Results of Research Run 11/30/99 - 2/11/00*

S. Bültmann, D. G. Crabb, and Y. Prok

University of Virginia, Physics Department
Charlottesville, VA 22903

April 20, 2000

Abstract

This technical note describes the polarization results achieved in a number of measurements over the past three months with the polarized target system in our laboratory, B28, in the Physics Department.

1 Introduction

The polarized target in B28 uses the same refrigerator and insert that is used on the SLAC target. The magnet however is an 8 T solenoid housed in a special cryostat. The solenoid has a uniformity of about 1 part in 10^5 over a 1 cm dsv. An on axis measurement with a Hall probe is shown in Fig. 1. From an operational point of view we found it convenient to operate the refrigerator with a standard transfer line from the supply dewar rather than using a little U-transfer line drawing helium directly from the magnet dewar. The magnet was topped up with helium, using the same transfer line, every twenty four hours. This mode of operation used less helium and it was possible to leave everything in a stable mode overnight.

The reason for the cool down was to polarize some of our stored target material, particularly that which had been cold irradiated in the beam in Hall C and/or Hall B. We polarized $^{15}NH_3$, $^{15}ND_3$, $^{14}ND_3$, ^6LiD, and CH_2. We looked at polarizations as a function of magnetic field, at 2.5 T, 5 T, and 7.55 T. We compared $^{15}ND_3$ polarizations of material treated in different ways and also looked at ways of enhancing the deuteron tensor polarization by both microwave enhancement and NMR RF saturation. The results are presented and discussed in the sections following.

*Supported by a University of Virginia grant from the Academic Enhancement Program *The Fundamental Structure of the Neutron and Proton* and a US Department of Energy grant *Electron Interactions with Nuclei*

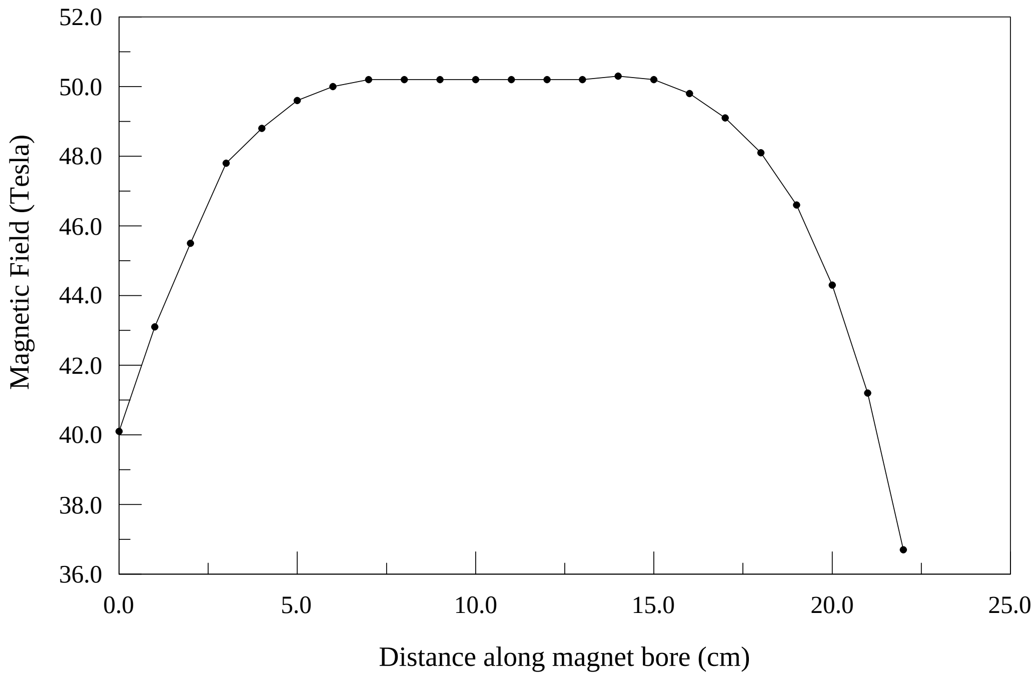

Figure 1: Hall probe measurement of magnetic field uniformity along central bore axis.

