# Implementing a Pulsed-NMR System for Studying Polarization of $^3$He Target Cell

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## Abstract

Polarized helium-3 ($^3He$) has proven to be an extremely effective neutron target for use in high-energy nuclear physics experiments. The unique quantum properties of $^3He$ cause the spins of its protons to pair up, allowing the neutron to carry the majority of the nucleus spin. Through spin-exchange optical pumping (SEOP), it is possible to achieve high polarization, which can then be measured using pulsed nuclear magnetic resonance (NMR). The focus of this study is to implement a pulsed-NMR system for use with the $^3He$ target. A pulsed-NMR system was developed at Jefferson Lab for the specific purpose of measuring the polarization of $^3He$ inside the target cell. This pulsed-NMR system works by sending out a radio frequency (RF) signal into the target cell, causing the spin of $^3He$ to be knocked off-axis with the magnetic holding field. As $^3He$ relaxes and its spin realigns with that of the magnetic field, an electric current is produced in the NMR pick-up coils. Preliminary results show that we are, in fact, seeing NMR signal being produced. These initial results are encouraging because this is the first time pulsed-NMR signal has been observed at Jefferson Lab. Further testing must first be done to confirm that the signal is accurate and to account for the initial spike in signal. If it is confirmed that pulsed-NMR signal was actually observed, it may be possible to implement the pulsed-NMR system on the new dual-chambered convection cell for 12 GeV experiments.

## Introduction

Thomas Jefferson National Accelerator Facility has been involved in many types of nuclear and particle physics experiments during its existence. One of these types of experiments involves neutron spin structure measurements using helium-3 ($^3$He) gas. Polarized $^3$He has shown that it is a very effective target for studying the neutron in high-energy nuclear physics experiments. This is due to the fact that $^3$He consists of two protons and one neutron within its nucleus. The significance of this is that the intrinsic spin of each proton pairs, cancelling each other out and allowing the neutron to carry the majority of the nucleus spin as can be seen in Fig. 1. This is useful because any alterations made to the nucleus spin will be reflected in the intrinsic spin of the neutron.

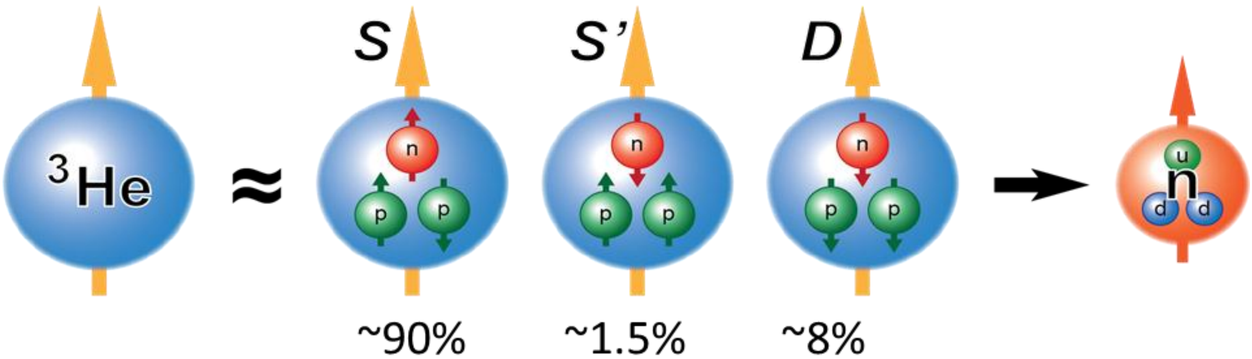


Fig. 1: Model of $^3$He atom

This property of $^3$He is useful because it allows physicists to study the neutron under different polarization conditions. In experiments such as electron-nucleon deep inelastic scattering experiments, this can be especially important. Modeling the internal structure of the nucleon is possible because of experiments involving polarized $^3$He. One difficult aspect of performing these experiments, however, is getting $^3$He to achieve high polarization at high density. The polarization of $^3$He can be measured using nuclear magnetic resonance (NMR). The main goal of this research is to set up a pulsed-NMR apparatus for studying the polarization of $^{3}$He in the target cell.

