Addressing the Tensor Spin Experiments Conditional Status

The Jefferson Lab b_1/A_{zz} Collaboration

May 19, 2022

Abstract

We review in this document the status of the E12-13-011 (b_1) & E12-15-005 (A_{zz}) experiments and request removal of the conditionals attached to their approval.

Contents

1 Physics Motivation

E12-13-011-b1 will measure the leading twist deuteron tensor structure function b_1. This observable describes quark distributions within a spin polarized deuteron, providing unique insight into how nuclear properties arise from partonic degrees of freedom. The experiment has been conditionally approved, contingent on target performance, with A^- physics rating to run with 30 days of 11 GeV incident beam on a tensor polarized solid target. E12-15-005-Azz will measure the tensor asymmetry A_{zz} in the quasi-elastic and elastic regions using the same equipment as the b_1 experiment. Similar to the b_1 experiment there is a condition on the approval contingent on demonstration of a 30% tensor polarized target.

b_1 provides novel information about nuclear structure, quark angular momentum, and the polarization of the quark sea that is not accessible in spin-1/2 targets. All conventional nuclear models predict a small or vanishing value of b_1 at moderate x. However, the first measurement of b_1 at Hermes [3] revealed a cross-over to a large negative value in the region $0.2 < x < 0.5$, albeit with relatively large experimental uncertainty. Recently, Miller [4] showed that exotic effects from hidden color 6-quark configurations could be at work. Critically, Miller showed that no conventional nuclear mechanism can reproduce the Hermes data, but that the 6-quark probability needed to do so ($P_{6q} = 0.0015$) is small enough that it does not violate conventional nuclear physics. With this in mind, a precise measurement of b_1 could provide a unique and unambiguous signature of hidden color. Teryaev [5] noted that measuring b_1 probes the gluon contribution to tensor structure, and also the coupling of quarks to gravity via an equivalence principle. And Kumano [1] pointed out that b_1 can be used to probe orbital angular momentum. He then extracted the tensor polarized quark and anti-quark distributions from a fit to the Hermes data [3] and found that a non-negligible tensor polarization of the sea is necessary to reproduce the data.

The PAC Theory report for E12-12-005 (A_{zz}) stated that: '*The measurement proposed here arises from a well-developed context, presents a clear objective, and enjoys strong theory support. It would further explore the nature of short-range pn correlations (SRC) in nuclei, the discovery of which has been one of the most important results of the JLab 6 GeV nuclear program.*' Tensor polarization enhances the D-state in the deuteron wavefunction and is sensitive to short-range QCD effects [6]. Knowing the properties of the deuteron's nucleon-nucleon potential is essential for understanding short-range correlations as they are expected to be largely dependent on the tensor force. In the quasi-elastic region, A_{zz} provides a unique tool to experimentally constrain the ratio of the S- and D-state wavefunctions at large momentum [7], which has been an ongoing theoretical issue for decades. First calculated in the 1980's [7], A_{zz} was recently revisited using modern relativistic virtual-nucleon and light-cone methods, which are used in understanding short range correlations and predict differences up to a factor of two in A_{zz} that can be distinguished experimentally. Additionally, the calculations were done using multiple wavefunctions that diverge at large x, making A_{zz} an ideal observable for providing insight into the decades-old question of whether the deuteron wavefunction is hard or soft.

We note that these tensor spin observables are likely to be of high interest at the electron ion collider, so the Jefferson Lab fixed target measurements will provide important input and guidance for those efforts.

2 Addressing the PAC Conditional Requirement

PACS 40 and 44 reviewed the b_1 and A_{zz} proposals and approved them with conditional status. The PAC required demonstration of tensor polarization '*close to 30%*' for A_{zz} and '*at least 30%*' for b_1 under experimental conditions. Although not explicitly stated, these conditions implied that we must also develop reliable techniques to measure tensor polarizations. In the remaining part of this section we discuss the steps we have taken to address these conditional requirements.

