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Optimized Condition for Buffer Gas in Cesium Atomic Magnetometer

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Abstract This paper described the principle of an all-optical cesium magnetometer based on absorptive detection. In order to reduce transverse relaxation rate and to maximize spin polarization time of the alkali-metal atoms, it is usually to fill the inert gas He and the diatomic molecule N2 which are used as buffer gases into the cell to achieve high measuring sensitivity. Not only the collision probability of polarized atoms with the cell wall but also the radiation trapping can be reduced or avoid by this approach. The relationships between the output signals of this magnetometer with buffer gas pressures were expressed here. After a detail theoretical analysis, it was found that the optimal gas pressure of the buffer gas was about 3.9×10^4 Pa for helium (He) and 3.6×103 Pa for nitrogen (N_2).

Key words quantum optics; buffer gas; cesium; magnetometer; relaxation
OCIS codes 280.4788; 270.2500; 020.2070

铯原子磁力仪中缓冲气体的最佳条件研究

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摘要 介绍了基于共振吸收法检测椭圆率变化的全光铯原子磁力仪的基本原理。为了降低工作介质碱金属铯原子的横向弛豫速率,延长自旋极化时间,使磁力仪达到较高的磁测灵敏度,通常将最外层电子排列稳定的惰性气体He和双原子分子N_2作为缓冲气体充入铯原子气室中,这样既能有效地减少极化原子与气室壁碰撞的几率,又可以很好地避免辐射陷阱现象。分析了He和N_2的压强对Cs原子极化程度及磁力仪输出信号的影响,给出了100 ℃时实现无自旋交换弛豫铯原子磁力仪的最佳压强:He约为3.9×10^4 Pa,N_2约为3.6×10^3 Pa。

关键词 量子光学;缓冲气体;铯;磁力仪;弛豫
中图分类号 O562.5;O562.4 **文献标识码** A **doi**:10.3788/LOP50.072802

1 Introduction

Sensitive magnetometers have been widely used in the fields of nuclear magnetic resonance[1] and medical diagnoses by detecting the magnetic fields from the heart and the brain[2]. Usually, these magnetic fields are too weak to be detected by general magnetometers, so highly sensitive magnetometers are of cardinal significance. To the best of our knowledge, so far, atomic magnetometer[3-6] has held the highest sensitivity among kinds of existing magnetometers[7-10]. The design of alkali-metal atom vapor cell is a key technique that affects the sensitivity of atomic magnetometer, which involves the pressure of the buffer gas. In order to achieve high sensitivity, it is necessary to maximize the electron polarization of the alkali-metal atoms in the cells. Alkali spins depolarize immediately after colliding with the glass walls of the vapor cell or other atoms. It is well known that filling the cell with an inert buffer gas of a high pressure is a good method to prevent these collisions and maintain spin polarization as long as possible, e.g., helium (He). In addition, polarized alkali-metal atoms that spontaneously decay back to the ground state will emit a randomly polarized resonant photon, which is highly likely to be reabsorbed by another

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atom within the cell. This complicated process is called radiation trapping[11]. A quenching gas, typically a diatomic molecule such as nitrogen (N_2), is usually used to suppress or eliminate this phenomenon[12]. However, the pressures of the buffer gases that satisfy this optimal spin-polarization condition are still unclear.

In this paper, we describe the principle of an all-optical cesium (Cs) magnetometer and discuss the dominant relaxation mechanisms of this magnetometer. Analyzing the relationships between the output signals based on absorptive detection and buffer gas pressures, we found that the optimal gas pressure of the buffer gas is about 3.9×10^4 Pa for He and 3.6×10^3 Pa for N_2.