2 Polarization

The material was polarized using EIO tubes at the frequencies corresponding to 2.5 T, 5 T, and 7.55 T, but mostly at 5 T. The tubes were powered with CPI power supplies run via SOLA line conditioners. The power in B28 is not known for being particularly stable, but there was no PS breakdown as occurred in Hall C during G_E^n and at SLAC during E155X. A first conclusion is that the SOLAs isolated the supplies from line spikes etc., so that the first FET (the one which was exclusively destroyed in the past) was protected.

The polarization was measured with our standard NMR Q-meter system operating with a STAC unit and with modulations of ±300 kHz (±400 kHz) for deuterons (protons).

In general the polarizations quoted are obtained after several hours of polarizing but are not necessarily the maximum that could have been obtained if the polarizing had continued. The reasons for stopping were usually weariness or the lateness of the hour, but the liquid level dropping below the target (the level probe was not working) also happened more than once.

2.1 Protons

2.1.1 $^{15}NH_3$

This material was last used in Hall C, sixteen months previously. At 5 T the polarizations were +89.6% and -90.7%, consistent with expectations and shown in Fig. 2.

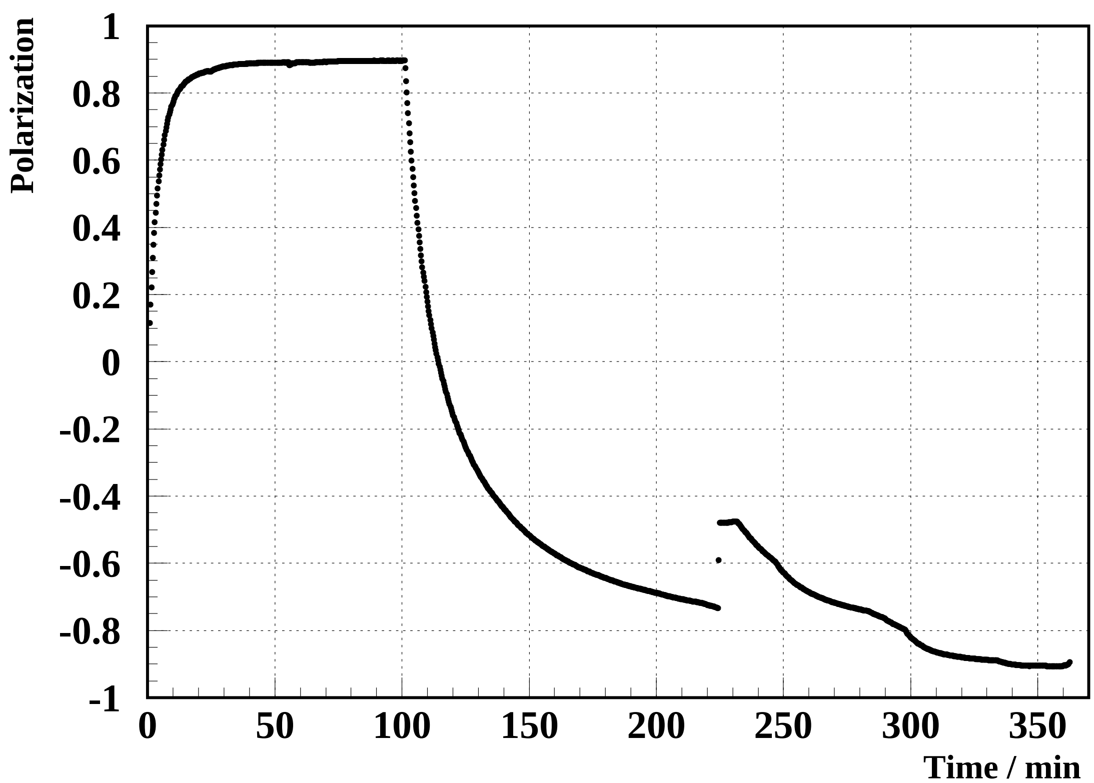

Figure 2: Proton polarizations in $^{15}NH_3$. The drop in polarization at 220 mins was due to the liquid helium level dropping below the target.

2.1.2 CH_2

This material was irradiated at the beginning of E143, while being used as a set up target. The amount of beam it received is not known with any certainty. However, a polarization of only -10% was reached.