2.1 Improving Tensor Polarization

There are several key points of progress that we believe indicate a clear demonstration that the condition has been met and that a full approval is now appropriate. To summarize:

1. When the original b_1 proposal was submitted the maximum tensor polarization available was about 10-12%. Since that time significant progress has been made. **We have demonstrated a maximum tensor polarization of** $36.5\% \pm 3.5\%^{\dagger}$ utilizing a variation of RF hole-burning known as selective semi-saturated RF (SS-RF) combined with physical rotation of the target material. We discuss this in detail in Sec. 5, Table 2 of Ref. [9].
2. Significant progress has been made in understanding the CW-NMR lineshape of tensor enhanced samples. Details are provided in Sec. 2 of Ref. [9]. But in summary, the uncertainty on the large tensor polarization mentioned above is less than 10% relative.
3. The large tensor polarizations mentioned above were demonstrated in deuterated butanol (C_4D_9OD). The production of polarizable deuterated ammonia (ND_3) requires a so-called 'cold irradiation' that is normally completed under experimental conditions in the CEBAF beam at 1 K. This makes (ND_3) studies prohibitive. However, Ref. [9] demonstrated that there is an equality between deuterated butanol and ammonia that can be exploited to demonstrate the necessary condition. **In short, the two materials are equivalent for the purposes of demonstrating tensor polarization.**

2.2 Tensor Polarization Measurement

Considerable advancement in the spin-1 CW-NMR lineshape theory has taken place in the last few years leading to significant measurement accuracy of polarizations in the Boltzmann equilibrium state as well as RF manipulated states [8, 9, 11]. Details of the differential energy levels and their NMR signal under arbitrary RF manipulation have lead to leaps forward in polarization extraction techniques as well as advancement in precision NMR technology specific to the deuteron and materials without cubic symmetry where the interaction of the with the electric field gradient breaks the degeneracy of the energy transitions, leading to two overlapping absorption lines in the NMR spectra, which indicates a quadrupolar splitting. The overlapping transition lines are invaluable in using phase sensitive detection in combination with artificial intelligence to simultaneously manipulate and measure the differential polarization [11]. The bins of manipulation and resolution in frequency are only limited by the NMR DAQ and the detector limitation defined by the Q-meter its self. This limit is on the scale of 1% relative error. This limit has been achieve with simulations of RF manipulated signal at various levels of enhancement. However, in polarized target experiments the limiting factor is often not the theoretical limit but the time needed for multiple and accurate thermal equilibrium measurements (TEs) [10]. Even though the Pake double lineshape reduces the reliance on TEs, the way to reach the lower threshold of uncertainty is still to take many TEs that are well thermalized at various temperatures.

2.3 Reliably modeling the RF-manipulated lineshape

Prior to recent work there has been significant challenge in measuring RF manipulated deuteron NMR signals due to the distortion of Boltzmann equilibrium of the ensemble. Under equilibrium, the tensor and vector polarization have a clean mathematical relationship that allows us to know what the tensor polarization is for any vector polarization. It has also been understood since the 1980s that hole burning (applying RF at a particular frequency in the NMR signal) could be used to enhance tensor polarization, but measuring such a signal proved to be quite challenging.

[†] 9.7% (relative uncertainty)

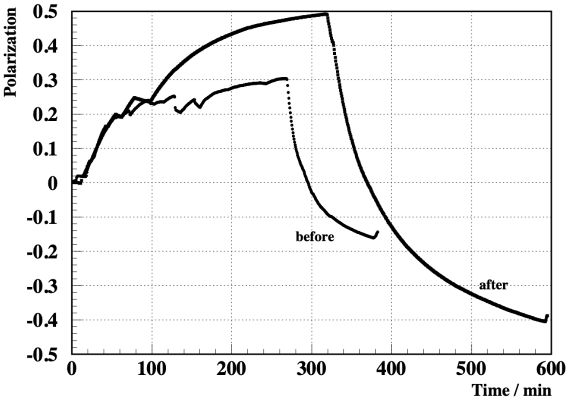

Figure 1: Vector polarization has been demonstrated to reach 50% for ND_3 following cold irradiation and tempering at 1 K and 5 T [12].

