QUADRUPOLAR INTERACTION INDUCED FREQUENCY SHIFT OF $^{131}\text{Xe}$ NUCLEAR SPINS ON THE SURFACE OF SILICON

A PREPRINT

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September 29, 2021

ABSTRACT

The combination of micro-machined technology with the Atomic Spin Gyroscope (ASG) devices could fabricated Chip Scale Atomic Spin Gyroscope (CASG). The core of the gyroscope is a micro-machined vapor cell which contains alkali metal and isotope enriched noble gases such as $^{129}\text{Xe}$ and $^{131}\text{Xe}$. The quadrupolar frequency shift of $^{131}\text{Xe}$ is key parameters which could affect the drift of the ASG and is related to the material of the cell in which they are contained. In micro machined technology, the typical utilized material is silicon. In this article, we studied the electric quadrupolar frequency shift of $^{131}\text{Xe}$ atoms with the silicon wall of the micro-machined vapor cell. A cylinder micro-machined vapor cell is utilized in the experiment and a large part of the inner cell surface is composed of silicon material. We studied the temperature dependence of the $^{129}\text{Xe}$ spin relaxation and $^{131}\text{Xe}$ frequency shifts to evaluate the interaction of the nuclear spin with container wall and the alkali metal atoms. The results show that the average twisted angle of the $^{131}\text{Xe}$ nuclear spins as they collide with the silicon wall is measured to be $29 \times 10^{-6} \text{rad}$. The desorption energy for the $^{131}\text{Xe}$ nuclear spin to escape from the silicon surface is $E_{\text{si}} = 0.009 \text{eV}$. This study could help to improve the bias stability of the CASG which is a key parameter for the gyroscope as well as may develops a method to study the surface property of various material.

Keywords: Nuclear Magnetic Resonance Gyroscope, Atomic Co-magnetometer, Atomic Spin Gyroscope

1 Introduction

Hyper polarization of isotope enriched nuclear spins [Walker and Happer [1997]] could find wide range application, including atomic spin gyroscopes [Kornack et al. [2005], Chen et al. [2016], Larsen and Bulatowicz [2012], neutron spin filters [Qin et al. [2021]], magnetic resonance imaging of the lungs for COVID-19 study [Li et al. [2016a]], testing physics beyond the standard model [Li et al. [2018], Lee et al. [2018], Bulatowicz et al. [2013]], etc. Isotope enriched noble gas nucleus such as $^{131}\text{Xe}$, $^{21}\text{Ne}$ and $^{83}\text{Kr}$ whose nuclear spin are larger than 3/2 own nuclear quadrupole moments. Thus, the study of the nuclear quadrupolar interaction between the nuclear spin and the surrounding environment take attention in several area. For example, in a nuclear magnetic resonance gyroscope or an atomic co-magnetometer [Sorensen et al. [2020], Xu et al. [2021]], the nuclear quadrupolar frequency shift and relaxation of $^{131}\text{Xe}$ through colliding with the container wall could affect the bias instability and detection sensitivity of the gyroscope respectively.
The combination of atomic devices with chip-scale fabrication technology could greatly reduce the size and cost of the atomic sensors. For atomic sensors based on an alkali vapor cell such as atomic clock, magnetometer, and spin gyroscope, the key is an alkali vapor cell in which several kinds of gases are filled. Especially in a spin exchange relaxation free (SERF) gyroscope, the vapor cell is also utilized to change the quadrupolar interaction strength. The desorption is thermally activated and there is a parameter named activation energy $E_A$ which is 0.12 eV for the nuclear-glass surface interaction. Moreover, the shape of the vapor cell is also related to the quadrupolar interaction. We can control the temperature, material and shapes of the vapor cell to change the quadrupolar interaction strength. For example, in order to study the crossover between the NMR and the nuclear quadrupole resonance interaction regimes, alkali vapor cells with a different kind of materials are utilized to make the nuclear quadrupolar frequency shifts more clearly. A rectangular alkali vapor cell is also utilized to change the quadrupolar interaction strength. The nuclear quadrupole resonance (NQR) spectroscopy could also be utilized to identify chemicals and it is sometimes called the fingerprint of the chemicals. Thus, the NQR spectroscopy could be utilized to detect explosives. In this paper, we mainly focus on the NQR spectroscopy study in ASG application. Especially in micro-machined AGs, the alkali vapor cell’ material is composed of both glass and silicon. The quadrupolar interaction between the nuclear spins and the silicon surface is studied. We measured the temperature dependence of the $^{131}Xe$ frequency shift. The NMRG bias instability is close related to the NQR spectroscopy. Thus, this study could help to give solutions to improve the bias instability of the chip scale ASG.