2.2 Deuterons

2.2.1 $^{15}ND_3$

Several examples were polarized. The most interesting was the material recovered from the G_E^n experiment after the magnet accident. After a rapid warm up (temperature unknown), the material survived in a helium atmosphere for about an hour before being recovered and has since (for 15 months) been stored under liquid nitrogen. The material itself had no purple color and was yellowish. There were two target loads of differing granule size, 3 mm (granules) and 1 mm (slush). These were each polarized several times and consistently gave polarizations $\geqslant$40%. Typical curves are shown in Fig. 3. A comparison between the 'granules' and 'slush' shows the 'slush' to be marginally worse. We confirmed, that above $\sim$ 20% polarization the peak height ratio method agrees with the TE calibration method.

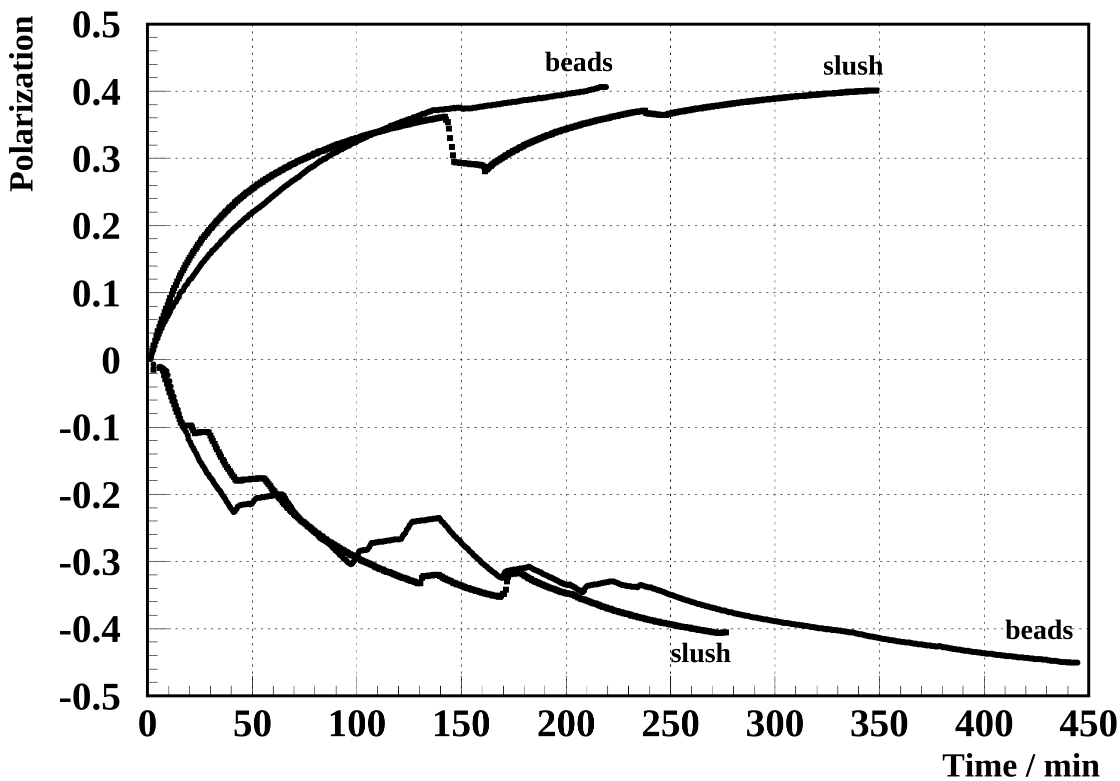

Figure 3: ND_3 polarization with material recovered after the Hall C accident. The kinks are either due to loss of liquid helium or changes in the microwave frequency.

The second sample to be investigated had again come from Hall C for use in Hall B and was purple. However, this sample only polarized to +30.3% and -16.1%, before turning off the microwaves.

Other deuterated ammonia material polarized was:

1) $^{14}ND_3$ from the Saskatoon irradiation of 1992. This polarized to -10%. No measurement was made on the positive enhancement.

