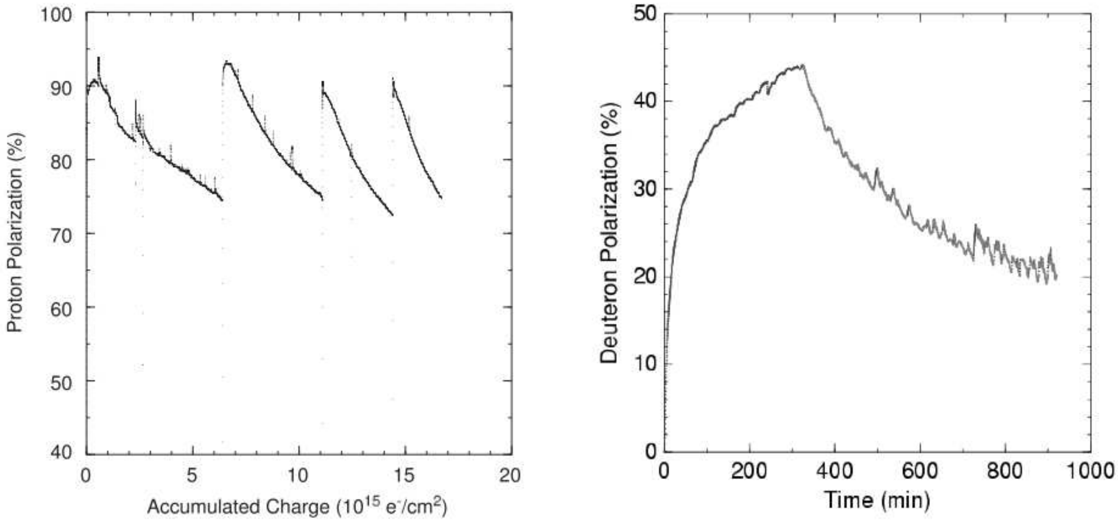

Figure 1: Typical NH_3 and ND_3 vector polarization in an electron beam. The polarization decays as radiation damage accumulates, but can be re-established via annealing as described in the text.

1 Polarized Target

1.1 Enhancing Tensor Polarization

A spin-1 system placed in a magnetic field will give rise to three magnetic sublevels due to the Zeeman interaction: $I_z = +1, 0, -1$ with populations p_+, p_-, p_0, respectively. The populations in these levels are described by both a vector and a tensor polarization:

$$\begin{aligned} P_z &= (p_+ - p_0) + (p_0 - p_+) = p_+ - p_- \\ P_{zz} &= (p_+ - p_0) - (p_0 - p_+) = 1 - 3p_0 \end{aligned} \quad (1)$$

which are subject to the overall normalization $p_+ + p_- + p_0 = 1$.

In the case of deuteron spins in thermal equilibrium with the solid lattice, and neglecting the small quadrupole interaction [1], the tensor polarization is related to the vector polarization via:

$$P_{zz} = 2 - \sqrt{4 - 3P_z^2} \quad (2)$$

The maximum absolute value of $P_{zz} = -2$ occurs only for vanishing populations in the $m = \pm 1$ states. If, on the other hand, only the $m = 1$ or $m = -1$ state are occupied, the vector polarization reaches its maximum value of $+1$, and $P_{zz} = +1$.

The energies [2] of the three magnetic sublevels are:

$$E = -h\nu_D m + h\nu_Q \left[(3\cos^2(\theta) - 1\right] \left[3m^2 - I(I+1)\right] \quad (3)$$

where ν_D is the deuteron Larmor frequency and ν_Q is a function of the deuteron quadrupole moment eQ. The quadrupole interaction shifts these levels depending on the angle θ between the magnetic

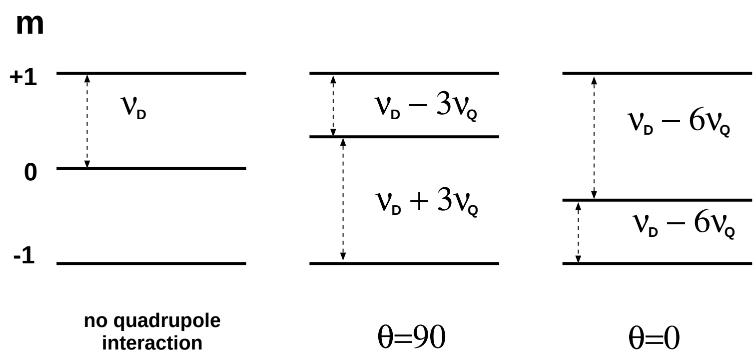

Figure 2: Energy levels in ND_3. The level spacing is shifted by the quadrupole interaction, which depends on the angle θ between the magnetic field and the electric field gradient.