2 Theory

The quadrupolar interaction happens as the nuclear spin collides with the container wall. The atoms will be absorbed on the surface for a while. This process will cause both the relaxation and frequency shift of the $^{131}Xe$ nuclear spin. The nuclear spin of $^{131}Xe$ atoms is $3/2$ and there is a nuclear quadrupole moment in the nucleus. The energy level of the nuclear spin should shift if the nuclear quadrupole moment feels Electric Field Gradient (EFG) as well as the relaxation of the nuclear spin could occur if EFG fluctuation exists.

The vapor cell utilized in our paper is made of both silicon and glass. As shown in Fig. 1, the main body of the vapor cell is made of silicon and the geometry is cylindrical. The inner diameter is 3 mm and the length is 2 mm in our experiment. The two ends of the vapor cell is covered by glass and it is connected to the silicon through anode bonding. The details about how to fabricate the vapor cell could be found in our paper. As the polarized nuclear spin of $^{131}Xe$ atoms colliding with the cell walls, they will be adsorbed by the cell wall for a short period as well as diffuse from site to site during the adsorbed period. The mean adsorption time $\tau_a$ is defined as the average time that the atoms are adsorbed on the surface of the cell wall. The adsorption time is related to the temperature of the cell and the time should be decreases if the temperature of cell rise. There is a parameter named activation energy $E_A$ which is defined to be the activation energy of desorption to characterize $\tau_a$. The relation is $1/\tau_a \propto \exp(-E_A/k_B T)$. Since both of the frequency shift and relaxation due to quadrupole interaction with cell wall are related to the desorption energy, we can do a measurement of the dependence of frequency shift and relaxation with the cell temperature.

According to this reference, there is a good experiment evidence that the magnitudes of the fluctuating field gradients at the cell wall are quite large compared to the mean value of the field gradients, and then we assume that:

$$\langle \frac{\partial^2 V_w}{\partial x_i \partial x_j} \rangle \gg \langle \frac{\partial^2 V_w}{\partial x_i \partial x_j} \rangle^2$$

where $V_w$ is the electric field potential at the wall surface, $x_i$ and $x_j$ are unit vectors in the $i$ and $j$ directions. $i$ and $j$ could be $x, y$ or $z$ directions. When the atoms are adsorbed on the glass surface wall of the cell, it is plausible to make
an assumption that the fluctuations are nearly isotropic, i.e., we assume that the microscopic structure of the wall is sufficiently rough that any tensor components of the electric field gradient have approximately the same mean-squared amplitude as any other. We believe that the silicon surface is also rough and the EFG and its fluctuation are isotropic too.

While every material has a characterize deactivation energy. It is reported that in a vapor cell with RbH surface coating, $^{131}\text{Xe}$ atoms would stay for a shorter time than that of the glass surface. Thus, the relaxation time of $^{131}\text{Xe}$ atoms could be longer[1990]. In our experiment, we divided the vapor cell into two parts. One is the glass part and the other one is the silicon part. Both of the two parts can cause the nuclear quadrupole splitting of the energy level and relaxation. According to the reference[1988], the NQR shifts for the $|3/2><-1/2|$ and $|3/2><1/2|$ coherence as:

$$
\Delta \Omega = \Delta \Omega_g + \Delta \Omega_{si} = \frac{\nu S}{2V} \left[ \int_{S_g} \frac{dS_g}{S} \langle \theta_g \rangle \left( \frac{3}{2} \cos^2 \psi - \frac{1}{2} \right) + \int_{S_{si}} \frac{dS_{si}}{S} \langle \theta_{si} \rangle \left( \frac{3}{2} \cos^2 \psi - \frac{1}{2} \right) \right]
$$

