The study of Polarized $^3$He target cell lifetime

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Abstract

The $^3$He target cell polarized by spin-exchange optical pumping (SEOP) is used as a neutron substitute to study the inner structure of the neutron via electron scattering experiment. However once polarized, $^3$He target cell depolarizes itself exponentially. The lifetime of a cell is the decay constant of the polarization. The typical lifetime of cells produced in our lab is about 22 hours. Longer lifetime indicates higher electron beam effective time and thus reduces uncertainty. My work presents the study of cell lifetime improvement. With a newly designed vacuum system where the base pressure is as low as $10^{-8}$ torr and the new vacuum alkali ampoule that promises alkali purity for cell production, we hope to see a longer cell lifetime.

1 Introduction

In the William and Mary Polarized $^3$He target lab, we produce cells for Jefferson Lab where researchers perform electron scattering experiments to study the inner structure of neutrons. We use polarized $^3$He nucleus as the target instead of a neutron because firstly a free neutron is unstable and has a lifetime of only $(885.7 \pm 0.8) s$ [1], and secondly the $^3$He nucleus is a perfect substitute. Figure 1.1 shows the most probable ground state configuration of $^3$He nucleus (88.2%) [2] and we can see from it that the spin state of the $^3$He nucleus is mostly determined by that of the neutron[3]. Thus we can conclude that the polarization of the neutron states the polarization of $^3$He nucleus.

1.1 Cell

A cell is a, for example as shown in figure 1.2, spherical container made of glasses that holds only $^3$He, $N_2$ and alkali inside. We use spin exchange optical pumping (SEOP) method to spin-polarize the alkali atoms. To ensure polarize the alkali atoms we will bake the cell up to $180^\circ$C and vaporize the alkali. After the alkali atoms are polarized, they will transfer their polarization to the $^3$He nucleus via spin exchange. In my experiment, I intentionally choose rubidium ($^{85}$Rb and $^{87}$Rb) only as the alkali, because in our lab the average lifetime of mixed cells, which contain both rubidium and potassium is lower compared to that of the cells using only rubidium as the alkali. When
Figure 1.1: The most probable ground state configuration of $^3$He nucleus (88.2%). In this case, neutron polarization represents $^3$He nucleus polarization.

Figure 1.2: Cell tom used for my experiment. $^{85}$Rb is also inside the cell but not included.
rubidium atoms are polarized through the absorption of circularly polarized laser light with a wavelength of 794.68nm, some electrons inside the atoms will decay radioactively and thus depolarize the atoms. To solve this problem, we use N\textsubscript{2} to quench those excited electrons.

### 1.2 Polarization

As a fermion, the $^{3}\text{He}$ nucleus has two spin states, $T_{+}$ and $T_{-}$. Thus the polarization of $^{3}\text{He}$ nucleus is defined as:

$$P = \frac{T_{+} - T_{-}}{T_{+} + T_{-}}$$

(1)

Once polarized within a holding magnetic field, $^{3}\text{He}$ nucleus loses its polarization exponentially from time to time and this process is defined as the relaxation. Thus the amount of time the $^{3}\text{He}$ nucleus in our cell needs to decay by about 63\%. The average lifetime of rubidium only cells produced in our lab so far is about 22 hours. We hope to increase cell lifetime because by doing so we increase beam effective time and reduce the uncertainty.[4]

### 2 Cell Production

In our lab, all cells are attached to a straight glass piece that is connected to our unique gas system consisting of the gas part and the cell part as shown in figure 2.1. In my experiment, I use two spherical cells called Tom and Jerry. Unfortunately cell Jerry was leaking so it is out of the game. To produce our cells, firstly we pump the gas out of our system and then bake the cell with our oven till the base pressure inside the connection between gas part and cell part reaches $10^{-8}$ torr. After that we perform alkali chasing to the dip as shown in figure 2.1 by heating the alkali with the torch. Once most alkali atoms reach the dip, we do the first pull-off. Then we pump in N\textsubscript{2} and $^{3}\text{He}$ separately from our gas part. We calculate the amount of gas we need based on estimated cell volume and ideal gas law. When both N\textsubscript{2} and $^{3}\text{He}$ are pumped into the cell part, we close the valve that connects the two parts and cool down our cells to 4K with a Dewar filled with liquid $^{3}\text{He}$. Then all the gasses will liquefy, flow into our cells and stay there for good. Finally we perform the second pull-off at 4K.