2) $^{15}ND_3$ slush. Unfortunately the bottle looked as if part of it had been exposed to high temperatures; a layer of white fragments sat on top of a purple layer. Mostly white beads were loaded. Polarization was attempted, but nothing was seen above a noise signal which was eventually tracked to RF coming from the microwave power supply.

Tempering The most interesting aspect of the deuterated ammonia polarizations was that both sets of material retrieved from the damaged target gave polarizations $\geq$ 40%. It was decided to try and reproduce the conditions. The purple material which, as indicated above, polarized to +30% and -16% was tempered. This was achieved by shaking the granules in a mesh container in cold nitrogen vapor and observing the purple color disappear. When the granules had obtained a yellowish color they were plunged back into LN_2. After loading and calibrating in the usual way, the beads were polarized.

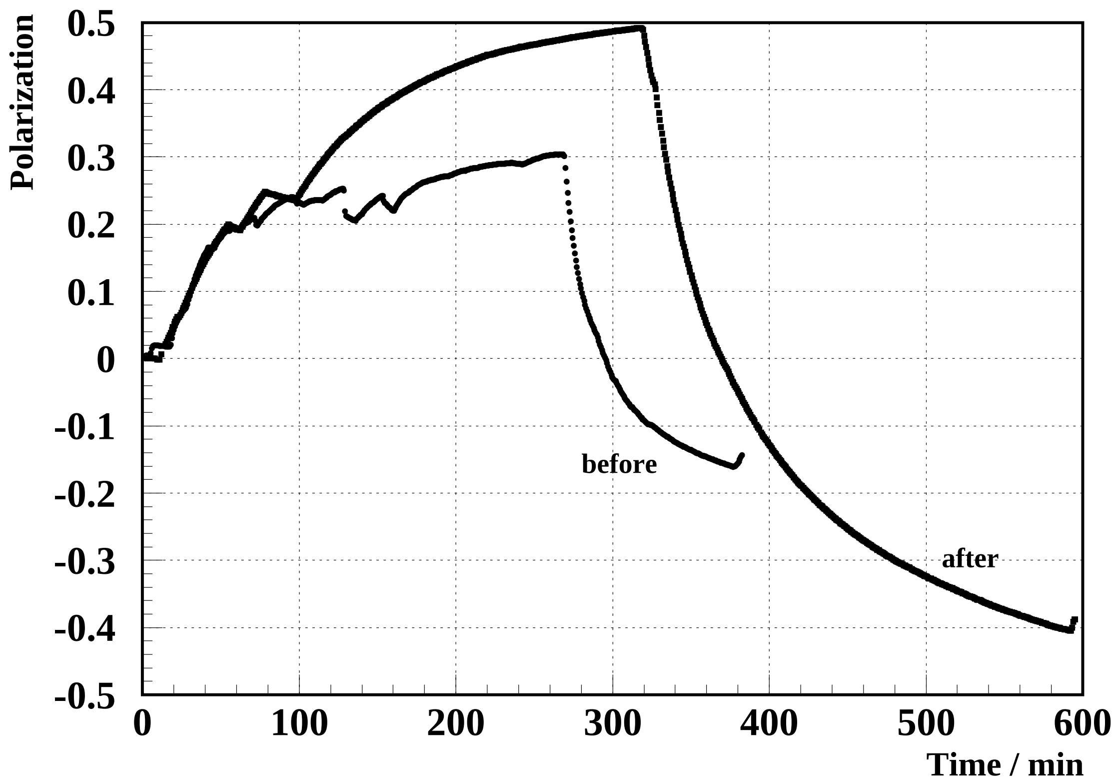

Figure 4: ND_3 polarization, before and after tempering.

The data are shown plotted in Fig. 4 along with the result obtained before tempering. There obviously is a big improvement with +50% and -40% polarizations achieved. The negative enhancement was curtailed because of running out of helium. These results need to be investigated further. One question is whether warm and cold irradiation is necessary for tempering to work or can improvements be made by tempering after only warm irradiation?

2.3 ^{6}LiD

One of our LiD samples had been prepared for SLAC and was used in E155X. It polarized to +21% and -24.5%. However the positive enhancement was stopped prematurely. These numbers were similar to those obtained at SLAC.

