte Carlo simulation. An alkali vapor cell ( 1 cm in diameter × 30 cm in length ) is located at the center of a superconducting solenoid magnet ( 19 cm in bore diameter × 56 cm in length ). The alkali vapor cell uniformly contains alkali atoms with a vapor density $\rho = 2 \times 10^{14}$ atoms/cm$^3$ and zero in the outside region. The magnetic field is uniformly distributed throughout the inside region of the solenoid magnet and is zero in the outside region. Only the processes (1) $^3He^+ \rightarrow {}^3He^0$, and (2) $^3He^0 \rightarrow {}^3He^+$ were taken into account by the present Monte Carlo simulation as possible multiple collision processes with large cross sections in the present $^3He^+$ energy ( = 20 keV ). A series of these processes are repeated until the $^3$He ion/atom hits the cell wall or reaches an exit of the alkali vapor cell either. We carry out these trials 5000 times. In the process (1), the $^3He^+$ ion moves spirally by the Lorenz force and becomes a $^3He^0$ atom by the electron capture collision. Then, in the process (2), the $^3He^0$ atom goes straight and becomes a $^3He^+$ ion again by the electron stripping collision. The cross sections of (1) and (2) are $1.15 \times 10^{-14}$ cm$^2$ and $0.123 \times 10^{-14}$ cm$^2$ [1-3], respectivery. Thus, the mean free paths are $\lambda_{+0} = 1/(\sigma_{+0} \cdot \rho) \approx 0.43$ cm and $\lambda_{0+} = 1/(\sigma_{0+} \cdot \rho) \approx 4.06$ cm, respectively. We assume an incident $^3He^+$ beam emittance of $(\pm 1mm) \times (\pm 25mr)$ at the entrance of the alkali vapor cell.

## 3 Results and Discussion

### 3.1 Beam emittance growth and transmission

The beam emittance is found to be $(\pm 5mm) \times (\pm 25mr)$ which is five times larger than that at the entrance of the cell, $(\pm 1mm) \times (\pm 25mr)$, where the alkali vapor density is $2 \times 10^{14}$ atoms/ cm$^3$, and the magnetic field is 3 T. The emittance growth by a factor 5 results only from the beam size enlargement.

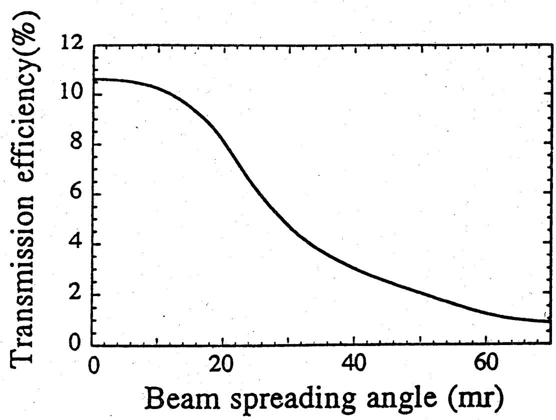

Fig. 1. The calculated results of the $^3He^+$ beam transmission efficiency plotted as a function of a spreading angle. See text for further detail.

Figure 1 shows the calculated results of the $^3He^+$ beam transmission efficiency plotted as a function of the spreading angle of the incident $^3He^+$ beam with the alkali vapor density of 2 × $10^{14}$ atoms/cm$^3$ at B = 3 T. From this figure, it is found that the transmission efficiency is a constant, i.e., 10% when the beam spreading angle is smaller than 10 mr. This efficiency corresponds to a fraction of $^3He^+$ in an equilibrium charge state at a $^3He^+$ beam energy of 20 keV. On the other hand, when the spreading angle becomes larger than 10 mr, the transmission efficiency tends to decrease in Fig. 1. This decrease is due to a loss of the incident $^3He^+$ ion by the wall collision of the alkali vapor cell.

### *3.2 Physical background of emittance growth and concept of effective magnetic field*

Figure 2 shows the size and the phase space of the beam at the exit of the cell for the following two cases; with no alkali vapor (case A; collisionless) and with dense alkali vapor (case B; multiple collisions). To see the effect of the magnetic field, the calculations are carried out at the magnetic fields, B = 0.01, 0.1, 1, and 10 T. In the case A, at a weak magnetic field ( B = 0.01 T ), the beam profile (Fig. 2-(a),-(e)) is approximately determined by the drift space. As increasing magnetic field, the spatial image of the beam tends to converge upon the center point (0,0) in the (x,y) plane gradually rotating clockwise around the z-axis.

On the other hand, in the case B, the spatial image also tends to converge upon the center point (0,0) in the (x,y) plane. However, the speed of convergence as a function of the magnetic field is considerably slow compared to the case A. Based on this aspect, the beam profile in the case B (-(k), -(o)) at B = 1 T seems to resemble that in the case A (-(b), -(f)) at B = 0.1 T. The difference in the strength of the magnetic field between two cases is almost the factor of 10. This resemblance seems to further hold at higher magnetic fields, e.g., at B = 10 T in the case B (-(l),-(p)) and B = 1 T in the case A (-(c), -(g)), though a spatial diffusion in the case B is significant.