But recent work in Ref. [8] provides a detailed description of how the rate equations can be used to accurately measure the RF manipulated NMR signal of target materials of interest. In addition, an RF-induced steady-state condition can be used simultaneously with DNP to enhance tensor polarization in polycrystalline materials such as ND_3. We call this condition selective semi-saturated RF (ss-RF), which differs from standard hole burning in that it partially saturates the NMR line to meet a critical condition for every frequency in the NMR signal that maximizes the difference in the two absorption lines. A plausible model is used for the polarization mechanism allowing the measurement of tensor enhancement.

It is later shown in Sec. 3 of [9] that the ss-RF manipulation is completely independent of the polarization mechanism and that the polarization depends only on the differential intensities in each absorption line. This considerably simplifies the mathematics and makes it very easy and clear how to measure the vector and tensor polarization under any RF conditions. This means there is no model dependence in the resulting polarization measurements and the polarization mechanism is independent of the NMR lineshape. The implications of this are critical. An equivalence between polycrystalline materials with degenerate energy levels can be made such that any experimental measurements of NMR or ss-RF NMR for one material would be the same for another if the lineshape is the same.

In short, since the lineshapes are similar and we can achieve a similar maximum of vector polarization ($\approx 50\%$) for d-Butanol and ND_3, the former can serve as a proxy for optimization of ND_3 tensor polarization. This is helpful because optimization of ND_3 requires cold irradiation (1 K) at higher energy and so it is much more difficult to make outside of running in the beam at JLab, as shown in Fig. 1.

In the work presented in Ref. [9], the method of target rotation is used simultaneously with ss-RF to further increase the tensor polarization. The results use the simplest form of target rotation in the holding field to optimize the target alignment through the duration of continuous DNP. These results indicate a value of 36.5% tensor polarization can be achieved with a relative uncertainty of 9.7%, as shown in Fig. 2. Full development of the automated RF controls and measurement system is expected to result in an uncertainty that is not much larger than the present error achieved from other solid polarized target experiments.

2.4 Tensor polarization under JLab experimental conditions

The large tensor polarizations discussed above will decay in-beam during the b1/Azz experiments . The target material heating from the beam brings all polarization down about 3-4% at 100 nA, as soon as the electron beam impinges on target. The polarization reduction estimates come from previous experiments ran at Jefferson lab as shown in Ref. [10]. However, the experiments' overall FOM can be improved by running at a slightly lower beam current of ~70-80 nA. This would reduce this effect of beam heating down to approximately 2%. Additionally, the ss-RF can offset the degradation of polarization due to

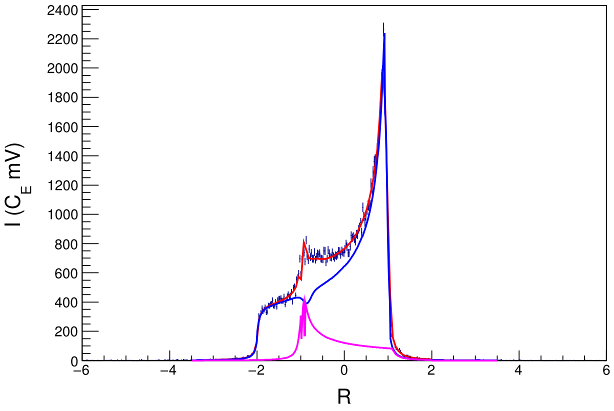

Figure 2: NMR measurement of tensor enhancement maximized by using two locations of ss-RF while rotating continuously at a fixed rate. The resulting tensor polarization was approximately 36%. Figure from [9].

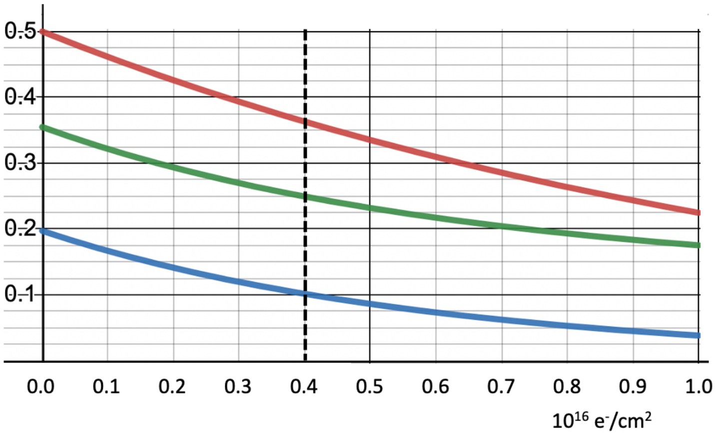

Figure 3: The simulated polarization decay of ND_3 vector polarization (red), tensor polarization at Boltzmann equilibrium (blue), and tensor polarization with ss-RF enhancement (green) due to radiation damage. The horizontal axis shows accumulated dose in units of electrons per square cm. The vertical dotted line indicates the dose at which an anneal is planned in order to keep the average enhanced tensor polarization at 30%.