2.4 Magnetic Field Dependence

With the aid of a 212 GHz EIO loaned by Alan Krisch of the U. of Michigan and the participation of Richard Raymond and Beracah Yankama we were able to look at the magnetic field dependence of the polarization of $^{15}NH_3$, $^{15}ND_3$, and ^{6}LiD at nominal field values of 2.5 T, 5.0 T, and 7.55 T.

The results are shown in Table 1.

Field (Tesla)	$\mathbf{NH_3}$	$\mathbf{ND_3}$	**LiD**
2.5	+25.5, -22.5	+5.1, -3.5	+11.5, -13.1
5.0	+89.6, -90.7	+40.1, -40.5	+21.0, -24.6
7.55		+29.6	+30.0

Table 1: Proton and deuteron polarizations (%) at three magnetic fields.

Comments:

There was not sufficient time to polarize NH_3 at 7.55 T (212 GHz). However, the NMR was tuned to the appropriate frequency (321.88 MHz), but was extremely sensitive to the $\lambda/2$ cable length. A change of 2 cm was sufficient to affect the Q-curve and signal significantly. Together with the E155 experience and much discussion with G. Court and M. Houlden of Liverpool University it was decided to start a new NMR initiative where there was no $\lambda/2$ cable and instead a cold resonant circuit near the target coil.

In agreement with the experience at PSI and other places with other materials, the polarization of both ammonia cells showed large differences between 2.5 T and 5.0 T, except that in our case the optimum polarization was at 5.0 T. At 7.55 T the ND_3 polarizing was probably power limited because the tube had a max. output of 2.5 W (cf. 15 W at 140 GHz).

For LiD the situation is different because of the long relaxation times. The power requirement is less and thus there is an improvement in polarization with increasing field, see Fig. 5. However the long relaxation times make it difficult to calibrate LiD. At 7.55 T and 1.8 K it took almost three days to thermalize. The improvement in polarization with field is on a par seen by Abragam et al. [1], except on a different scale because Abragam used a dilution refrigerator and operated at $\sim$ 200 mK.