#### 2.1 Improvements

One important part for filling the cell is to maintain alkali purity. It’s very challenging to transfer the alkali, rubidium in my experiment, to the cell part of our system without exposing it to the air. Because rubidium is extremely reactive to the oxygen, a tiny leak will ruin the whole experiment. Cell Jerry was experiencing a small leak and all my data about it was completely useless because once rubidium reacts with the oxygen, there would be no rubidium vapor left there to be polarized. To ensure the purity, we apply the new rubidium ampoule shown in figure 2.2. A rubidium ampoule is a small vacuum rubidium container. We simply put both the ampoule and a piece of magnet into our cell part before we pump the whole system and produce cells. Right before we
Figure 2.1: The cell part of our gas system along with cell Tom and cell Jerry. (Modified based on figure 3.1 from ref [2] with the help of Jiangnan Fu)

Figure 2.2: The rubidium ampoule.
Figure 2.3: The gas part, the vacuum system of our gas pumping system. The cell part is connected to valve BV 11 and the gas sources are connected to the valve on the bottom near letter F.
chase the rubidium, we use another piece of magnet to attract the one inside and break the ampoule to release the rubidium as shown in figure 2.1. In this case we the purity is higher.

The other important part for filling the cell is an extremely clean pumping gas system. The word clean is defined by a good vacuum pressure the gas system can achieve. With almost a whole year’s work, I designed and built the new vacuum system shown in figure 2.3. I used all new plumbing pieces made of stainless steel instead of copper. I also installed a new getter which embraces far more surface areas and thus does a good job filtering the gas but increase the base pressure unfortunately if used. Thus we only use the getter when we pump the \( \text{N}_2 \) and \(^3\text{He} \) into the manifold, the connection part between gas part and cell part. Then we close the valve that connects to the getter. Our base pressure inside is about \( 10^{-8} \), which is the best we can achieve so far.

3 Experiment set-up

Figure 3.1 shows my experimental set-up. The two huge green coils provide the uniform holding field, and the two relatively smaller red coils are used for Nuclear Magnetic Resonance (NMR) measurement to broadcast oscillated RF. Cell Tom is installed almost right in the center inside the oven, which helps heat the cell up to 180°C to fully vaporize the rubidium. After our cell is polarized, we then read NMR signals from the pick-up coils. Both the photodiode and the EPR coils are used for rubidium polarization measurement, which is more for future work.

![Figure 3.1: The experiment set-up. (Modified based on figure 2.2 from ref [2])](image-url)
Figure 3.1 also shows that the laser is coming from the side of the oven, and one crucial part for laser set-up is the alignment. We are using two lasers, QPC and Raytum, at the same time and thus we need to align both. Given that the two lasers are combined through optical fibers, it’s very challenging to focus the two on one spot. But we align them so perfectly near that our experiment will not be affected.

4 Method

The Nuclear Magnetic Resonance (NMR) measurement gives the relative polarization of $^3$He nucleus. When we broadcast the oscillated RF through RF coils, we generate an oscillating magnetic field and thus flip the spin of $^3$He nucleus. Once the spin is flipped, current is induced inside our pick-up coils. Through sweeping the holding field, we perform NMR sweep and plot induced voltage vs time or sweep number. Then we find the resonance by looking for the maximum amount of voltage ever induced, and document all the peak heights, those induced voltages at resonance. Finally we plot those peak heights with respect to time. Since we sweep the holding field up and down, we will have two set of data. One is for up sweep and the other is for down sweep.

We perform spin-up and spin-down measurements which are based on the NMR measurement to find out the cell lifetime. The spin-up measurement is the NMR measurement we run right after we turn the laser on and optically pump the cell, and the spin-down measurement is the one we run when we turn off both the laser and heater and wait till the oven is at around 30°C. We believe that the polarization goes like for spin-up:

$$P = P_{max} \times (1 - e^{\frac{t-o}{\tau}})$$

(2)

where $t_o$ is the time offset and $\tau$ is NOT cell lifetime. And the depolarization goes like for spin-down:

$$P = P_{max} \times (e^{\frac{t-o}{\tau}})$$

(3)

where $\tau$ is the cell lifetime.

5 Result

We can clearly see from figure 5.1 that cell Tom requires about 4.05 hours to reaches 67% of it’s maximum polarization, and from figure 5.2 that cell Tom requires about 2.69 hours to depolarize by about 67%. The result is really astonishing because without any of my improvements the cell seemed to do a much better job before. My cell Tom’s lifetime is only about 12% of the average lifetime of those previous cells. The uncertainty is too trivial to affect my result by this amount. Unfortunately because cell Jerry got abandoned due to its leak during the experiment, I could not take any data about it to compare.
Figure 5.1: The spin-up measurements of both NMR up sweep and down sweep of cell Tom.

Figure 5.2: The spin-down measurements of both NMR up sweep and down sweep with $\tau$ equals 2.69 hours of cell Tom.
6 Conclusion

Given that $\tau$ equals 2.69 hours and the average cell lifetime in our lab is 22 hours, I successfully increase the cell lifetime by -88%. The reason for such an absurd result is not well known. Possibly the polarization of my cell was affected when we installed and tested our new EPR amplifier since running EPR measurements will depolarize the cell for a moment. Also maybe the gas density inside our cell was not correct. My next project in the upcoming semester is to figure out where my experiment went wrong.
References