radiation damage by a small amount as the level of potential tensor enhancement is greater for lower vector polarizations. The amount of tensor enhancement that is possible goes up as the polarization is damaged by the beam. This is only a small effect but does help with improving the average of tensor polarization over the dedicated beam time.

The polarization will also decay with accumulated dose under beam conditions. This is demonstrated in the simulated decay due to radiation damage show in Fig. 3 for vector polarization, tensor polarization at Boltzmann equilibrium, and tensor polarization with ss-RF enhancement. The target polarization can be largely returned to its previous maximum by annealing the material. **If this annealing is performed after an accumulated dose of 0.4×10^{16} e$^-$/cm^2, then the overall tensor polarization will be close to 30% under beam conditions, matching the PAC conditional requirements.** This is indicated with the dotted vertical line in Fig. 3.

We note that there is a maximum dose, after which target material tends not to respond favorably to annealing and must be replaced with fresh material.

2.5 Systematic Uncertainties

The uncertainties related with the polarization measurements evaluated in Ref. [9] for a 36.5% tensor polarization combine the standard NMR contributions and the fit uncertainty, the total relative uncertainty correspond to 9.7%. The NMR contributions have been studied and are summarized in Table 1 of Ref. [10]. Using this techniques, the vector polarization at equilibrium was measured to have a maximum of 50% with a relative uncertainty of 3.2%. It is expected that further work in the optimization of the analysis will decrease the relative uncertainty of the tensor porlarization measurement.

2.6 Future Work

Target deployment will be done in collaboration with the polarized target groups of UVa, UNH and Jefferson Lab. Work to improve the results presented here continues at UVa and UNH. In particular, great progress has been made in extracting polarization values from tensor enhanced lineshapes, and in the techniques to enhance tensor polarization. Between UVa and UNH there are presently three graduate students, three FTE faculty and two FTE postdocs dedicated to this effort. Systematic studies continue at these two institutions using deuterated Butanol data, with plans to produce the necessary irradiated ND_3 in progress.

An example of the lineshape analysis is shown in Figure 4. The signal corresponds to a DNP enhanced measurement, with 32.1% and 10.0%, vector and tensor polarization, respectively. The fitting analysis is heavily based on the analytic functional form of Dulya et al. [13] and the model [14] is founded in the work of Cohen et al. [15]. The model has successfully predicted the polarization lineshapes seen at UNH.

The techniques and technology are now available to design and build a new type of NMR system that can accurately measure while provide the enhancing RF manipulation simultaneously. Such a divide would be driven by artificial intelligence and provide a intensity sensitive power profile for each and every NMR sweep. The system would effectively be continually extracting the vector and tensor polarization vales in any RF manipulated signal with greater precision in the online monitoring mode than traditional Q-meter based NMR systems using offline polarization values.

In addition there is an array of new tools, materials and techniques not cover here that deserve further research. A full approval will help to attract the funds needed to further pursue these promising avenues.

3 Summary

We have discussed the progress made by the b1/Azz collaboration in addressing the Jefferson Lab PAC conditional requirements. The current maximum tensor polarization achieved is 36.5% ± 9.7% (relative uncertainty). This polarization will decay with accumulated dose under beam conditions, but with appropriate annealing of the material when the accumulated dose reaches $0.4 \times 10^{16} e^-/cm^2$, the average target tensor polarization is anticipated to be near 30%, matching the PAC conditional requirements. This is a dramatic improvement over the previous tensor polarization available when the proposals were first submitted and we anticipate the active target research programs at the University of Virginia and New Hampshire will continue to increase this target performance in the next few years.

