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RF techniques for enhancing tensor polarization in solid targets

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The availability of high quality tensor polarized solid targets is an important milestone for the Jefferson Lab physics program, and is necessary for several high-impact approved experiments as well as other future studies on the tensor structure of deuterons. Deuterium, commonly employed in experiments as deuterated ammonia (ND_3), can be relatively easily vector polarized with the help of Dynamic Nuclear Polarization (DNP). However, reliably enhancing tensor polarization remains an area of active research. The most successful technique involves the usage of focused high-power RF, used in several relevant techniques such as semi-selective RF (ssRF) hole-burning and adiabatic fast-passage (AFP). In this proceedings we discuss the current status of the new RF system in the polarized target lab at the University of New Hampshire.

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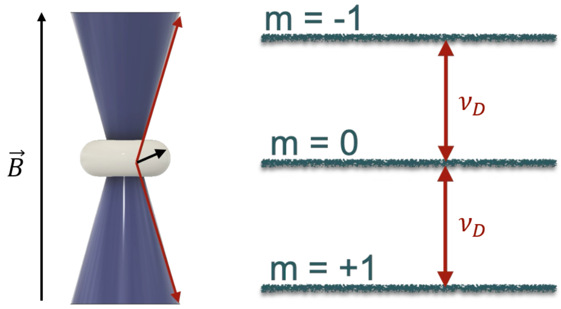

Figure 1: Energy levels of the deuteron in a magnetic field B.

1. Background

Tensor observables introduce a new class of measurements that will enhance our understanding of the structure of the lightest nucleus, deuterium. Several approved experiments at the Thomas Jefferson National Accelerator Facility (E12-13-011 [1] and E12-15-005 [2]) plan to probe some of these observables, and there is growing interest in more studies of deuteron tensor structure, such as LOI12-24-002 [3]. These experiments all require a high quality solid polarized target with enhanced tensor polarization. The tensor polarization P_{zz} of a sample of spin-1 nuclei is defined as [4]:

$$P_{zz} = \frac{N_1 + N_{-1} - 2N_0}{N_{\text{tot}}} \tag{1}$$

with N_i designating the number of nuclei in spin state i (-1, 0, 1), and N_{tot} the total number of nuclei in the sample.

By introducing a strong magnetic field to the sample, we create an energy level splitting the spin states according to the Zeeman effect, as shown in Figure 1. The gap between these levels is the deuteron Larmor frequency, ν_D. This creates two distinct allowed energy level transitions, between $0 \leftrightarrow +1$ and $-1 \leftrightarrow 0$.

The final energy level splitting of the deuteron is shown in Figure 2, wherein the quadrupole frequency ν_Q of the deuteron creates a distortion in the energy level gap between the two transitions.

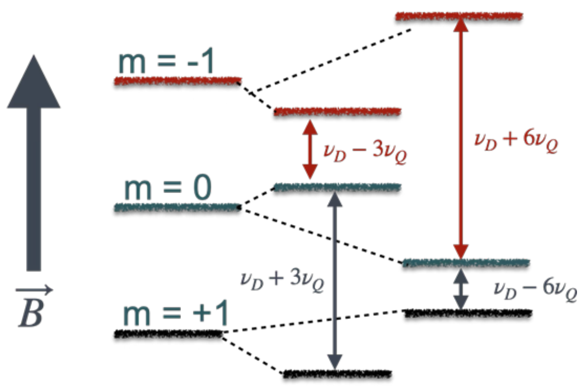

Figure 2: Energy levels of the deuteron in a magnetic field. The energy levels may be shifted based on the quadrupole angle due to the quadrupole effect.