## Experimental Methods

$^{3}$He target cells have been developed at Jefferson Lab that take advantage of $^{3}$He's unique intrinsic spin properties. These $^{3}$He gas cells consist of a pumping chamber where the $^{3}$He gas is initially polarized, a target chamber where the electron beam enters making contact with the polarized $^{3}$He nuclei, and transfer tubes that transport polarized $^{3}$He from the pumping chamber to the target chamber. The current target cell works via diffusion where polarized $^{3}$He enters the target chamber due to the temperature gradient between the pumping and target chamber. Unfortunately, the low diffusion rate limits the maximum polarization of $^{3}$He achievable inside the target chamber. A new convection cell, as seen in Fig. 2, is being developed at Jefferson Lab to increase the polarization of $^{3}$He inside the target chamber. This new cell uses convection to keep a steady flow of polarized $^{3}$He into the target chamber at all times. As a result, a higher concentration of polarized $^{3}$He can be found in the target chamber of the convection cell than it can in the original diffusion cell.

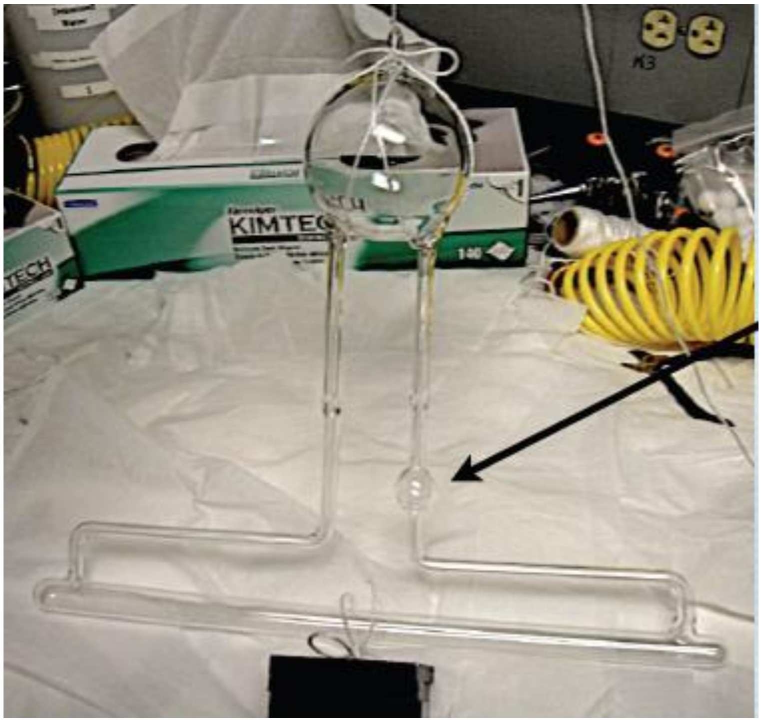

Fig. 2: New Convection Target Cell

Through a process called spin-exchange optical pumping (SEOP), it is possible to manipulate the polarization of $^3$He using polarized laser light. According to the Pauli Exclusion Principle, no two electrons occupying the same orbital can have the same intrinsic spin. This makes it difficult to polarize atoms in which their orbitals are filled. Elements such as helium are difficult to polarize because its outermost electron shell is filled. If the Pauli Exclusion Principle holds true, this means that the spin of helium’s two electrons pair up, cancelling each other out and making it difficult to polarize. Alkali metals, however, only have a half-filled shell in their highest-energy orbital. Since alkali metals have only one valence electron, they are an ideal choice for use in this SEOP process.

In SEOP atoms are placed in a magnetic field in which Zeeman splitting occurs, that is the atoms separate into their higher and lower energy spin states. Using polarized light with a wavelength equal to that of the alkali metal's absorption line, it is possible to pump these valence electrons to a higher energy orbital in which the desired spin state can be achieved, as seen in Fig. 3. These electrons will proceed to relax back down to their original orbital, maintaining the desired spin state in the process. Through collisional mixing alkali metals, such as rubidium and potassium, are able to transfer their given spin states to the nuclei of certain atoms such as $^3$He [1]. Through this SEOP process it is possible to polarize nuclei to a desired overall spin state.