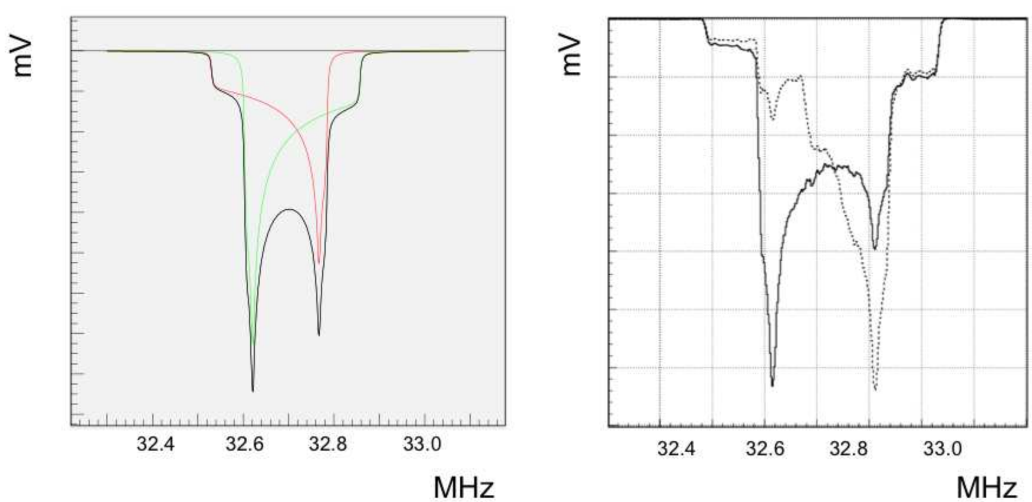

Figure 3: **Left**: Model prediction [3] of the NMR response for an ND_3 sample with a vector polarization of approximately 20%. The two discrete transitions (red and green) blend into the characteristic double peaked structure. **Right** : Demonstration of RF hole burning in ND_3. Solid line: ND_3 sample with about 30% vector polarization. Dashed line: the same sample after application of a saturating RF field. Notice the strong suppression of the left peak. Reproduced from [4].

field and the electrical field gradient, as shown in Fig. 2. This gives rise to the asymmetric double peaked NMR signal which is shown in Fig. 3.

Fig. 1 reveals that the average vector polarization of ND_3 during a typical scattering experiment is about 30%. From Eq. 2, we see that this limits the natural tensor polarization to less than about 10%. But this value can be enhanced by disturbing the thermal equilibrium of the sample using a frequency modulated RF source to stimulate transitions from the m=0 level. This changes the population of the m=0 level, thus changing the tensor asymmetry.

This method of 'burning holes' in the NMR line with a saturating RF field was demonstrated by deBoer [5], and Meyer [2, 1] in 1985. Bueltmann *et al.* [4] also briefly investigated this technique in 1999, and claimed to demonstrate tensor polarizations of about 30%, as shown in Fig. 3. However, the results were not published, and this line of research was not pursued further since there was no physics motivation for tensor polarized targets at the time. Recent interest [6, 7, 8, 9] in the b_1 tensor function [10, 11] justifies revisiting this technique. Hole burning can be performed with a solenoidal coil placed around the target sample driven by an additional function generator. The specifications for such a coil are less restrictive than those set by the requirements of adiabatic fast passage, which are discussed in Sec. 1.2.

A second method exists to simultaneously stimulate transitions from two of the deuteron's three sublevels by using two independent microwave sources tuned to the closely spaced transitions. Initial unpublished studies [4] demonstrated the feasibility of this technique, with the curious caveat that the CPI microwave cavities typically used in this process have a tendency to couple and lock to a common frequency when operated in close proximity. Discussions with the manufacturer [12] have revealed that this is a well known feature of the cavities, and can be easily suppressed with isolating circuitry. A 'magic tee' 3 dB coupler will be tested in order to simultaneously deliver the two microwave frequencies to the sample. If the two cavities can not be prevented from resonant coupling, then a second isolated waveguide will be added to the target insert.

Given the hints of success in the literature, we are optimistic that one of these two methods will deliver tensor polarizations of 30%, which would likely be sufficient to remove any JLab PAC concerns and move PR-12-11-110 to approved status. Beyond this, there will be considerable work to fully characterize the polarization and to investigate systematic uncertainty of the polarimetry. The NMR line shape for a vector polarized spin-1 target is well understood, and can be described by an analytic function [3] that is useful for extracting the absolute polarization. We will need to generalize this approach to a tensor polarized target, and will also pursue methods to independently determine the tensor polarization. The elastic (quasielastic) scattering asymmetry is typically monitored in vector polarized targets in order to extract the product of beam and target polarization. There is some indication [13] that this technique should be generalizable to the extraction of tensor polarization.

