Conditional Review for Tensor Polarized Target
Final Report (Draft)
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Executive Summary
A review was held Monday August 1, 2022 to consider the C1 conditional status of two experimental proposals, E12-13-011 and E12-15-005, both requiring a tensor-polarized target in Hall C. The requirement for full approval, imposed by PAC43 and reiterated by PAC45, is:

> *"… a tensor polarization of at least 30% be achieved and reliably demonstrated under experimental conditions."*

Based on the material presented at the review, **we hereby remove the C1 condition.** Still, we remind the collaboration that they are a long way from having truly viable experiments, and **the bar for passing an eventual Experimental Readiness Review will be far higher**. The panel unanimously agrees that substantial effort and continued R&D will be needed to make the two experiments truly viable under experimental conditions. Therefore, we endorse and encourage **further cooperation between the lab and the collaboration** to develop and implement a plan to fully achieve the PAC condition and allow a meaningful scientific impact from the experiments under realistic conditions.

The panel commends and thanks the collaboration for their hard efforts needed to reach this point. Although tensor enhancement via RF manipulation of the deuteron NMR line has been around for more than four decades, the UVa and UNH groups have made substantial strides beyond previous work, particularly in the analysis of the deuteron lineshape following RF manipulation. In the strictest sense, the collaboration has shown that tensor polarizations exceeding 30% can be produced in dynamically polarized deuteron samples at 5T and 1K. However, the polarizations were not really met "under (anticipated) experimental conditions", nor has the collaboration demonstrated that a key, preexisting condition needed for 30% tensor polarization can be met with any reliability in irradiated ND_3.

All the results presented at the review were obtained with lightly-irradiated samples of deuterated butanol, not the heavily-irradiated ND_3 that will be used under actual experimental conditions. The collaboration further stated that a vector polarization of 50% is required to achieve a tensor one of 30%. While this polarization has been demonstrated in ND_3 at 5T/1K, these results are far more the exception than the rule. Moreover, the average vector polarization that has heretofore been maintained in intense electrons beams is significantly less than 50%. These issues will be scrutinized much more closely in any Experimental Readiness Review (ERR) at JLab and must be addressed before the collaboration can request beam time in Hall C.

Charge item 1: What technique(s) will be used to produce "a tensor polarization of 30% under standard experimental conditions".

Findings

Partial RF saturation of portions of the deuteron NMR line (aka semi-saturating RF or ssRF), combined with level inversion of another part of the NMR line using adiabatic fast passage (AFP) will be used to decrease the overall population of the m=0 magnetic substate, thereby increasing the tensor polarization.

Comments

RF saturation of the NMR line is a well-established process that has been previously utilized to modify the tensor polarization of dynamically polarized deuteron targets. It can be performed while simultaneously maintaining vector polarization with 140 GHz microwaves. Extracting the tensor polarization from the resultant NMR lineshape has been problematic in the past, but the collaboration has developed impressive new analysis tools that promise to overcome this problem. On the other hand, the efficacy of AFP may require further consideration. This is a "one-shot" process, and after the spin populations are inverted by AFP, the microwaves will tend to drive them back to their initial values. It may be better to simply RF saturate this part of the NMR line.

Although additional tensor enhancement can be achieved by rotating the target sample in the magnetic polarizing field, the rotation introduces spin-relaxation pathways that are more complex to quantify and thus increases the polarization uncertainty. Rotation also presents technical issues that may be difficult to resolve, such as limiting the number of ND_3 samples on the target ladder, and requiring the NMR coil to be outside the sample and thus more sensitive to an under-rastered beam spot. For these reason, the panel feels it is sensible for these experiments to concentrate on the ssRF technique alone to improve the tensor polarization.

Charge Item 2: How will the tensor polarization be measured and with what uncertainty? What crosschecks or auxiliary measurements can be made to validate the results? Will this uncertainty be sufficient to achieve meaningful physics results?

Findings

The tensor polarization will be extracted from the deuteron NMR lineshape utilizing Voight profiles to simulate those portions of the line affected by ssRF. It is assumed that the magnetic populations in the affected regions can be described by Boltzmann statistics with a single, characteristic spin temperature, while the unaffected regions are described by a second temperature. It is also assumed that spectral diffusion between these two portions is small. In this case, the area destroyed by the saturating RF should be twice the area that is gained on the opposite side, and from this the resultant tensor polarization may be determined. The relative uncertainty in the lineshape analysis $\Delta P_{zz}/P_{zz}$ is said to about 7% when only RF is used to enhance the tensor polarization, 8.5% when AFP is included, and 9.5% if the sample is rotated.

A measurement of the known tensor analyzing power T_{20} at Q^2 = 2 GeV^2 will be used to independently extract P_{zz} with an uncertainty of 8.6%.