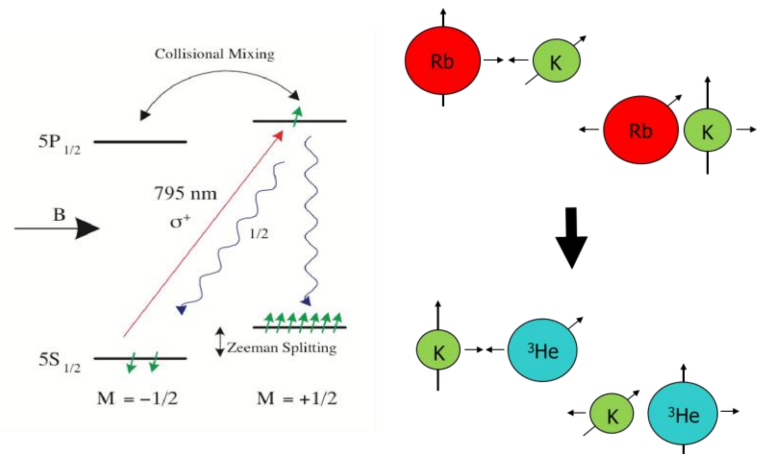


Fig. 3: Diagram of SEOP Process

To accomplish this, diode lasers were used to create the polarized light necessary to successfully polarize the rubidium atoms. Each laser diode emits circularly polarized light at a wavelength of 795 nm, matching the absorption line of rubidium. This circularly polarized light is passed through a series of optics so that only the final p-wave component of light is actually absorbed by the rubidium atoms [2]. Once initially polarized by the laser light, the rubidium atoms can begin the process of transferring their spin to $^3$He nuclei. Fig. 4 shows a diagram of the optics setup.

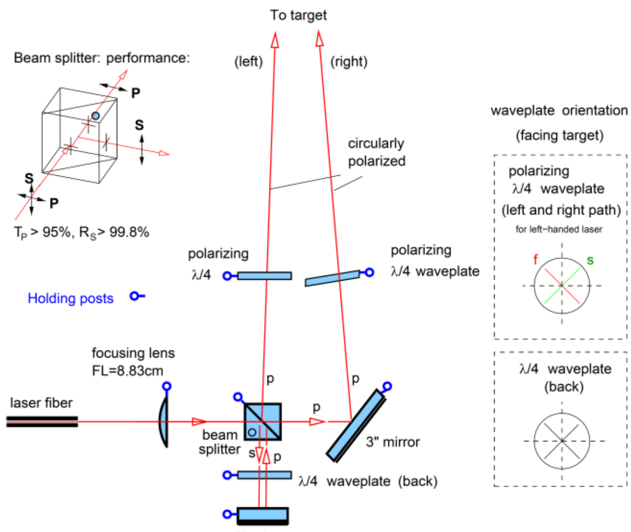


Fig. 4: Optics Setup

Each diode laser was tested in order to find the maximum possible power output each can supply. Ideally, each laser should have a power output of 30 W in order to achieve a high polarization of $^{3}$He gas. During testing, three lasers were used at any given time to polarize $^{3}$He meaning that the combined overall power output should be at least 90 W. These lasers were first tested at different temperatures and currents to see what combination yielded the best power output and wavelength. Each combination of power supply, temperature controller, cable, and diode was tested in order to determine which combination gave maximum power output. Each laser was also given at least thirty minutes to stabilize before a spectrum was taken.

There are also certain conditions that must be met by the target cell itself in order for polarization of $^{3}$He to occur, as can be seen in Fig. 5. At room temperature, the pressure inside the cell is about 10 atm. The pumping chamber of the target cell is kept in a ceramic oven at 230°C. This condition is necessary in order for the alkali metals in the pumping chamber to vaporize, allowing collisional mixing to occur.