(2)

where $\Delta \Omega_g$ and $\Delta \Omega_{si}$ are the frequency shifts from collision with glass and silicon surfaces respectively. $\nu$ is the velocity of the atoms, $S$ is the inner surface area of the vapor cell and $V$ is the inner volume of the vapor cell. $I$ is the nuclear spin of the atoms. $\langle \theta_g \rangle$ and $\langle \theta_{si} \rangle$ are the average angles as the nuclear spin colliding with the glass surface and silicon surface respectively. $\psi$ is the angle between the holding magnetic field and the normal direction to the inner surface of the vapor cell. For example, if the holding magnetic field is directed to the z direction and there is a small area $dS_{si}$ on the silicon surface, the angle between the holding magnetic field and the normal direction which is perpendicular to the small area is 90 degree.

3 Experimental Setup

The configuration of the experimental setup is shown in Fig[1]. The micro-machined alkali vapor cell is at the center of the experiment and the geometry is cylinder. The inner diameter is 3mm and the height is 2mm. A small amount of cesium metal, 5 Torr natural abundance Xe gas and 650 Torr Nitrogen gas are filled in the vapor cell. The natural abundance Xe gas contains 26.4% $^{129}\text{Xe}$ and 21.2% $^{131}\text{Xe}$. The pump laser is circular polarized and tuned to the Cs D1 line absorption center. The beam is expanded to cover the cell as large as possible. A second 3W 1550nm heating laser is utilized to heat the vapor cell to the desired temperature. After passing through the vapor cell, a PD (photo diode) is used to accept the transmitted pump laser light. 3 sets of magnetic field coil are utilized for the holding magnetic field in the z direction, the modulation magnetic field $B_y \cos(\omega t)$ in the y direction and the compensation magnetic field in all the three directions. Several layers of magnetic field shields together with a MnZn ferrite shield are utilized for shielding the vapor cell from the earth’s magnetic field. The Xe nuclear spins are hyper-polarized through spin exchange optical pumping with Cs atomic spins. The hyper-polarized Xe nuclear spin will produce magnetic field which could be experienced by the Cs electron spins. The effective magnetic field will be approximately $B^K = 8/3\pi \mu_K[N] P^K$[1998]. In the equation, $B^K$ is the magnetic field produced by the nuclear spin such as $^{129}\text{Xe}$ or $^{131}\text{Xe}$. $\mu_K$ is an enhancement factor[1989] which could enhance the magnetic field experienced by the Cs electron spins during spin exchange collision. $\mu_K$ is the nuclear magnetic moment for spin species K. $[N]$ is the number density of the nuclear spins and $P^K$ is the polarization of the nuclear spin species K.

Since the vapor cell is quite small, it is hard to use free space laser beam for the experiment. A polarization maintaining fiber is utilized for guiding the pump laser to the vapor cell. A multi-mode fiber with 400$\mu$m core is utilized for the heating laser. The temperature of the vapor cell is measured by the Cs D1 absorption line. We first do a measurement of the line-width of the D1 absorption line, then the Cs atom density could be calculated by the absorption line. Thus we can get the temperature of the vapor cell through the measured number density. We also measured the temperature of the vapor cell through a temperature sensor. The temperature measured by the absorption method is around 5 degree larger than that of the temperature sensor. Here we will use the absorption method, since it directly measures the number density of the Cs atoms.

The free induction decay(FID) signal is a typical way to measure the precession frequency and relaxation of the nuclear spins. Fig[2] shows one of the FID signal. A holding magnetic field in the z direction $B_z$ is added to the system. After several minutes’ spin exchange optical pumping, The polarization tends to be stable. We suddenly add a step magnetic field which is around $10^{-3}$ of the holding magnetic field in the y direction to let the nuclear spin precess around the total magnetic field. After around 1 second, we removed the y step magnetic field and the nuclear spins will precess around...
Figure 1: The configuration of the vapor cell, pump laser and the holding magnetic field.