We can define the vector polarization for a spin-1 particle as

$$P_z = \frac{N_1 - N_{-1}}{N_{\text{tot}}} \tag{2}$$

The most successful technique for creating vector polarization is Dynamic Nuclear Polarization (DNP), wherein microwaves are tuned to the energy level transition created by combining Figure 2 with the Larmor frequency of an electron [5]. The target material must have paramagnetic centers created either by radiation dose or by a chemical dopant. The microwaves stimulate a coupling between these paramagnetic centers and the deuterons in the target sample, allowing for exploitation of the naturally high polarization of the sample's free electrons in a strong magnetic field [5]. However, this technique only produces a small amount of tensor polarization, defined in terms of the vector polarization as

$$P_{zz} = 2 - \sqrt{4 - 3P_z^2} \tag{3}$$

Consequently, DNP enhances the vector polarization to around 40-50%, which carries a tensor polarization of only 10-15%. This amount of tensor polarization is not enough to perform an experiment with acceptable statistics. It is necessary then to introduce additional methods to further enhance the tensor polarization.

So far, the most successful method has proven to be the manipulation of the deuteron polarization by applying additional radio-frequency (RF) light at high power to increase the number of transitions into a desired spin state [4]. This method can be used to enhance the tensor polarization beyond the equilibrium polarization obtained in DNP.

The polarization of solid polarized targets is usually measured with Nuclear Magnetic Resonance (NMR), wherein the spin flips of the desired target particle couple with the inductance of a coil surrounding the target material. The magnitude of the polarization then correlates to the change in the real part of the inductance of a connected inductance-resistance-capacitance (LRC) circuit. This is observable as a signal, which takes a roughly lorentzian shape for a spin-$\frac{1}{2}$ particle without a quadrupole moment, but has a more complex structure for the deuteron due to the two spin transitions and the quadrupole moment of the target particle [6]. An example deuteron signal is shown in Figure 3. Each of the peaks visible in this structure represents one of the two allowed spin state transitions.

The most successful technique for generating tensor enhancement is known as semi-selective RF (ssRF) [4]. With this technique, a secondary coil is added to the target cup, which provides RF tuned to a specific part of the NMR spectrum, driving the population of the two spin states involved in the targeted transition towards equality. Because the area under the peaks includes contributions from both the I_+ and I_- transitions, targeting them cannot cleanly select for only one transition, while targeting the shoulders of the signal can, albeit at much lower effectiveness due to the shoulder representing a smaller percentage of spins in the sample. Therefore, the highest effectiveness is obtained when applying RF at the frequencies of both the peak and shoulder for one of the transitions: the peak includes the highest magnitude of spins in the undesired state, while the shoulder allow allows for the cleanest impact on the undesired transition without affecting any of the desired transition. Applying RF to both frequencies effectively reduces the undesired transition's magnitude while preserving the desired transition as much as possible. This method has been demonstrated to produce tensor polarization up to around 30% or more [4].

The University of New Hampshire (UNH) is home to a polarized target laboratory dedicated primarily to preparation for the tensor-polarized program at Jefferson Lab. The UNH polarized target consists of a 5 T superconducting solenoid, a Liquid Helium (LHe) evaporation refrigerator capable of producing temperatures around 1 K, and an NMR system developed by Los Alamos National Laboratory [7]. We have recently added a new RF system for the purposes of performing ssRF and other RF enhancement methods to increase the tensor polarization of deuterons. In this proceedings, we discuss the new UNH RF system and present recently obtained cooldown data on tensor-enhanced polarized deuterated butanol.

2. UNH RF System & Polarized Target

RF hole-burning requires a coil surrounding the target material which is perpendicular to the holding field. In a typical design, this coil is concentric with the NMR coil used to measure the polarization as seen in figure 4. When RF frequency is applied at ν_{RF}, the intensity of the NMR around that frequency will decrease. For positive P_z, burning the $0 \leftrightarrow -1$ transition decreases the population of the m=0 spin state, which increases the tensor polarization P_{zz}.