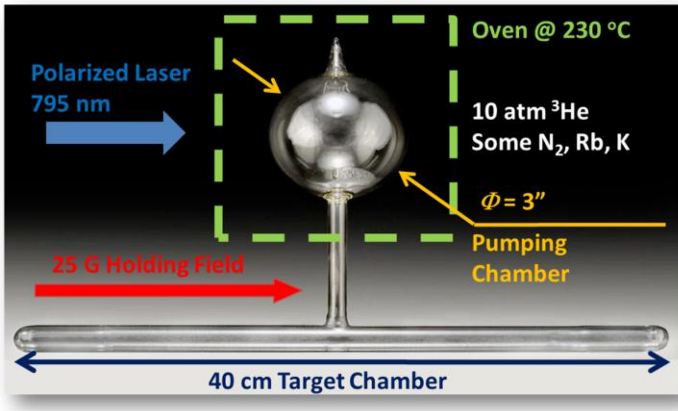


Fig. 5: Target Cell Conditions

It is often useful to measure the polarization in a local area of the cell at a given time. Nuclear magnetic resonance (NMR) is a very useful tool that can be used to measure the polarization of $^3$He within the target cell. In the target apparatus, large Helmholtz coils are used to the align $^3$He nuclei in a given direction. NMR pick-up coils are placed along the length of the target chamber as well as surrounding the pumping chamber. Fig. 6 shows a diagram of the entire target setup. Initially a trigger sends a square wave pulse which, at high voltages, causes a function generator to emit an RF signal from the pick-up coils located along the target chamber. These short-burst RF signals knock the magnetic moments of the $^3$He nuclei off their aligned axis with the magnetic holding field. These same pick-up coils are also used to receive the electrical signal produced by the relaxation of $^3$He as it realigns itself with the holding field. After the initial RF signal is sent, a switch is triggered by the square wave, closing off the RF channel and opening the NMR channel. The signal received by the NMR pick-up coils is sent to a lock-in amplifier where it can then be measured. Fig.7 represents a diagram of the NMR setup. By measuring the transverse relaxation signal for the sample, we are able to determine the polarization of $^3$He inside the cell.