Figure 2: The free induction decay (FID) signal of the $^{129}$Xe and $^{131}$Xe nuclear spins. The solid curve is the experiment data and the dashed line is the fitted curve. In order to see the fitting more clearly, we selected a part of the FID signal and amplified it in the embodied figure.
the holding magnetic field $B_z$. Note that the residual magnetic field in the shield is below 5nT and we compensated this residual field by the coils with the single beam Cs atomic magnetometer. We mention that the modulation amplitude of the magnetometer only affect the relaxation of Cs atoms. We set the modulation amplitude as small as possible to do the measurement.

The FID signal composes several frequencies. We did a fft analyse of the signal shown in Fig.2. We can see that there are 4 frequencies in the signal. The precession frequency of $^{129}$Xe is single and it is around 3 times of the $^{131}$Xe’s precession frequencies. There are 3 components in the $^{131}$Xe’s precession. Due to the quadrupolar interaction, the frequency difference of the 3 peaks are the same and equal to $\Delta \Omega$. From Fig.2 we can see that the high frequency precession is from $^{129}$Xe. There is also the $^{131}$Xe precession frequency with smaller frequency. The beating signal of $^{131}$Xe is caused by the nuclear quadrupolar interaction. In order to acquire the frequencies and the relaxation times of the 4 precession components, we do a fitting to the FID experiment data with the following equation:

$$V(t) = A\exp(-\Gamma_{129}t)\cos(2\pi f_{129}t + \phi_{129}) + \exp(-\Gamma_{131}t)\left[B_1\cos(2\pi f_{131}t + \Delta \Omega t + \phi_{131}^1) + B_2\cos(2\pi f_{131}t + \phi_{131}^2) + B_3\cos(2\pi f_{131}t - \Delta \Omega t + \phi_{131}^3)\right]$$

where $A$, $B_1$, $B_2$ and $B_3$ are the amplitudes of the 4 precession components. $\Gamma_{129}$ and $\Gamma_{131}$ are the decay rates of the nuclear spin. $f_{129}$ and $f_{131}$ are the precession frequencies of $^{129}$Xe and $^{131}$Xe without the nuclear quadrupole shift. $\phi_{129}$, $\phi_{131}^1$, $\phi_{131}^2$ and $\phi_{131}^3$ are the phase of the 4 components respectively. From the fitting result in Fig.2, we can see that the equation could fit well to the experiment data. In order to see the $^{129}$Xe precession frequency, we substract the signal of $^{129}$Xe from the FID signal. Fig.4 shows the pure signal. We can clearly see the beating signal of $^{131}$Xe precession.
We can also get the desorption energy of Xe atoms on the surface of silicon $E_{si}$. With the increasing of the temperature, the time that nuclear spins stay on the material will be shorter. Thus, the average angle will be reduced and finally the quadrupolar frequency shift will decrease. In equation (3), it is reasonable to suppose that the average angle $\langle \theta \rangle$ is proportional to $Exp(I/E/k_BT)$ in which $E$ is the desorption energy of the material. Suppose that there are coefficients $k_1$ and $k_2$ which connect the average angle and the desorption energy for the glass and silicon. It is reasonable to set the average thermal velocity of the nuclear spin to be $245 m/s$ which is the velocity under 373K since the thermal velocity is weakly temperature dependent. At 373K, the average angle for the glass is $45 \mu rad$ and the desorption energy is $E_g = 0.12 eV$. We can calculate that $k_3$ is equal to $1.1 \times 10^{-6}$. Together with the experimental condition, we can get:

$$\ln \left(\frac{2\pi}{\Delta \Omega}\right) = 4.53 - \frac{1391.3 x}{c + e x}$$

(4)

where $c = Ln(600661 k_2)$. $x = 1/T$ and $e = E_{si}/k_b$. We fit the experimental data shown in Fig.5 with equation (4). The fitting results show that $e$ is 109 and $c$ is 0.89. We can get that $E_{si}$ is 0.009 and $k_1$ is equal to $4.0 \times 10^{-6}$. From the results we see that as the nuclear spin absorbed on the silicon surface, they seems to stay much shorter time than that of the glass. It seems that the EFG is larger on the surface of silicon since the factor $k_2$ is around 3 times larger than that of the glass.

