Investigation into tensor polarization enhancement of solid polarized targets

D Keller
University of Virginia, Physics Department, 382 McCormick Rd, Charlottesville, VA 22904-4714, USA
E-mail: dustin@jlab.org

Abstract. A discussion of tensor polarization of solid targets produced by Dynamic Nuclear Polarization and Dynamic Nuclear Orientation in the use of nuclear physics experiments is presented. Techniques in the deuteron tensor polarization enhancement and enhanced tensor polarization measurement uncertainty are also discussed in the interest and preparation of future experiments.

1. Introduction
In recent years there has been a rise in the interest of solid tensor polarized targets for the use in nuclear physics experiments. Research in optimization and measurement of tensor polarization is now currently underway at the University of Virginia’s polarized target lab. Some methods and direction of that research is discussed.

For the explicit use in nuclear experiments the polarized target system is prepared so that the momentum and spin state of the deuteron can constitute the beam target. For the sake of optimizing luminosity of a tensor target, a new investigation has begun to maximize the desired helicity state in an ensemble comprised of a large number of deuterons present in a macroscopic solid target. What is expected to be achievable for use with a photon beam is considerably greater tensor enhancement of a target due to the frozen spin state available using a dilution fridge. The large current desired for electron beams makes the frozen spin state not a consideration at present. There is still the possibility to enhance the tensor polarization that is achieved with a ~1 K evaporation fridge that can be used with an electron beam.

Naturally a minimization procedure of polarization errors [1] is always essential, but there will be additional uncertainties that pertain only to the tensor polarization. This is true no matter the technique of acquiring the tensor polarization.

2. Tensor Polarization at Equilibrium
The deuteron, a spin-1 target, has energy levels which split three ways in a magnetic field, \( m = -1, 0, +1 \). The target spin orientation can be described using the vector and tensor polarization. The tensor polarization, \( P_{zz} \), can be expressed in terms of the vector polarization as \( P_{zz} \approx 2 - \sqrt{4 - 3P^2} \) where the dot implies the relation is true when thermal equilibrium exists within the deuteron spin species. The definition of vector polarization for spin-1 is,

\[
P = \frac{n_+ - n_-}{n_+ + n_- + n_0} = \frac{r^2 - 1}{r^2 + r + 1}.
\]
Figure 1. Deuteron magnetic resonance line shape and peak intensities $I_+$ and $I_-$. 

with the tensor polarization defined as,

$$P_{zz} = \frac{n_+ - 2n_0 + n_-}{n_+ + n_- + n_0} = \frac{r^2 - 2r + 1}{r^2 + r + 1}. \quad (2)$$

Where the second equality in each case is not part of the definition but a relation to the transition ratio $r$ defined as $r = I_+/I_-$, see Figure 1. These relations in terms of $r = e^{\beta \hbar \omega_d}$ are true to first order in $\beta \hbar \omega_q$, where $\omega_d$ ($\omega_q$) is Larmor (quadrupole interaction) frequency. The intensities $I_-$ and $I_+$ can be determined using a fitting procedure [2]. The resulting polarization measurements can be used complementary to the TE signal polarization calibration. For vector polarizations over 30% the two independent methods result in a discrepancy smaller than 2.5%. This leads to a minimum uncertainty in the natural tensor polarization of approximately 5%. The relationship between the ratio of intensities and the absolute error with increasing polarization can be seen in Figure 2.

3. Tensor Polarization Enhancement

Tensor enhancement can be achieved in an inhomogeneously broadened DMR line by selectively saturating only some of its components. A homogeneously broadened line can saturate uniformly where the degree of saturation is dependent on the spectral density at that frequency and the power rate of the RF. The saturated part of the line will recover exponentially with a time constant. Cross relaxation has a central role in the deuteron alignment changes. Spatial inhomogeneity comes from local gradients in the external field. Different spin populations in different parts of the sample can come into equilibrium by spin diffusion in space. This is a slow process so RF saturation can readily occur. A perturbation at a single frequency or frequency range will recover uniformly in a time set by the cross relaxation rate and then return to equilibrium over a longer time interval defined by the time constant.