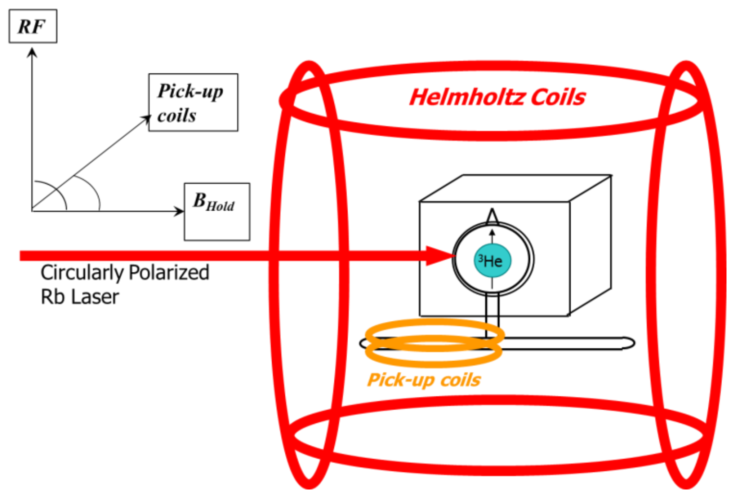


Fig.6: Target System Setup

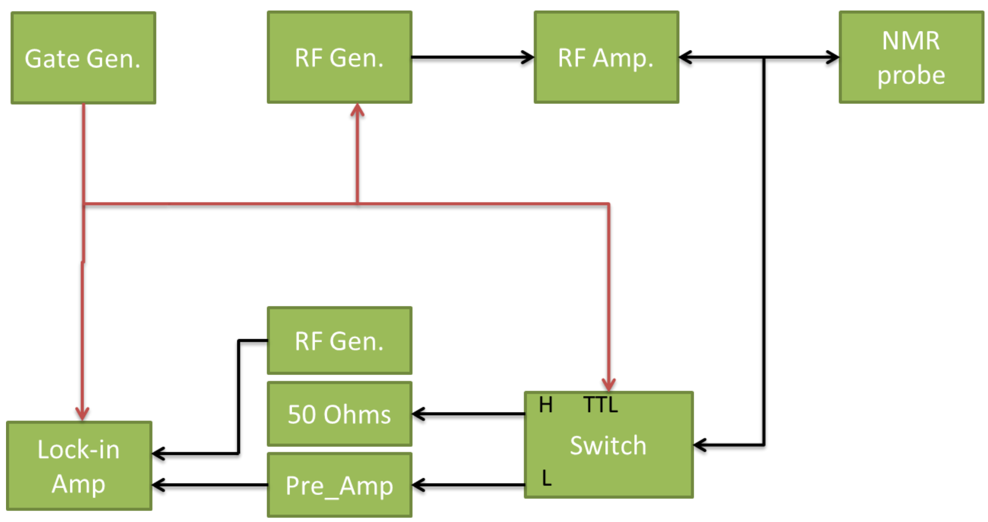


Fig. 7: NMR Setup

Equation 1 models the polarization of $^3$He within the target cell over time. $P_0$ is the initial polarization of $^3$He, $\gamma_{se}$ is the polarization rate due to spin-exchange, $\Gamma$ is the spin-relaxation rate, and $P_A$ is the polarization of the alkali vapor. In the case of polarization within the target chamber, because there is not spin-exchange taking place in the target chamber, the equation modeling the polarization of $^3$He simplifies to that of Equation 2 [3]. This equation can also be used to find the transverse component of the polarization as can be seen in Equation 3 where $P_1$ is the transverse component of polarization.

$$P_{He}(t) = P_0 e^{-(\gamma_{se}+\Gamma)t} + P_A \frac{\gamma_{se}}{\gamma_{se}+\Gamma}[1 - e^{-(\gamma_{se}+\Gamma)t}]$$

Equation 1: Polarization of $^3$He in target cell over time

$$P_{He}(t) = P_0 e^{-(\gamma_{se}+\Gamma)t}$$

Equation 2: Polarization of $^3$He in target chamber over time

$$P_1(t) = P_0 \sin\theta \, e^{-(\gamma_{se}+\Gamma)t}$$

Equation 3: Transverse polarization over time

Increase in density and electron current will require that that the target chamber be made out of a material other than glass. Most likely the target chamber will be required to be made out of some sort of metal material. Since RF signals are incapable of penetrating metal surfaces, a new method has to be considered in order to measure polarization of $^3$He within the target cell. Pulsed-NMR performed along one of the transfer tubes is a potential option for measuring the polarization of $^3$He inside the target cell.

To model the polarization dynamics on the new convection cells, the pulsed-NMR setup will first be tested on a convection cell made entirely of glass. In this case, NMR data can be taken from both the target chamber and transfer tube because there is nothing preventing the RF signal from penetrating the surface. By comparing the NMR data from both the target chamber and transfer tube, it is possible to model the polarization of $^3$He inside the target chamber based on the polarization of $^3$He inside the transfer tube. The new convection cell contains a chamber in the transfer tube for pulsed-NMR to take place. This way polarization for $^3$He inside the target chamber can be extracted even after the metal target chamber is put in place.

## Results

Results for the diode lasers show a maximum power output of 22.6 W for one laser with a combined maximum power output of 63.5 W for three lasers. The following tables show the results from testing with different combinations of power supplies, temperature controllers, cables, and diodes. Table 1 shows the results of each laser combination test. In these tables 1 means JLab #1 (i.e. C1 is JLab #1 cable), 2 means JLab #2, 3 means Rutgers, and 4 means William & Mary. As can be seen, the maximum power output of 22.6 W was achieved when the William & Mary temperature controller was combined with all other components of JLab #1. It was also found that the William & Mary diode performed well when combined with all other components of JLab #1.

| **Test Cables** | **C1** | **C2** | **C3** |
|---|---|---|---|
| D1, T1, P1 | 15.8 W | 15.9 W | 16.0 W |

| **Test Temp. Cont.** | **T1** | **T2** | **T3** | **T4** |
|---|---|---|---|---|
| D1, P1, C1 | 15.8 W | 15.3 W | 16.1 W | 22.6 W |

| **Test Pwr. Sup.** | **P1** | **P2** | **P3** |
|---|---|---|---|
| D1, T3, C1 | 16.1 W | 16.2 W | 16.3 W |

| **Test Diodes** | **D1** | **D2** | **D3** | **D4** |
|---|---|---|---|---|
| T1, P1, C1 | 15.8 W | 16.2 W | 19.1 W | 21.8 W |

Table 1: Laser Diode Combinations

Preliminary results show that we are, in fact, getting signal using the pulsed-NMR apparatus on the diffusion cell. The decay time for each NMR signal is approximately 10 ms. An initial spike in signal is also observed in both the target and pumping chamber. At this time there is still inconclusive evidence as to why the initial spike in signal is being observed. Fig. 8 shows the results of the pulsed-NMR test run.