1.2 Adiabatic Fast Passage

When measuring small asymmetries, instrumental effects which cause false asymmetries must be suppressed. The typical approach is to reverse the target polarization periodically. This can be done by simply rotating the holding field, but this does not cancel out any systematic effects due to possible misalignment of the target field with respect to the beamline. It is also a time consuming exercise which requires either physically rotating the magnet, or ramping up a perpendicular holding field while the main field is swept through zero. Limitations on the ramping rate of a superconducting magnet require that this process must take on the order of several hours.

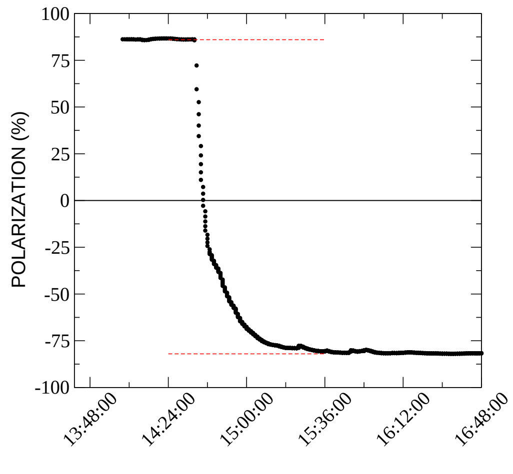

Figure 4: DNP spin flip of NH_3 material.

Another possibility is to simply irradiate the opposite ESR line with the appropriate frequency. This 'DNP spin flip' method is the most commonly used, but takes of order 1 hour as shown in Fig. 4. The DNP spin flip time is inversely proportional to the delivered microwave power, which in turn drives the (very expensive) liquid helium consumption rate of the refrigerator. The data shown here is from the recent g2p experiment, and demonstrates the 'best case scenario' for DNP spin flips. Jefferson Lab supports one of the world's largest helium liquefier plants, so we were able to increase the incident microwave power by about a factor of 2-3 beyond normal operating conditions, and compensate for this with increased helium consumption in the evaporation refrigerator. This is simply not a practical (or prudent) solution in most experiments. Under normal operating conditions, the DNP spin flip takes about 300 minutes as documented in Ref. [4].

An attractive alternative to rapidly reverse the spin orientation is adiabatic fast passage [14], or AFP, which has been used to great success in the polarized gas target program. In AFP, an RF field of amplitude 2 H_1 is introduced perpendicularly to the main holding field. The frequency ω_1 of H_1 is swept through the Larmor frequency $\omega = \gamma H_0$. At resonance, the spins perform a full reversal, which is essentially lossless if the following conditions are satisfied [15]:

$$\frac{1}{T_2} \ll \frac{1}{H_1}\left|\frac{1}{\gamma}\frac{d\omega_1}{dt}\right| \ll |\gamma H_1| \tag{4}$$

Here, T_2 is the spin-spin relaxation. The sweep must be slow enough that the spins can follow the direction of the changing field. This "adiabatic" condition is satisfied if the Larmor frequency of the precessing spins is large compared to the rate of change of direction of the field. The "fast" condition requires that the spins not be kept in resonance long enough such that T_2 becomes relevant.

In solids, T_2 is much shorter than in gases. This prevents strong satisfaction of Eq. 4, and implies that the flip can not be completely lossless. AFP efficiencies of 90% have been reported for a ^{7}LiH DNP target [16], but no results have been published for NH_3. Initial studies and modeling of AFP in solids [15] predicted very low AFP polarization losses in ND_3, but that the efficiency may be as low as 50% in NH_3 at 5T/1K [17].

Spin reversals are planned once an hour during the Jefferson Lab polarized proton transversity experiment [18] in order to control the systematic uncertainties to the 6.3×10^{-4} level. This implies 1000 pairs of spin flips in the 82.5 days of running with transversely polarized target. A similar spin flip rate will be needed during the polarized Drell-Yan experiment [19], but this experiment would run for several years. In both cases, the time required to perform DNP spin flips integrates to more than 100% overhead compared to the time spent collecting data. If the AFP process is only 70% efficient this overhead can be cut in half. Integrated over several years running, even an AFP efficiency of 50% would cut the overhead substantially.

In order to implement AFP, the reversal coil must satisfy the following considerations [15]:

1. The coil must be oriented transversely to the main field, and should produce an RF field with an amplitude of about 2 $H_1 = 10^{-4}$ T with good uniformity.

2. There must not be significant heating of the target material.

3. The Q-value should be below the maser threshold to avoid destructive losses.

A simple solenoid driven with an additional function generator and amplifier satisfies these conditions, and will be used initially to demonstrate feasibility. This will need to be replaced eventually with either a saddle coil or bird-cage configuration if the technique is to be used in an incident beam.

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