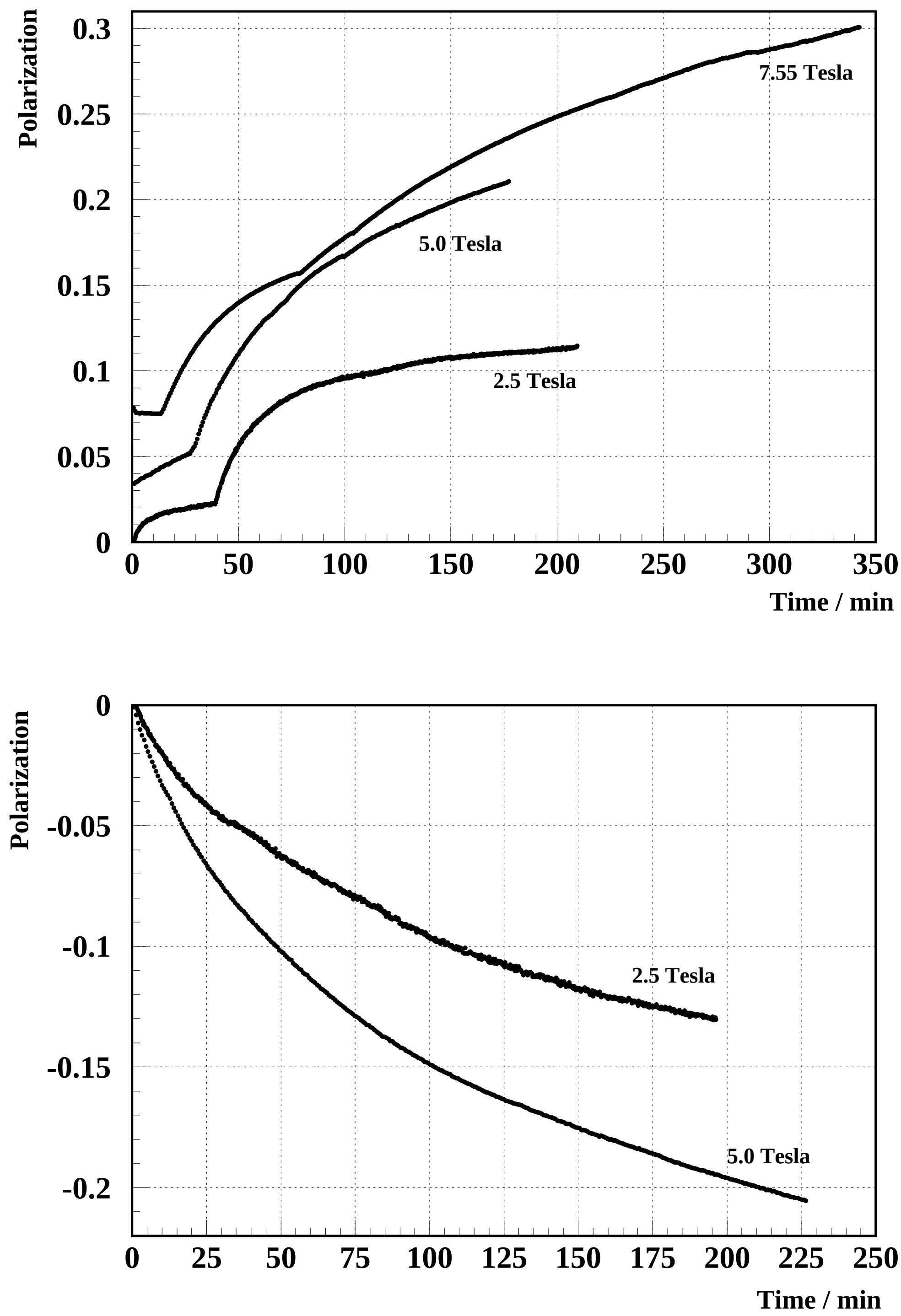

Figure 5: LiD polarization at 2.5 T, 5.0 T, and 7.55 T.

3 Tensor Polarization

3.1 Microwave Driven

It has been suggested [2] that the tensor polarization of the deuteron can be enhanced by using another microwave tube and driving another transition at the same time. Also it may be possible to enhance the vector polarization by driving another transition rather than frequency modulating (FMing) the microwaves around the main frequency. Much work was done with a 'magic Tee' to feed the microwaves from two tubes into a single waveguide, and by using both insert waveguides to irradiate the material in the bottom cell. No enhancement of vector polarization was seen, nor any obvious tensor polarization effect. After some thought we concluded that the original premise on which the enhancement of tensor polarization was founded was incorrect.

3.2 RF Saturation

In the usual NMR figure for a deuterated material the two peaks correspond to the net transitions $m = -1 \to m = 0$ and $m = 0 \to m = +1$, for negative vector polarization and $m = +1 \to m = 0$ and $m = 0 \to m = -1$ for positive polarization. The $m = -1 \to m = 0$ ($m = +1 \to m = 0$) transition dominates for negative (positive) vector polarization and the polarization can be derived from the ratio of the peak heights of the two transitions. Then, if the dominant peak can be RF saturated, i.e. the $m = 0$ and either $m = +1$ or $m = -1$ have equal populations, the population of the $m = 0$ level will have been increased relative to the Boltzmann population level and therefore the tensor polarization will have increased. Assuming there is complete saturation, it can be shown that $A = - \mid P \mid$.

We used the R&S and the NMR coil to RF saturate and, as a first attempt, applied a 900 mV RMS level at the peak frequency and swept over the peak width of ± 30 kHz of the negative transition with 200 double sweeps. Then, after reconnecting the NMR, it is seen that the negative transition peak has almost disappeared (Fig. 6), though one or two wiggles remain. For a first attempt this is very encouraging and, as far as we are aware, this technique has not been reported in the literature, though it is a simple extension of the more common technique of RF saturating unwanted spin species in the material, e.g. unreplaced protons in deuterated material. In Fig. 7 the recovery of the natural resonance signal under microwave irradiation is shown. The negative transition is growing again at the expense of the positive transition.

To proceed we will have to measure and fit the peaks individually, to be able to extract the tensor polarization more accurately and determine the degree of saturation more precisely. We will need to use another coil, probably wound on the outside of the target, rather then the NMR coil to make sure that the whole target has been saturated. To increase further the tensor polarization, an AFP similar technique needs to be employed: it has been shown by Patrick Hautle of PSI [3] that sweeping 'fast' adiabatically across half of the deuteron line enhances the $m = 0$ population.

