Relaxation mechanism due to effusion of Rb polarization

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Abstract

We studied the relaxation mechanism of an optically pumped Rb vapor in a strong magnetic field. The observed relaxation rate is represented as a sum of wall relaxation rate and relaxation rate due to effusion of Rb polarization by its thermal motion. We quantitatively investigated the latter effect which is reproduced by the simulated result based on kinetic theory of gases. We found that this effect is the most dominant in the relaxation mechanism.

1 Introduction

Recently, a novel method for production of a polarized $^3He^+$ ion beam, i.e. the electron pumping, has been experimentally verified [1]. In this method, a Rb metal is vaporized up to the density of 1.0×10^{13} atoms/cm^3. This density is much larger than the case used for an ordinary optical pumping polarized H^- ion source. Such a large density is needed for allowing multiple electron capture and stripping collisions between polarized Rb atoms and an incident $^3He^+$ ion. We observed a $^3He^+$ nuclear polarization of 7.5 % with a Rb polarization of 20 % [2]. The smallness of the obtainable nuclear polarization is due to the smallness of the Rb polarization. The smallness of the Rb polarization might be induced by the relaxation process of the Rb vapor with a high density under a strong magnetic field. However, there has been no attempt to study the relaxation mechanism at such an extreme condition.

The previous studies of the relaxation mechanism show that a polarization of an alkali vapor is relaxed when a polarized atom collides with a wall and other atom. These processes are known as the wall relaxation and spin-disorientation collision, respectively. In addition to these relaxation mechanisms, another process which reduce the polarization is also present: polarized atoms escape from an optical pumping cell by diffusion and interchange with unpolarized atoms evapolated from a reservor. This process, called an effusion process, has not been well investigated so far. In the strong magnetic field, the wall relaxation is expected to decrease. The high vapor density is provided by a high wall temperature which results an increase of a velocity in a thermal motion of the vapor atom. Thus, the effusion effect may become a dominant relaxation process.

In this paper we will discuss the relaxation mechanism of the Rb polarization in such an extreme condition observed by means of the time differential measurement. Especially, we report about the relaxation mechanism due to effusion effect.

2 Experiments

A schematic view of an experimental apparatus is shown in Fig.1. A Rb metal was vaporized at wall temperature range from 90 to 130 °C ($0.2-2.0\times10^{13}$ atoms/cm^3) in the Rb cell. The Rb cell is located in the center of a superconducting solenoidal coil, which applies magnetic field strength up to 5 T. A Rb vapor was optically pumped by a 795-nm laser light extracted from a 4 W Ti:Sapphire laser excited by an Ar ion laser. The pumping laser was periodically swiched by using a combination of the Pockels cell and a polarizer. The Rb thickness and the Rb polarization were determined by means of the Faraday effect[?]. The Rb polarization was measured with a precision better than 1%.

The experimental procedures are as following: First, we measured the relaxation rate as a function of magnetic field strength range from 1 to 5 T at wall temperature of 125 °C. Next, we measured the relaxation rate as a function of wall temperature range from 90 to 130 °C in magnetic field strength of 1, 1.5, 2, and 3 T. The typical results of these three experimental procedures are shown in Fig.2 and 5, respectively.

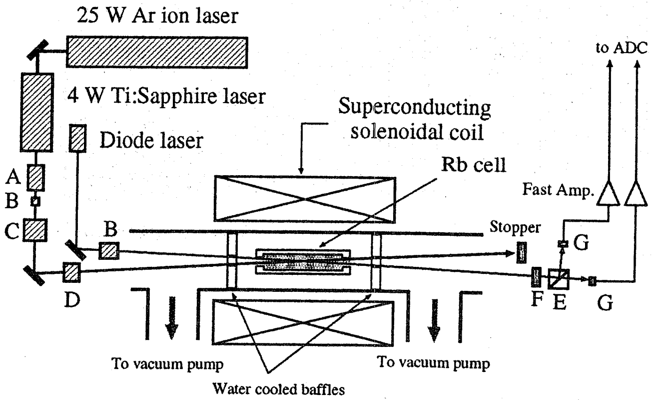

Fig. 1 Show a schematic diagram of the experimental apparatus. A pumping laser and a probe laser are injected to the Rb cell as the same direction from left to right. "A" is a Pockels cell, "B" are polarizers, "C" is a beam expander, "D" is a $\lambda/4$ plate, "E" is a polarizing beam splitter cube, "F" is a wavelength filter, and "G" are two photo diodes.