Deuteron spin alignment can be manipulated at a specific frequency when exposed to a modulated RF field using an external coil around the target cup, as seen in Figure 3. The accuracy and enhancement of the tensor polarization is greatly dependent on the polarization technique. For nuclear experiments with the use of an electron beam the focus is presently on positive enhanced tensor polarization which can be expressed as,

$$P_{zz} = C(A_+ - A_-). \quad (3)$$
This is an expression that assumes the knowledge of the area of each of the two transition in the manipulated DMR line. Here $C$ is the calibration constant. A positive tensor polarization enhancement occurs only when the $n_+ + n_-$ population increases with respect to $n_0$ population. To optimize the tensor polarization the vector polarization must be maximized using DNP at which point the RF-modulation can be used to distort the spectral density over time. The RF-modulation induces thermal cooling with frequency dependence by simultaneous flip-flops while also suppressing transitions between either the $m = -1 \rightarrow m = 0$ or $m = 0 \rightarrow m^+ = 1$. A full saturation of the smaller transitions non-overlapping region (pedestal) can be especially helpful for enhancement. Tensor optimization will occur when the range in RF-modulation is chosen as to maximize the area of the resulting signal while minimizing the area in the overlap. The usefulness and associated uncertainty depends greatly on knowing the area of each of the two transitions under the RF manipulation. This has yet to be shown.

A solid tensor polarized target using both negative and positive tensor polarizations is plausible for use with a photon beam or low current electron beam. One way to achieve negative tensor polarization is to use dynamic nuclear orientation on a material that contains a separate proton spin-spin reservoir such as the -diol compounds. Applying a RF-modulation slightly off the Larmor frequency of the proton spins can lead to enhanced alignment of the deuteron spins independent of the vector polarization. The off-resonance RF field cools the proton spin-spin interaction reservoir and is transmitted to the deuteron quadrupole interaction reservoir [3]. The deuteron spin alignment increase can be calculated in much the same way with the accuracy purely dependent on the knowledge of the separate area of each peak.

Another very quick and simple technique is Adiabatic Fast Passage (AFP). This is also a very likely option for the frozen spin target. Spin-polarization reversal by using the adiabatic-fast passage (AFP) mechanism allows for quick target helicity reversal. This procedure is used frequently with gas targets (ie. Helium gas) but has yet to be employed for a solid polarized target in nuclear physics experiments.

The AFP process requires the nuclear-spin system to be placed in a strong magnetic field $H_0$ while being irradiated with a RF field $H_1$, linearly polarized in a plane perpendicular to $H_0$. 

Figure 2. Polarization and absolute error with increasing $r$. 

[Graphs showing polarization and absolute error with increasing $r$]
with frequency close to the NMR frequency. The passage is performed by varying the frequency $\omega$. This can be understood as a transfer of order from the Zeeman system to the quadrupole system for deuterons, then back to the Zeeman system with opposite spin orientation. The condition for adiabaticity is,

$$\frac{dH}{dt} \ll \gamma H_1^2,$$

where $dH/dt$ is the sweep rate.

The quality of the coupling between these subsystems by the field $H_1$ along with the RF field characteristics and the sweep time $\tau$ lead to an efficiency which is defined by the loss in the magnitude of polarization.

Once the AFP procedure is well understood for solid polarized targets, the RF field characteristics and sweep time must be investigated for many materials so that the AFP efficiency can be correlated to optimal polarization and target performance at the required temperature.

4. Conclusion

Tensor enhancement can be achieved by keeping the system in equilibrium at a higher holding fields or perhaps using non-standard target materials, outside of this, enhancement must be achieved through other means. One possibility is with the use of RF to manipulate the alignment of the deuterons in the ensemble. Some plausible methods are mentioned, all of which require further research and development in the lab as well as research into the measurement techniques.

References

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[2] Dulya C et al. 1997 *Nucl. Instr. and Meth.* A 398 109
[3] de Boer W et al. 1973 *Phys.Lett.* B 46 143