In the current UNH setup, a Rohde & Schwarz SMC100A signal generator is used to generate an RF signal of the desired frequency. This signal connects to an RF switch, which can be used to toggle the connection open and closed. The switch is kept open while doing NMR to protect the NMR system from the high power of the RF. After the switch, the RF is then amplified by an LZY-22+ RF Amplifier, which increases the signal power by approximately 44 dBm. Losses in the system between the signal generator and the target insert have been measured at around -5 dBm, primarily from the switch and the cables. Finally, the amplified signal enters an SMA port on the target insert where it is transmitted to the perpendicular coil surrounding the target material. This setup is shown in Figure 5.

For the UNH setup used to collect recent cooldown data, the hole-burning coils were placed in a Helmholtz configuration antiparallel to the NMR coil, as shown in Figure 6. The NMR system employed is the Los Alamos National Laboratory designed VME-Crate based Q-Meter, which is a

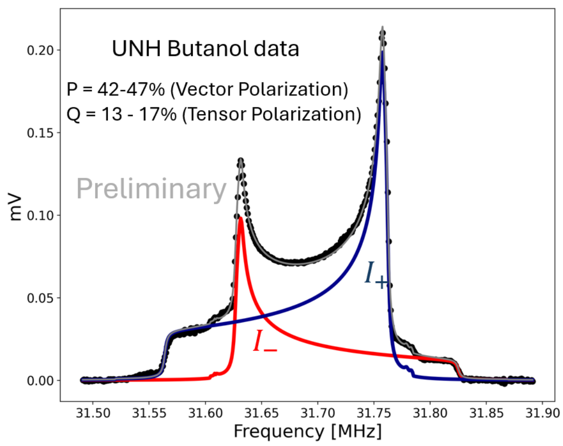

Figure 3: A deuteron NMR signal produced from UNH cooldown data on deuterated butanol.

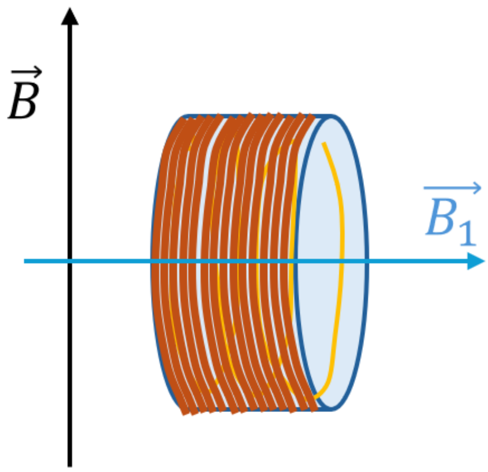

Figure 4: Idealized placement of the ssRF Coil with a simple solenoid. B is the direction of the holding field, and B_1 is the direction of the RF field perpendicular to the holding field.

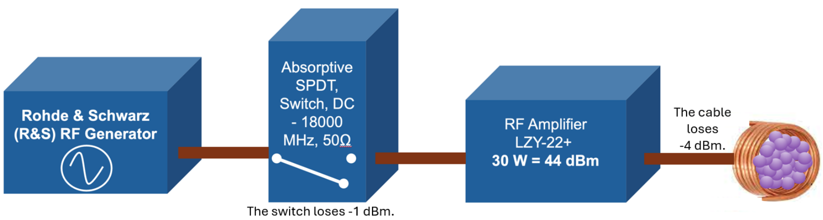

Figure 5: UNH RF System diagram. The Rohde & Schwarz signal SMC100A signal generator creates an RF signal at the desired frequency, which is connected to an RF switch used to disable this system during NMR. The output of the switch connects to a LZY-22+ amplifier which adds 44 dBm to the signal power before it reaches the target insert and the RF coils.

modernized equivalent to the well-known Liverpool Q-Meter that has traditionally been used for similar polarized targets [7]. This system is used in combination with a cold NMR circuit, which is placed around 2 cm away from the target cup to guarantee a consistent temperature across the tank circuit, and to minimize the effect of the $\frac{\lambda}{2}$ tune. Signals produced by this cold board are amplified by +20 dB as they leave the target stick, and then attenuated by the same before entering the VME crate to reduce the impact of external noise along the cable length.