Physical meaning of the factor, 10, could be explained as follows: The mean free path $\lambda_{0+}$ is approximately 10 times larger than $\lambda_{+0}$. This indicates that a $^3He$ ion/atom is in a +1 ionic state for 10 % of the whole traveling time, while in a neutral atomic state for the rest of the whole traveling time. The magnetic field influences only a trajectory of a $^3He^+$ ion through the Lorenz force. The effect of the $^3He^+$ ion upon the magnetic field is proportional to $\omega_c \times t$, where $t$ is a traveling time for a $^3He^+$ ion and $\omega_c$ is a cyclotron frequency defined by the equation (1). This suggests that an effective magnetic field for the $^3He^+$ ion is expressed by

$$B_{eff} \simeq \frac{\lambda_{+0}}{\lambda_{+0} + \lambda_{0+}} B. \qquad (1)$$

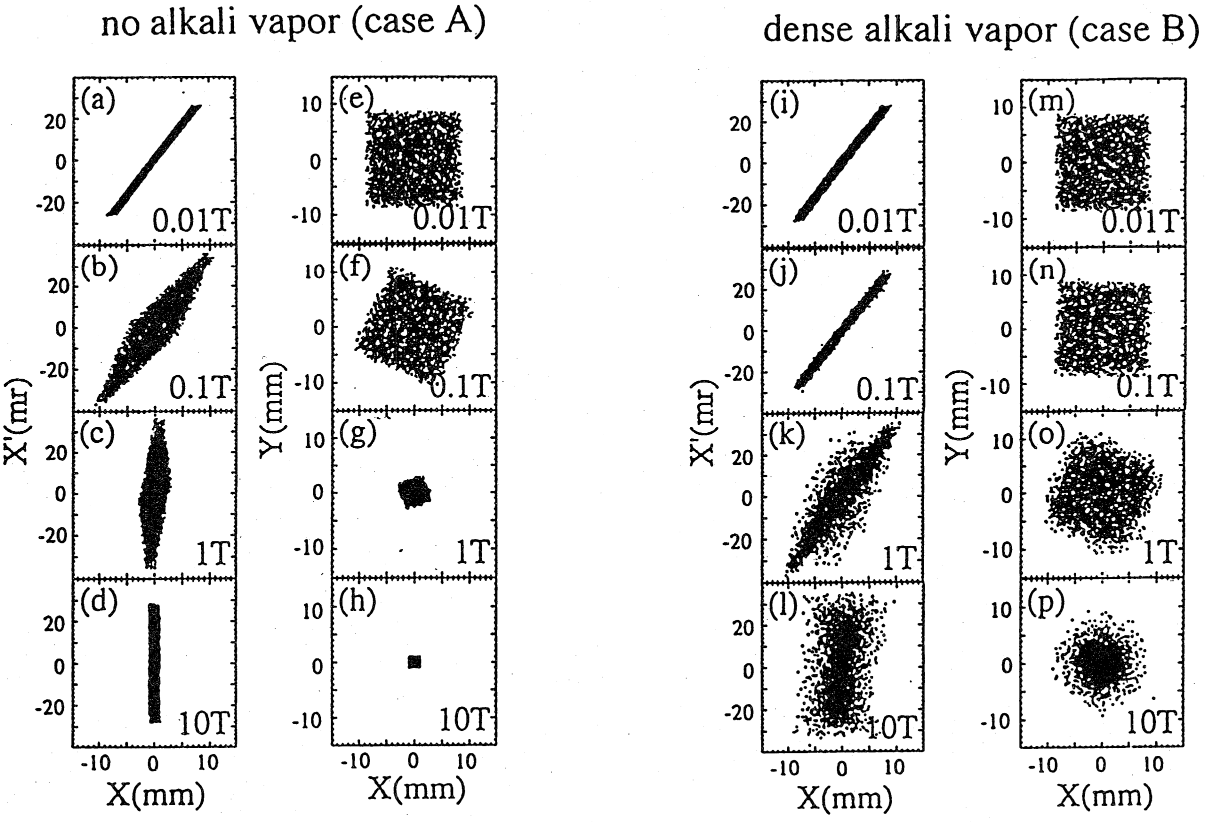

Fig. 2. The phase space (x-x') and position (x-y) of the $^3He^+$ beam at the exit of the alkali vapor cell. The left figures (a)-(h) are the case for no alkali vapor (case A; collisionless) and the right figures (i)-(p) are the case for dense alkali vapor (case B; multiple collisions). An alkali vapor thickness of case B is 6 × $10^{15}$ atoms/cm$^2$. To see the effect of the magnetic field, the calculations are carried out at magnetic fields, 0.01, 0.1, 1, and 10 T. See text for further detail.

Using $\lambda_{+0} \approx 0.43$ cm and $\lambda_{0+} \approx 4.06$ cm, we can conclude $B_{eff} \approx \frac{1}{10}B$. The effective field will provide a convenient tool in simply the calculating beam optics with a solenoid field inside which the multiple collisions accompanying charge changes are allowed. Furthermore, the restriction of this scalling law is discussed in the paper [4].

## 4 Summary

In the present parameter for polarized $^3$He ion source, It was found that the emittance grows from $(\pm 1mm) \times (\pm 25mr)$ to $(\pm 5mm) \times (\pm 25mr)$, i.e., the emittance growth occurs not in the spreading angle, but in the spatial size. At the initial beam spreading angle less than 10 mr, the transmission efficiency was about 10 %. The concept of the effective magnetic field was established from the emittance comparison between the beam profiles with an alkali vapor and without an alkali vapor.

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