2 Working principle

We used the pump-probe arrangement shown in Fig. 1. Cs atoms were contained in a spherical cell, whose radius is 1.5 cm. It was placed in a double-wall oven constructed from high-temperature plastic materials and heated by flowing hot air. The cell temperature can be measured by fiber Bragg grating with a demodulator, whose sensitivity is 0.1 ℃. In order to reduce the effect of earth magnetic field, we used a set of three nested cylindrical magnetic shields with a shielding factor of 10^5 experimentally. A pair of Helmholtz coils making a weak magnetic field along the y direction was inside the shields. The short-term stability of magnetic field can be controlled to 0.06 pT level[13]. Cs atoms were optically pumped by a circularly polarized laser light along the z direction transmission which was tuned to the center of the Cs D1 line. A linearly polarized probe beam tuned to the center of Cs D2 line propagated in the x direction through the cell[14]. Optical rotation of the probe laser caused by the circular dichroism medium (Cs atomic vapor) was measured using a balance polarimeter.

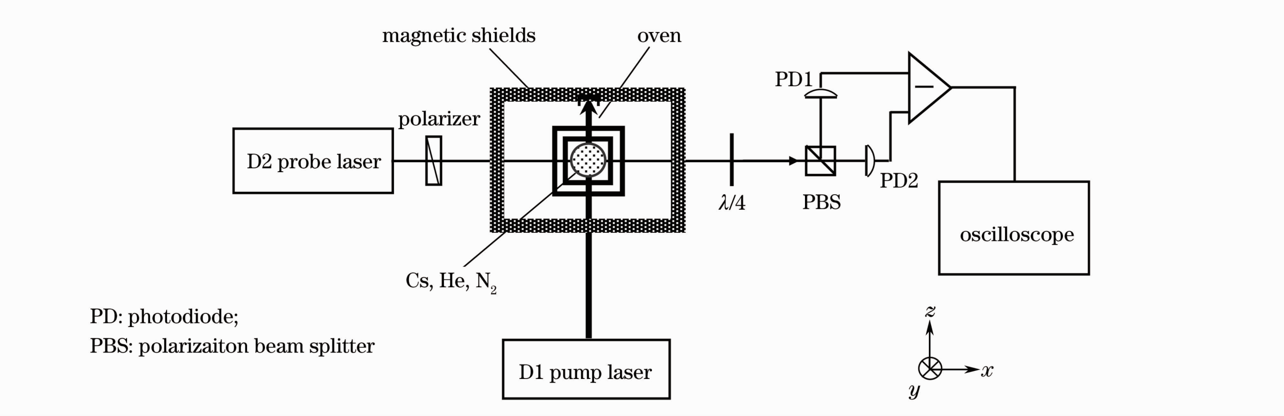

Fig. 1 Schematic diagram of the experimental arrangement for Cs magnetometer

3 Analysis and discussion

3.1 Helium in cesium cell

The pump laser optically pumps the Cs atoms into a spin-polarized state. The most important method for optimizing the magnetometer sensitivity is to maximize the electron polarization. We describe the Cs polarization in the presence of buffer gas using a standard equation written by[15]

$$P_{\mathrm{Cs}} = \frac{\Gamma_{\mathrm{op}}}{\Gamma_{\mathrm{op}} + \Gamma_{\mathrm{rel}}}, \tag{1}$$

where Γ_{rel} represents the sum of all spin destruction mechanisms,

$$\Gamma_{\mathrm{rel}} = \Gamma_{\mathrm{wall}} + \Gamma_{\mathrm{col}}. \tag{2}$$

From Eq. (1) and Eq. (2), one can get that the polarization depends on several factors, including the pumping rate Γ_{op}, which is proportional to laser intensity, the diffusion rate of Cs through the buffer gas to the walls Γ_{wall}, and the depolarization of Cs electron spin after collisions with Cs or He atoms Γ_{col}.

The relaxation due to diffusion was modeled by Allred *et al.*[16] assuming that the Cs electron and nuclear spins completely depolarize on contact with the cell walls. When R is the radius of the spherical cell, the diffusion rate of Cs atoms to the walls will be

$$\Gamma_{\mathrm{wall}} = Q\frac{D_0 P_0}{P_{\mathrm{He}}}\left(\frac{\pi}{R}\right)^2, \tag{3}$$

where the diffusion constant D_0 for Cs in He buffer gas is 0.37 $\mathrm{cm^2/s}$ at 26 ℃[17] (one can get the D_0 value at 100 ℃ according to the $T^{3/2}$ dependence of D_0[18]), P_0 is equal to one atmospheric pressure (1.01×10^5 Pa), P_{He} is the He pressure, and the enhancement factor Q accounts for the destruction of both electron and nuclear spin polarizations at the cell walls.