3 Analysis

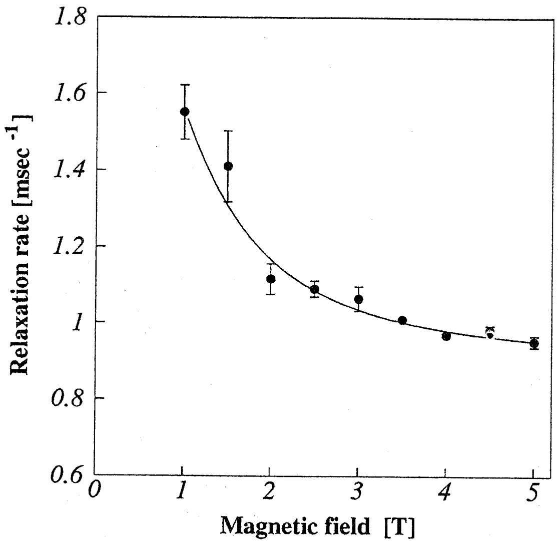

Fig. 2 Show the observed relaxation rate as a function of magnetic field strength.

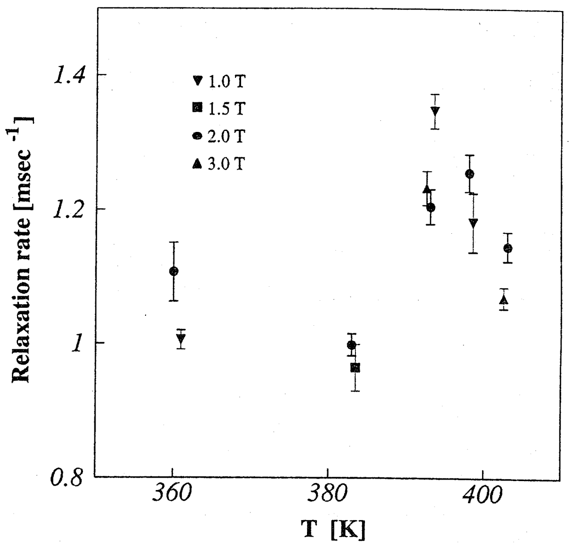

Fig. 3 Show the observed relaxation rate as a function of wall temperature.

3.1 Introduction of simplified model based on kinetic theory of gases

Relaxation rate due to effusion effect depends on thermal motion of a Rb vapor and the geometry of pumping region where a Rb vapor is optically pumped. Then, we estimated relaxation rate due to effusion effect from a simplified model based on kinetic theory of gases.

The concept of effusion effect is as shown in Fig.4, where "A" is the polarized Rb atom to escape from pumping region through both ends of the cell, "B" is the polarized Rb atom to escape from pumping region through the slits. In this model, Rb atoms are assumed to move like as elastic balls in the rectangle cylindrical cell, hence Rb polarization decayed with time is given by

$$P(t) = \left(1 - \frac{S'}{S}\right)^{vt/L} \times \left(1 - \frac{C'}{C}\right)^{2vt/2R}, \qquad (1)$$

where S/S' and C/C' are the areal ratios of aperture to the surface for the transverse and longitudinal sides of the cell, and L and R are the length and radius of the cell, respectively. v is a mean thermal velocity of Rb atom which is given as $v = \sqrt{kT/2\pi M}$ from Maxwell-Boltzmann distribution, where k is Boltzmann constant, T is wall temperature, and M is mass of a Rb atom, respectively. From Eq.(1), relaxation rate due to effusion of Rb polarization are given as,

$$\tau^{-1} = -\sqrt{\frac{k}{2\pi M}} \left(\frac{\ln(1 - S'/S)}{L} + \frac{\ln(1 - C'/C)}{R}\right) \sqrt{T} \quad (2)$$

We see that relaxation rate is proportional to the square-root of wall temperature, and depends on the geometry of pumping region. The simulated result is 1.10 msec^{-1} at wall temperature of 125 °C.

Swenson et al. suggested that the sticked Rb atom on the wall surface is re-emitted with a non-uniform angular distribution. "C" in Fig.4 is shown as a bouncing Rb atom on the wall surface with a non-uniform angular distribution. In order to reproduce relaxation rate due to effusion effect more realistically, we also calculate it by means of the Monte Carlo simulation. Assumptions in this simulation are as following: The velocity distribution of thermal motion of Rb atoms is given in Maxwell-Boltzmann distribution. The sticked Rb atom on the wall surface is re-emitted to a direction θ with a probability $P(\theta) = \cos\theta$, where θ is the angle between the direction of the atom as it leaves the wall and the normal to the surface. The velocity of a re-emitted Rb atom is initialized again in Maxwell-Boltzmann distribution. The simulated relaxation rate is derived at 0.96±0.08 msec^{-1} at wall temperature of 125 °C.