Although generating large values of negative tensor polarization are not feasible, the same RF techniques for enhancing the tensor polarization can be used to suppress it. The collaboration therefore intends to switch between enhanced and suppressed tensor polarization a few times an hour. Likewise, the collaboration will use AFP to reverse the sample's vector polarization at a similar rate. Combined, these two actions have the potential to lower systematic uncertainties due to drifts by almost one order of magnitude and offset a higher uncertainty in the target polarization.

Comments

The new lineshape analysis is very impressive, and the collaboration is commended for their efforts in this area. While it hews closely to the analysis described by Delheij et al. at TRIUMF in 1993, it is clearly more sophisticated and should permit a more precise determination of the tensor polarization. However, the scattering results subsequently obtained by the same TRIUMF group were consistent with little or no tensor enhancement, making the proposed T_{20} measurements absolutely critical.

It may be possible to test both spectral diffusion and the relation $A_{lost} = 2A_{gained}$ by saving the NMR scan prior to RF saturation, and subtracting subsequent, RF-manipulated NMR scans from this "background" scan. Ideally, the difference will be flat aside from the hole at the RF burning frequency, and a half-sized peak with the same width on the other side. This is especially true in regions of the line where there is only one spin-transition (i.e. the pedestal), in which case the relation $A_{lost} = 2A_{gained}$ is essentially guaranteed.

The collaboration is further commended for considering new methods to reduce systematic uncertainties. These procedures will require optimization, and the goal of spin-flipping multiple times per hour will be optimistic unless the efficiency of AFP approaches 100%. The growth of the deuteron polarization can be slow, and it may take one or more hours to reach a polarization of 50%. Assuming that AFP reverses the polarization with 95% percent efficiency to -45%, it can still take the better part of an hour to grow the polarization back to -50%. At the ERR, the collaboration should convincingly demonstrate that a full cycle of vector polarization reversal, tensor polarization enhancement/suppression, etc. can be performed with a frequency that significantly reduces the overall systematic uncertainties.

Charge Item 3: What assumptions are made regarding the vector polarization of the target? How is the tensor polarization expected to respond as the vector polarization decays in beam?

Findings

A vector polarization of 50% is required in order to achieve an enhanced tensor polarization of 30% using only ssRF. As the vector polarization is destroyed due to radiation damage, the achievable tensor polarization will likewise decay in beam, albeit at a slower rate. The collaboration suggested that the ND_3 sample would be annealed or replaced after an electron dose of $4x10^{15}$ e^{-}/cm^{2}, at which time the vector polarization is expected to have decayed to about 35% and the tensor to about 20%.

Comments

While 50% vector polarization in ND_3 at 5T/1K has been demonstrated, it is far from the value that has been achieved on a regular basis. More importantly, the *average* vector polarization that has been historically maintained in intense electron beams is closer to 30%. Based on figures presented at the review, this would translate to an average enhanced tensor polarization of about 20%, less than 1/2 the assumed figure-of-merit. The collaboration should therefore continue their efforts to improve both the tensor and *vector* polarizations that can be achieved in ND_3. (The collaboration is reminded that a vector polarization of 60%, provides almost 30% tensor polarization without the need for RF manipulation.)

Thus far, high ND3 polarizations at 5T/1K are only achieved after the samples receive an additional dose of electrons at 1 K (a so-called “cold dose”), a procedure that is not entirely understood nor perfectly reproducible. The collaboration should work with the lab on a plan to better understand the cold-dose and its “beam rattle-and-shake magic”, and/or pursue alternative paths to achieve higher polarizations. Paths that come to mind include:

- Higher magnetic field. This will require a new superconducting magnet and will not *a priori* guarantee much higher polarization;
- Lower temperature. This will almost certainly yield higher polarization but probably at the cost of lower experimental luminosity;
- Single crystals of ND_3. Properly oriented in the field, the NMR signal will no longer be a Pake doublet but will consist of a few distinct lines where the $-1 \leftrightarrow 0$ and $0 \leftrightarrow -+1$ NMR transitions do not overlap. This will allow full saturation of the $-1 \leftrightarrow 0$ lines and yield higher tensor polarization. This technique was demonstrated by the Bonn group many years ago, but to our knowledge, never fully pursued.

Charge Item 4: What is the current experimental situation? What is the maximum tensor polarization that has been achieved under the anticipated polarizing conditions of 5 T and 1 K?

Findings

All results presented at the review were obtained at the expected operating conditions of 5 T and 1 K. An enhanced tensor polarization of 30% has been achieved using saturating RF only. This increases to 32% if, in addition to ssRF, portions of the NMR line are reversing using AFP, and 36% if the sample is rotated.

Comments

All results that were presented at the review were demonstrated on samples of lightly-irradiated d-butanol, which is not suitable for electron experiments at JLab. It was explained that the ND_3 vector polarization that can be achieved without a cold (1 K) dose of electrons is too low to display the full potential of ssRF and the other techniques that were discussed, but those techniques work equally well in ND_3. This latter statement is probably true but must be demonstrated in future reviews because the degree of spectral diffusion in the two materials may be different.