For this magnetometer, as another dominant relaxation mechanism, the relaxation due to spin-destruction collisions Γ_{col} can be written as

$$\Gamma_{\mathrm{col}} = R_{\mathrm{col}}^{\mathrm{Cs-Cs}} + R_{\mathrm{col}}^{\mathrm{Cs-He}} = n^{\mathrm{Cs\text{-}Cs}} \upsilon \sigma_{\mathrm{col}}^{\mathrm{Cs}} + n^{\mathrm{He\text{-}He}} \upsilon \sigma_{\mathrm{col}}^{\mathrm{He}}, \tag{4}$$

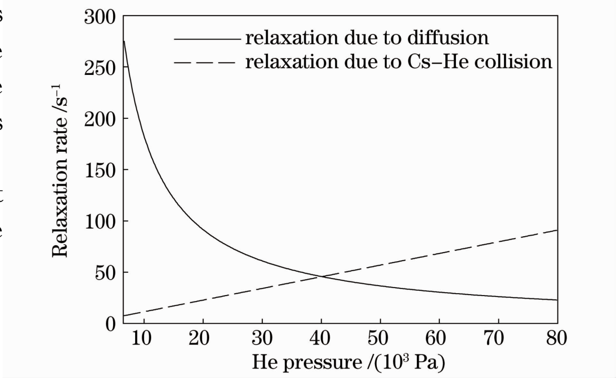

Fig. 2 Relaxation rates due to diffusion and spin-destruction collision at different He pressures

where $R_{\mathrm{col}}^{\mathrm{Cs-Cs}}$ and $R_{\mathrm{col}}^{\mathrm{Cs-He}}$ with spin-destruction cross sections $\sigma_{\mathrm{col}}^{\mathrm{Cs}} = 2 \times 10^{-16}$ cm^2[19] and $\sigma_{\mathrm{col}}^{\mathrm{He}} = 2.8 \times 10^{-23}$ cm^2[20] are the spin-destruction relaxations due to Cs - Cs and Cs - He collisions, respectively. Here, the number density n^{He} is dependent on the He pressure P_{He}.

When the temperature of the Cs vapor cell is 100 ℃ [it is thought that the Cs magnetometer works in spin-exchange relaxation free (SERF) regime around this temperature[21]], the relationships between Γ_{wall}, $R_{\mathrm{col}}^{\mathrm{Cs-He}}$ with He pressure P_{He} can be expressed by Fig. 2.

3.2 Nitrogen in cesium cell

Due to their short excited state lifetimes, the polarized Cs atoms will spontaneously decay back to the ground state. The reabsorption of the randomly emitted unpolarized resonant photons will cause the depolarization of the atomic ground state. The particularly important effect which must be considered in atomic magnetometer experiments is called radiation trapping.

Adding a diatomic molecular gas, typically N_2, to the vapor cell of the magnetometer is usually used to decrease the influence of radiation trapping. Cs magnetometer experiments can be operated with an optically thick cell but without depolarization result from fluorescent light due to the quenching process of N_2.

The spin-relaxation rate due to radiation trapping is expressed as[22]

$$\Gamma_{\mathrm{rt}} = K(M-1)\Gamma_{\mathrm{op}}(1-P_{\mathrm{Cs}})F, \tag{5}$$

where $K<1$ is a parameter which represents the degree of the depolarization due to radiation trapping. $(M-1)$ is the average number of times that an emitted photon is reabsorbed by Cs atoms before it escapes from the cell. We use F to express the fraction of the atoms that reach the ground state by spontaneous emission rather than quenching:

$$F = \frac{465.5\ \mathrm{Pa}}{466.5\ \mathrm{Pa} + P_{\mathrm{N_2}}}, \tag{6}$$

where $P_{\mathrm{N_2}}$ is the pressure of N_2.