3.2 Analysis of relaxation rate due to effusion effect

The observed relaxation rate is represented as $T^{-1} = T_w^{-1} + T_e^{-1}$ [3], where T_w^{-1} and T_e^{-1} are the wall relaxation rate and the relaxation rate due to effusion effect, respectively. It means that when we determine the relaxation rate due to effsion effect, we should determine the wall relaxation rate. Fortunately, the wall relaxation rate can be easily introduced since it has been known precisely. The wall relaxation rate is determined from the observed relaxation rate as a function of magnetic field strength. We fit these experimental results as $y = P_a/(1 + P_b \times x^2) + T_e^{-1}$. Here, y is the observed relaxation rate, x is magnetic field strength, and P_a=(1.3±0.3)×10^3 and P_b=0.97±0.37 are fitting param-

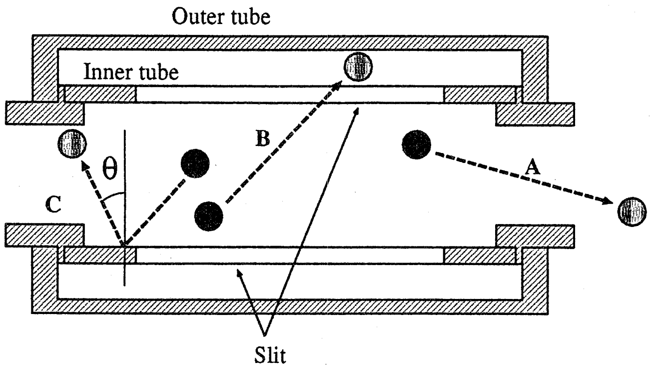

Fig. 4 Show the concept of the effusion of the polarized Rb atoms out of the pumping region. "A" is effused a Rb atom out of both sides of the cell, "B" is the effusion a Rb atom through the slits, and "C" is the bouncing of a Rb atom on the wall surface.

eters, respectively. From these results, we determine $T_e^{-1}=(0.90\pm0.01)\times10^3$.

Fig.5 shows relaxation rates as a function of square-root of wall temperature, where the plotted data are derived from the observed slow components subtracting to the analyzed wall relaxation rates. Hatched area represents the calculated relaxation rate by the Monte Carlo simulation.

4 Discussion

First, we find from Fig.2 that the observed relaxation rates due to effusion effect derived from relaxation rates as a function of magnetic field strength is in good agreement with the simulated result derived from the Monte Carlo simulation. Thus, we confirm that the experimental result is well reproduced by the simulated one.

Next, we compare the observed effusion rate derived from relaxation rates as a function of wall temperature with the simulated results. Fig.5 shows that the observed relaxation rates due to effusion effect depend on wall temperature like as the simulated results. Thus, we find that the relaxation rate is affected on wall temperature by effusion effect. In addition to these result, we find that the effusion effect is the most dominant in the observed relaxation rate in such an extreme condition.

5 Conclusion

We determine the relaxation rate due to effusion effect from the observed relaxation rate as a function of magnetic field strength and wall temperature. These experimental results are well reproduced by the simulated results derived from the Monte Carlo simulation based on kinetic theory of gases.

Other interesting results are introduced by study of the effusion effect. From a macroscopic point of view that it tests the kinetic theory of gases in thermal physics and from a microscopic point of view that it studies the

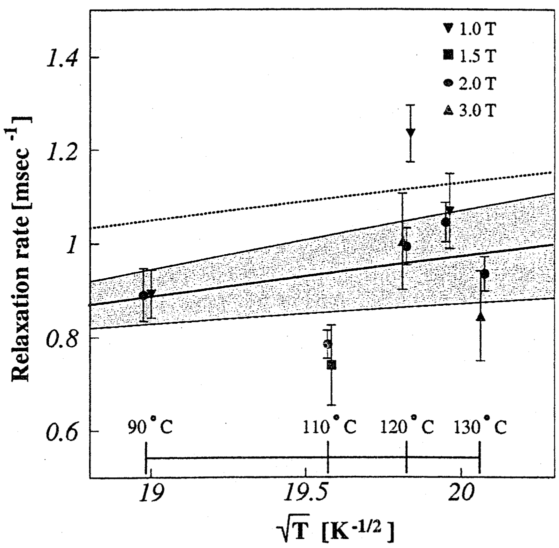

Fig. 5 Show the observed relaxation rate due to effusion effect. Hatched area shows the simulated results derived from the Monte Carlo simulation. Dotted line is derived from Eq.2.

bouncing mechanism of an alkali atom in surface physics.

References

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