Microwaves for DNP are created with a solid-state microwave system designed by mmWave design company Bridge12, and a gold-plated waveguide which transmits the microwaves to the target material. All data is collected at a holding magnetic field of 5 T, which is created by a superconducting Scientific Magnetics solenoid. The UNH group is collecting data on several different deuterated target materials, however, in the Summer 2024 cooldown which is discussed in the following section, data was collected using deuterated Butanol, which was chemically doped with the free radical Trityl.

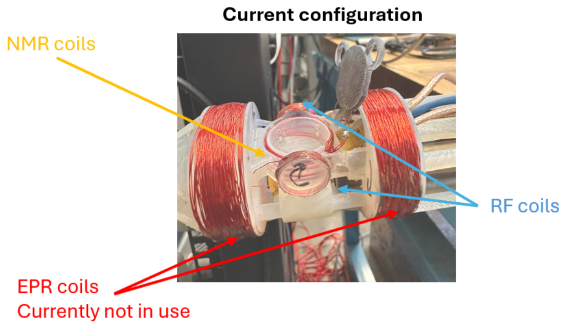

Figure 6: UNH Target Stick in Recent Cooldown

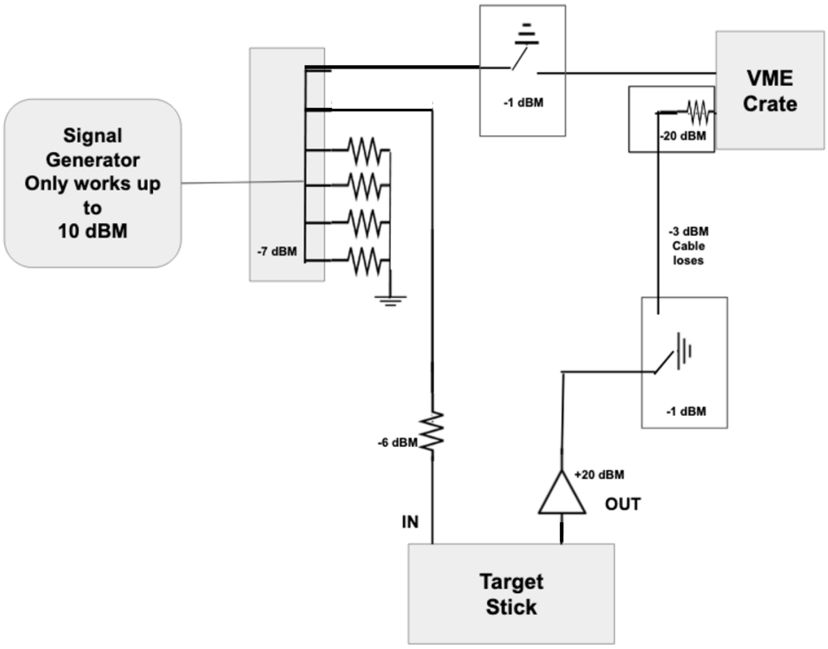

Figure 7: UNH NMR System, featuring Los Alamos National Laboratory designed Q-Meter inside a VME Crate [7]. Switches are used to disable the NMR during RF manipulation. The signal coming out of the target stick is amplified, and then attenuated before entering the NMR system to reduce the external noise which enters along the line in between amplifier and attenuator.

3. RF Manipulation Results

We have collected recent data with the system described above to enhance the tensor polarization of deuterons. We attempted to burn both the peak and the shoulder for the $0 \leftrightarrow -1$ (or I_-) transition to create a positive tensor enhancement. Results of burning the peak are shown in Figure 8. By duty-cycling the hole-burning RF power on and off for increments ranging between 30 seconds and 2 minutes, high vector polarization $P_z > 40\%$ was maintained while hole-burning.