According to Eq. (1), the Cs polarization in the presence of N_2 can be got with Γ_{rel} including the relaxation rate Γ_{rt}. We calculated the diffusion rate of Cs atoms to the walls without taking account of the enhancement factor Q.

3.3 Optical rotation

When a linearly polarized, resonance light propagates through the Cs cell, the transmission light after the cell will become elliptically polarized because of the anisotropic medium: polarized Cs atoms. Using a balance polarimeter, the ellipticity of the probe laser can be measured which represents the optical rotation θ of the probe laser:

$$\theta = -\frac{1}{2}\pi l c r_{\mathrm{e}} n f_{\mathrm{D2}} P_x L_{\mathrm{D2}}(\omega), \tag{7}$$

where l, c, r_{e}, n and f_{D2} are the optical path length, speed of light, radius of the electron, number density of Cs and oscillator strength, respectively; $L_{\mathrm{D2}}(\omega)$ is a constant with the laser frequency ω tuned to the center of the Cs D2 line; P_x represents the degree of polarization of Cs atoms in the probe laser direction. We make a simple premise that $P_x = \kappa P_{\mathrm{Cs}}$ with $\kappa < 1$.

According to Eq. (1), Eq. (2) and the above analyses in subsections 3.1 and 3.2, one can get the relationships between the output signals based on absorptive detection with He and N_2 pressures. From Fig. 3 and Fig. 4, it is found that the optimal gas pressure of the buffer gas is about 3.9×10^4 Pa for He and 3.6×10^3 Pa for N_2 with fixed values of Γ_{op}, K and M (here, $M < 100$ is assumed according to Ref. [23]).

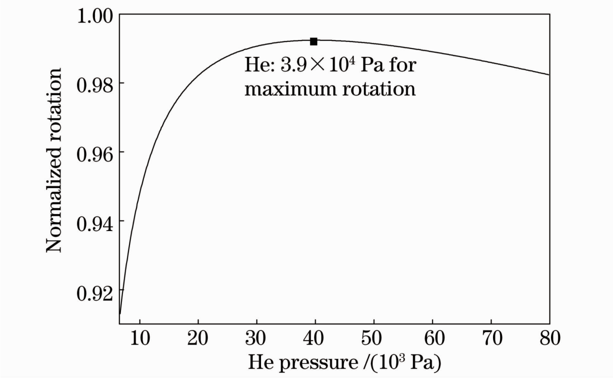

Fig.3 Output signals depending on helium pressure in Cs vapor cell

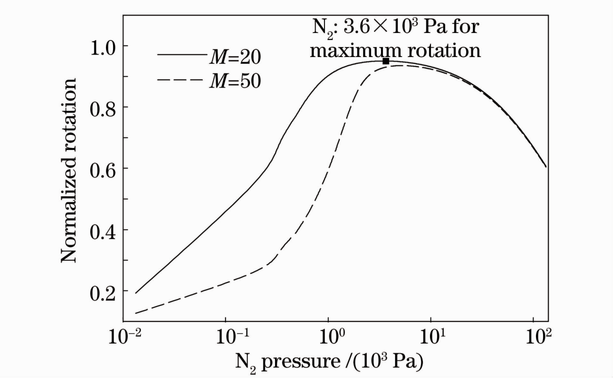

Fig.4 Output signals depending on nitrogen pressures in Cs vapor cell

4 Conclusion

This paper describes an all-optical cesium magnetometer based on absorptive detection. We have analyzed the dominant relaxation mechanisms in this kind of magnetometer theoretically, including spin-destruction relaxations and diffusion relaxation. After analyzing the relationships between the output signals and the buffer gas pressures, it was found that the optimal gas pressure of the buffer gas was 3.9×10^4 Pa for helium and 3.6×10^3 Pa for nitrogen.

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