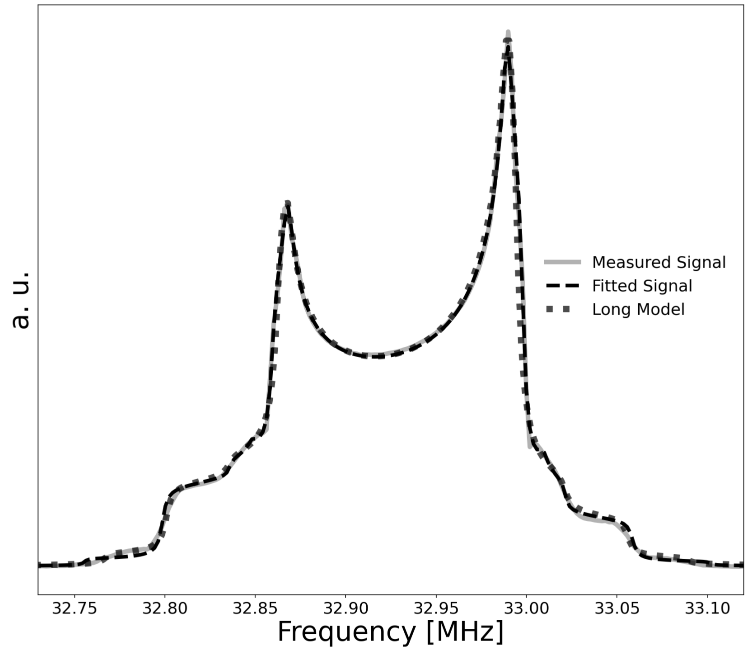

Figure 4: NMR measurement of vector enhancement by using DNP at UNH. The fitted signal is based on [13] and the model [14] follows the solid state work of [15].

References

[1] S. Kumano, Phys. Rev. D **82**, 017501 (2010) doi:10.1103/PhysRevD.82.017501 [arXiv:1005.4524 [hep-ph]].

[2] J. Carlson and R. Schiavilla, Rev. Mod. Phys. **70**, 743 (1998). doi:10.1103/RevModPhys.70.743

[3] A. Airapetian *et al.* [HERMES Collaboration], Phys. Rev. Lett. **95**, 242001 (2005) doi:10.1103/PhysRevLett.95.242001 [hep-ex/0506018].

[4] G. A. Miller, Phys. Rev. C **89**, no. 4, 045203 (2014) doi:10.1103/PhysRevC.89.045203 [arXiv:1311.4561 [nucl-th]].

[5] Efremov, Teryaev, JINR PreprintR2-81-857(1981), Yad. Phys. 36, 950 (1982) A.V. Efremov, O. V. Teryaev JINR-E2-94-95 (1999)

[6] J. L. Forest, V. R. Pandharipande, S. C. Pieper, R. B. Wiringa, R. Schiavilla and A. Arriaga, Phys. Rev. C **54**, 646 (1996) doi:10.1103/PhysRevC.54.646 [nucl-th/9603035].

[7] L. L. Frankfurt and M. I. Strikman, Phys. Rept. **160**, 235 (1988). doi:10.1016/0370-1573(88)90179-2

[8] D. Keller, Eur. Phys. J. **A**, (2017) 53:155. doi:10.1140/epja/i2017-12344-0

[9] D. Keller, Nucl.Instrum.Meth.A 981 (2020) 164504 doi:10.1016/j.nima.2020.164504

[10] D. Keller, Nucl. Instr. Meth. A728 133 (2013) doi:https://doi.org/10.1016/j.nima.2013.06.103.

[11] J. Clement, D. Keller, Submitted to Nucl. Instr. Meth. A (2022).

[12] S. Bultmann, D. Crabb, Y. Prok, UVA-LabNote 1999-2000

[13] C. Dulya *et al.* [Spin Muon], Nucl. Instrum. Meth. A **398**, 109-125 (1997) doi:10.1016/S0168-9002(97)00317-3

[14] E. Long, Private communication (2022).

[15] M. H. Cohen and F. Reif, Journal of Physics C: Solid State Physics 5, 321-438 (1957).