Similarly, the result of hole-burning the shoulder of the same transition is shown in Figure 9. We currently estimate that the maximal tensor polarization achieved by burning the shoulder or peak is around 13-14%. Analysis is ongoing to determine a final tensor polarization for this data set, but

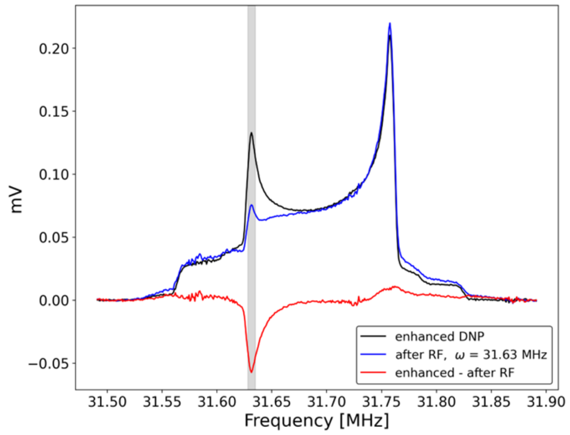

Figure 8: Result of ssRF hole-burning on the peak at 31.63 MHz of the $0 \leftrightarrow -1$ transition, for 5T polarized deuterated Butanol. The red line indicates a subtraction of the signal before and after RF manipulation, to show the impact of the RF hole-burning.

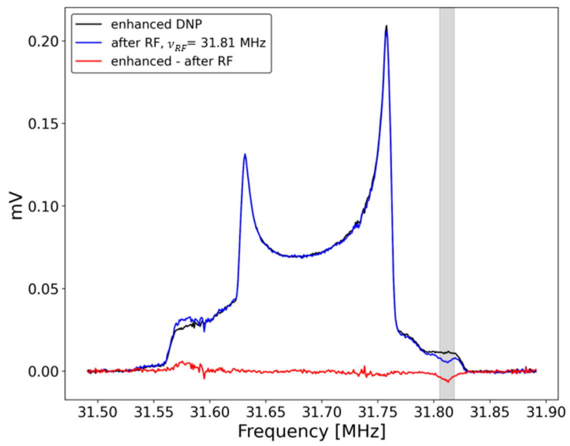

Figure 9: Result of ssRF hole-burning on the shoulder at 31.81 MHz of the $0 \leftrightarrow -1$ transition, for 5T polarized deuterated Butanol. The red line indicates a subtraction of the signal before and after RF manipulation, to show the impact of the RF hole-burning.

there is a clearly visible enhancement from the equilibrium tensor polarization obtained with DNP.

The holes displayed in the red curves on Figures 8 and 9 appear to be relatively wide, the reason for this is not currently known, but may result in some way from issues with the coils used, which were noted to be irregularly wound after the cooldown was complete. The next iteration of the UNH target insert has a more uniform solenoid in the RF circuit, which we believe may produce a more focused impact on the NMR spectrum when employing ssRF hole-burning.

The UNH group is also in the process of refining methodology for using the new RF system for Adiabatic Fast Passage (AFP). AFP is a technique which is crucial for quickly reversing the vector polarization, and involves using RF manipulation to sweep across the NMR spectrum with high power [8]. This has proven highly effective in previous experiments, and is currently being studied by our group.

4. Conclusion

RF Manipulation is an important technique for enhancing the tensor polarization P_{zz} in deuterated target materials. Reliable methods for ssRF hole-burning and adiabatic fast-passage are needed for an upcoming and growing program of tensor polarized experiments. The University of New Hampshire polarized target group has recently added a new RF system to our polarized target, and successfully demonstrated tensor enhancement beyond equilibrium in recent cooldown data. In the coming months the UNH group expects to further improve on the achievable tensor polarization and successfully demonstrate AFP, further refining an ever more reliable methodology for the Jefferson Lab program of tensor experiments.

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