Except the frequency shifts, we also studied the relaxation of the $^{129}\text{Xe}$ nuclear spins. We changed the number density of the Cs atoms and then measure the relaxation rate of the nuclear spins. The relaxation of $^{129}\text{Xe}$ is also measured through the FID method. The FID signal is fitted to Equation (3) and then the relaxation rate could be measured. The relationship between the Cs number density and $^{129}\text{Xe}$ relaxation rate is shown in Fig.6. The fitting shows that the slope is $3.7 \times 10^{-15} cm^3/s$ and the relaxation rate of $^{129}\text{Xe}$ nuclear spin tends to be $0.038 s^{-1}$ as the Cs number density is 0. Thus the wall relaxation rate of $^{129}\text{Xe}$ is 0.038. During the measurement of the relaxation rate, we find that the relaxation is strongly related to Cs polarization. This is because the polarized Cs atoms could produce magnetic field which could be experienced by the nuclear spins. As the precession frequencies of the nuclear spins and the Cs electron spins close to each other, Cs atom spins would damp the Xe precession. Thus, we lowered the

![Graph](image-url)

Figure 5: The relationship between the cell temperature and the quadrupole frequency shift of the $^{131}\text{Xe}$ energy level.

4 Results

The nuclear quadrupolar shift is related to the temperature of the vapor cell since the temperature could affect $\tau_s$. Finally, the average angle $\langle \theta_g \rangle$ could be affected by the temperature. We changed the vapor cell temperature and then measure the $^{131}\text{Xe}$ quadrupolar shifts. The relationship between the temperature and the frequency shifts are shown in Fig.5. According to Equation (2), we can simplify the equation into:

$$\Delta \Omega = \Delta \Omega_g + \Delta \Omega_{si} = \pm \frac{eS}{2V} \frac{1}{2T-1} \frac{d \langle \theta_g \rangle - h \langle \theta_{si} \rangle}{d + 2h}$$

(4)

where $d$ is the diameter of the vapor cell and $h$ is the height of the vapor cell. Since $Ln(1/\langle \theta \rangle) \propto -E_A/(k_BT)$, we set the horizontal axis to be $1/T$ and the vertical axis to be $Ln(2\pi/\Delta \Omega)$. As shown in this reference [Butscher et al. 1994], the average angle $\langle \theta_g \rangle$ for Pyrex glass is $45 \mu rad$ as the temperature of the vapor cell is 373K. From the fitting result of Fig.5, as the temperature of the vapor cell is 373K, we can calculate that the average angle for the silicon is $29 \mu rad$. This result is similar to the result in this reference [Donley et al. 2009] in which the angle for the silicon is $29 \mu rad$.

We can also get the desorption energy of $^{131}\text{Xe}$ atoms on the surface of silicon $E_{si}$. With the increasing of the temperature, the time that nuclear spins stay on the material will be shorter. Thus, the average angle will be reduced and finally the quadrupolar frequency shift will decrease. In equation (3), it is reasonable to suppose that the average angle $\langle \theta \rangle$ is proportional to $Exp(I/E/k_BT)$ in which $E$ is the desorption energy of the material. Suppose that there are coefficients $k_1$ and $k_2$ which connect the average angle and the desorption energy for the glass and silicon. It is reasonable to set the average thermal velocity of the nuclear spin to be $245 m/s$ which is the velocity under 373K since the thermal velocity is weakly temperature dependent. At 373K, the average angle for the glass is $45 \mu rad$ and the desorption energy is $E_g = 0.12 eV$. We can calculate that $k_3$ is equal to $1.1 \times 10^{-6}$. Together with the experimental condition, we can get:

$$\ln \left(\frac{2\pi}{\Delta \Omega}\right) = 4.53 - \frac{1391.3 x}{c + e x}$$