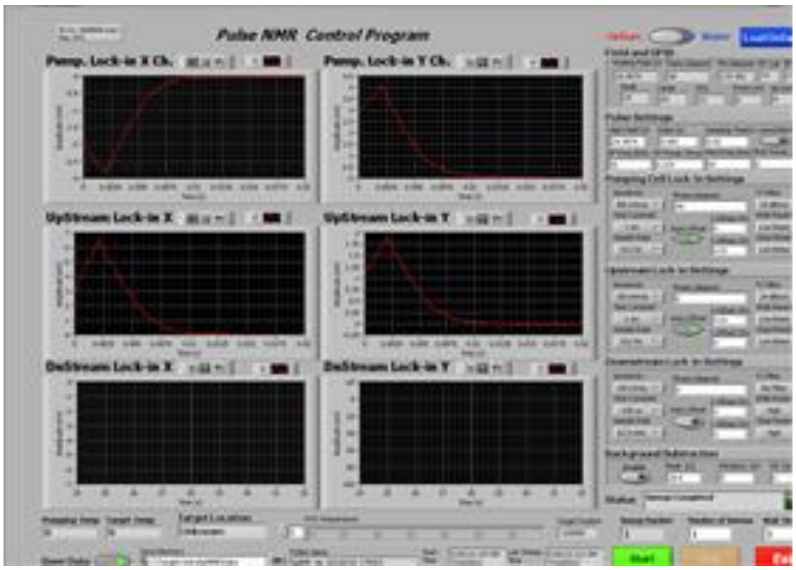


Fig. 8: Pulsed-NMR Results

## Discussion

Currently laser power is insufficient to reach maximum polarization of the $^3$He cells used at Jefferson Lab. It is expected that at least three lasers of minimum power output of 30 W is needed. Experimental data shows that currently maximum achievable power output is only 22.6 W. This power output is far too insufficient to achieve the desired polarization for $^3$He. This low power output across the board suggests that the laser diodes may be at the end of their lifespan and need to be replaced. Further testing with new lasers should be performed before conclusive evidence can be drawn regarding the effectiveness of the JLab owned Comet lasers to polarize $^{3}$He.

The initial pulsed-NMR results are encouraging. Pulsed-NMR signal can be seen, however, signal is weak and there is still no definitive conclusion that accounts for the initial spike in signal. One possible explanation for the initial spike is that the trigger is off-sync. If the trigger is off-sync, it is possible that the pulsed-NMR channel is opened early while the $^{3}$He nuclei are still being flipped. If this is true, the NMR data would show an initial spike in signal while the nuclei were continued to be flipped, before the signal would begin to decay during the relaxation period. Further development of the pulsed-NMR system must be performed in order to become a reliable $^{3}$He polarimetry method.

## Conclusion

While no definitive conclusions can be drawn from the preliminary results, observing the decay rate in the NMR signal is a significant step forward. Further testing must be performed to account for the initial spike in signal and to confirm the decay rate is accurate. Still, the fact that any signal was detected at all is a major contribution. The next step is to continue testing with the diffusion cell in order to observe why the initial spike in signal occurred and if obtaining the NMR signal is repeatable. Once it is determined that pulsed-NMR can be successfully performed on the diffusion cell, it will be straightforward to implement it on the new convection cell.

If it is determined that pulsed-NMR can be used on the new dual-chambered convection cell, it will be a substantial leap towards prepping the convection cell for use in actual nuclear physics experiments. If pulsed-NMR can be successfully implemented with the convection cell, it will be possible to take data regarding the polarization of $^{3}$He inside the cell’s target chamber, regardless of what material the chamber is composed of. This new pulsed-NMR setup with the convection cell will be used in 12 GeV experiments following Jefferson Lab's Accelerator 12 GeV Upgrade.

## Citations

[1] J. Huang, Ph. D. thesis, M.I.T., 2012

[2] Y. Qiang, X. Zhan, *Optics Alignment*, 2010

[3] P.A. M. Dolph *et al.* Phys. Rev. C 84, 065201 (2011)