(5)

where $c = Ln(600661 k_2)$. $x = 1/T$ and $e = E_{si}/k_b$. We fit the experimental data shown in Fig.5 with equation (5). The fitting results show that $e$ is 109 and $c$ is 0.89. We can get that $E_{si}$ is 0.009 and $k_1$ is equal to $4.0 \times 10^{-6}$. From the results we see that as the nuclear spin absorbed on the silicon surface, they seems to stay much shorter time than that of the glass. It seems that the EFG is larger on the surface of silicon since the factor $k_2$ is around 3 times larger than that of the glass.
According to the measured results for $E$ which could cause the relaxation is isotropic. The coefficients beside the square twisted angle is the inner surface area $131$ of the two material. According to the reference Butscher et al. [1994], the average of the squared twisted angle $\langle \theta^2 \rangle$ is the quadrupolar interaction. According to the reference Wu et al. [1988], the quadrupolar relaxation of $^{131}Xe$ for the $|3/2 > < 1/2|$ and $|-3/2 > -1/2|$ energy levels are determined to be:

$$
\Gamma_{Q_u}^{131} = \frac{2}{5} v S \left( \frac{2h}{d + 2h} \langle \theta^2 \rangle + \frac{d}{d + 2h} \langle \theta^2 \rangle \right)
$$

In the equation, $\langle \theta^2 \rangle$ is the average squared angle as the nuclear spin collide with the surface wall. We believe that this angle is different for the silicon and glass material. It is also reasonable again to suppose that the EFG fluctuation which could cause the relaxation is isotropic. The coefficients beside the square twisted angle is the inner surface area percentage of the two material. According to the reference Butscher et al. [1994], the average of the squared twisted angle $\langle \theta^2 \rangle$ is proportional to $\exp(2E/k_BT)$. Thus, equation 6 could be written:

$$
\Gamma_{Q_u}^{131} = \frac{3}{5} v S \left[ \frac{2h}{d + 2h} k_1 E \exp(\frac{2E_{si}}{k_BT}) + \frac{d}{d + 2h} k_2 E \exp(\frac{2E_{g}}{k_BT}) \right]
$$

According to the measured results for $E_g = 0.12eV$ and $\langle \theta^2 \rangle = 3.4 \times 10^{-6} \text{rad}^2$, under the temperature of 373K, we can calculate $k_2$ to be $1.95 \times 10^{-9}$ with the relation $\langle \theta^2 \rangle = k_2 E \exp(\frac{2E_{g}}{k_BT})$. We substitute these results into equation 8 to calculate the quadrupolar relaxation of $^{131}Xe$ nuclear spin could be:

$$
\Gamma_{Q_u}^{131} = 0.125 + 49100k_1 E \exp(\frac{2E_{si}}{k_BT})
$$

Now we turn to do a calculation of $\langle \theta^2 \rangle$. As the cell temperature is 393.5K, the number density of Cs is $6.6 \times 10^{13} \text{cm}^3$. The total relaxation of $^{131}Xe$ which includes the quadrupolar relaxation with surface and the spin collision with Cs...
Atoms is 0.21 sec$^{-1}$. First, we need to subtract the relaxation from collision with Cs atoms. There is rare study about the spin exchange collision relaxation between Cs and $^{131}Xe$ atoms. We can only do an empirical calculation of $Cs - ^{131}Xe$ spin exchange relaxation from the result of $Cs - ^{129}Xe$. Since the angular momentum of $^{131}Xe$ is 3/2 which is 3 times larger than that of the $^{131}Xe$. While the nuclear magnetic moments of the two isotopes are nearly the same. Thus it is reasonable to assume that the spin exchange rate coefficient $k_{se}$ for $Cs - ^{129}Xe$ is 3 times that of the $Cs - ^{131}Xe$ pair. The measured result for $Cs - ^{129}Xe$ pair is $3.7 \times 10^{-15} \text{cm}^3/\text{s}$ and thus we can calculate the spin exchange rate coefficient $k_{se}$ to be $1.2 \times 10^{-15} \text{cm}^3/\text{s}$. Under the temperature of 393.5K, the spin exchange relaxation of $^{131}Xe$ is 0.08 s$^{-1}$. We substract the spin exchange relaxation from the total relaxation and then we can get the quadrupolar relaxation of $^{131}Xe$ under 393.5K to be 0.13 s$^{-1}$. Since the squared average angle for collision with the glass material is temperature dependent, we can calculate the angle under 393.5K to be $2.3 \times 10^{-6} \text{rad}^2$. According to equation 4, we can calculate that the glass material induced quadrupolar relaxation to be 0.06 s$^{-1}$. Finally, we can calculate that $\langle \theta^2_{si} \rangle$ under 393.5K is equal to $2.2 \times 10^{-6} \text{rad}^2$ which is similar to that of the glass colliding.

5 Discussion

The glass material utilized in our vapor cell is boro-silicate glass with a thermal expansion coefficient of $3.3 \times 10^{-6} / \text{K}$. The limitation of this study is that we could not independently measure the quadrupolar interaction between $^{131}Xe$ and the glass surface. We took the parameters from other references for the desorption energy, the mean twisted angle and mean squared twisted angle. Since there is no data about the spin exchange rate between Cs and $^{131}Xe$ nuclear spins, we theoretically estimate this parameter based on the measured rate of $^{129}Xe$. Further studies could be done to directly measure the spin exchange optical pumping rate between Cs and $^{131}Xe$. For comparison, the spin exchange parameters between Cs and $^{129}Xe$ are well known. The other limitation of this study is that we could not measure the relaxation of $^{131}Xe$ in a wide range of temperature. At low temperature and high temperature, the $^{131}Xe$ FID signal will be very weak compared to the $^{129}Xe$ FID signal. Moreover, the FID signal is not so strong since the natural abundance Xe is utilized in our experiment. Other isotopes will contribute to a large part of the Cs spin relaxation and thus the sensitivity of the single beam atomic magnetometer will be low. Further studies could be done to just fill isotope enriched $^{131}Xe$ atoms in the vapor cell. Note that when we fabricating a micro-machined alkali vapor cell, the anode bonding chamber is quite large compared to the glass blown vapor cell fabricating system. It will waste a lot of expensive isotope enriched $^{131}Xe$ for making the micro-machined vapor cell. We are now developing a gas recycling system to improve the situation.

6 Conclusion

In conclusion, we have studied the quadrupolar frequency shift and relaxation of $^{131}Xe$ nuclear spins as they collide with the silicon container wall. The silicon material is a kind of widely utilized material in the MEMS technology. This study helps to know more about the surface property of the silicon. CSAG would be developed and this study will finally helps to improve the bias instability of the CSAGs. We divided the alkali vapor cell into the glass parts and the silicon part. Models for the frequency shift and relaxation were developed to measure the quadrupolar interaction between the nuclear spins and the surfaces. The desorption energy of $^{131}Xe$ on the silicon surface is measured to be 0.009eV. At 373K, the average twisted angle $\langle \theta_{si} \rangle$ as $^{131}Xe$ collide with the silicon surface wall is 29 $\mu$rad. The relaxation of $^{131}Xe$ was also studied and we acquired the average square twisted angle $\langle \theta^2_{si} \rangle$ which could decide the relaxation of $^{131}Xe$ nuclear spin to be $2.2 \times 10^{-6} \text{rad}^2$ under 393.5K.

7 Acknowledgement

This work is supported by Open Research Projects of Zhejiang Lab under grant number 2019MB0AB02, China Postdoctoral Science Foundation under grant number 2020M683462, National Natural Science Foundation of China under grant number 62103324 and Natural Science Foundation of Jiangsu under grant number BK20200244.

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