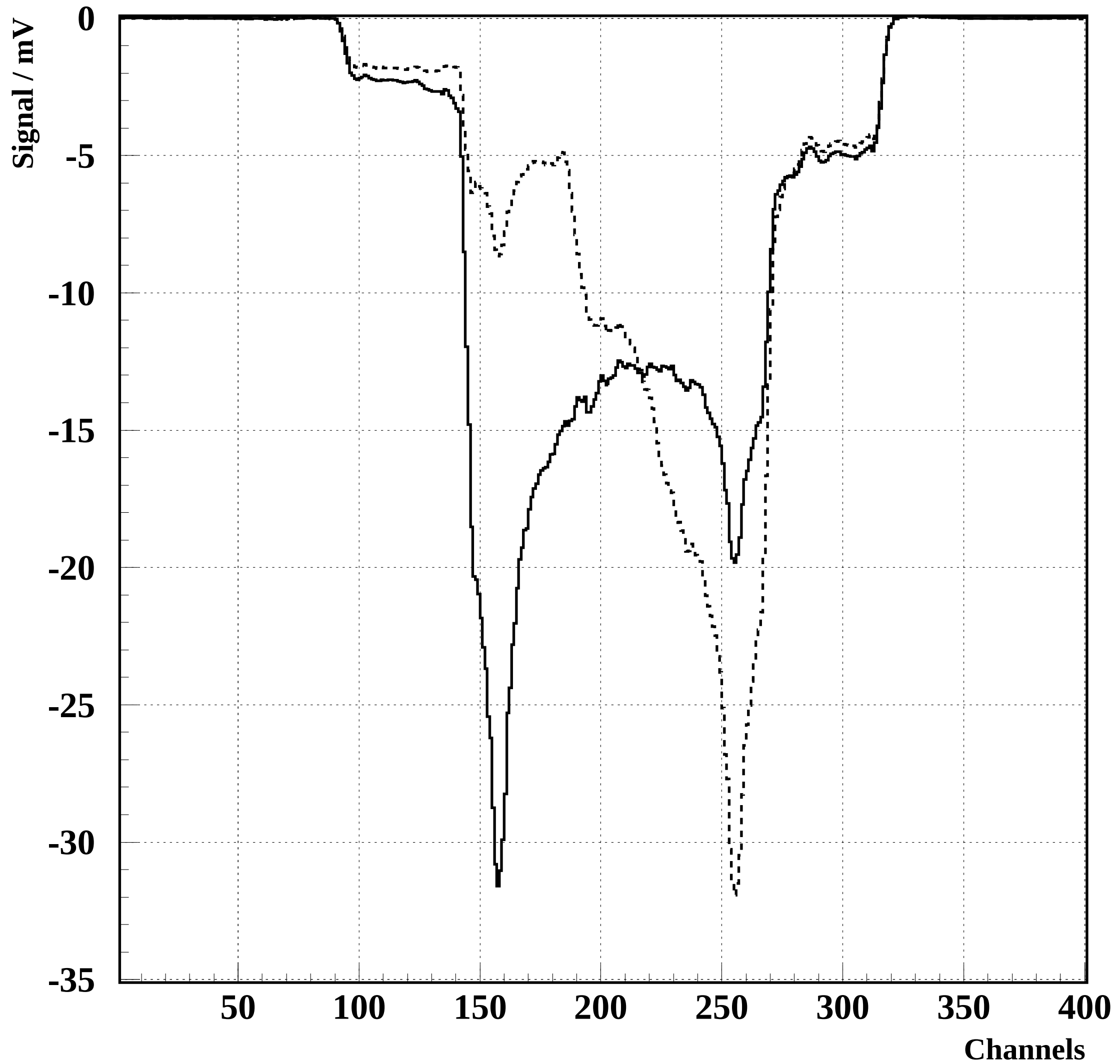

Figure 6: Deuteron signal before (solid line), and after (dashed line), RF saturation. The 400 channels correspond to 600 kHz range around the centre frequency of 32.709 MHz.

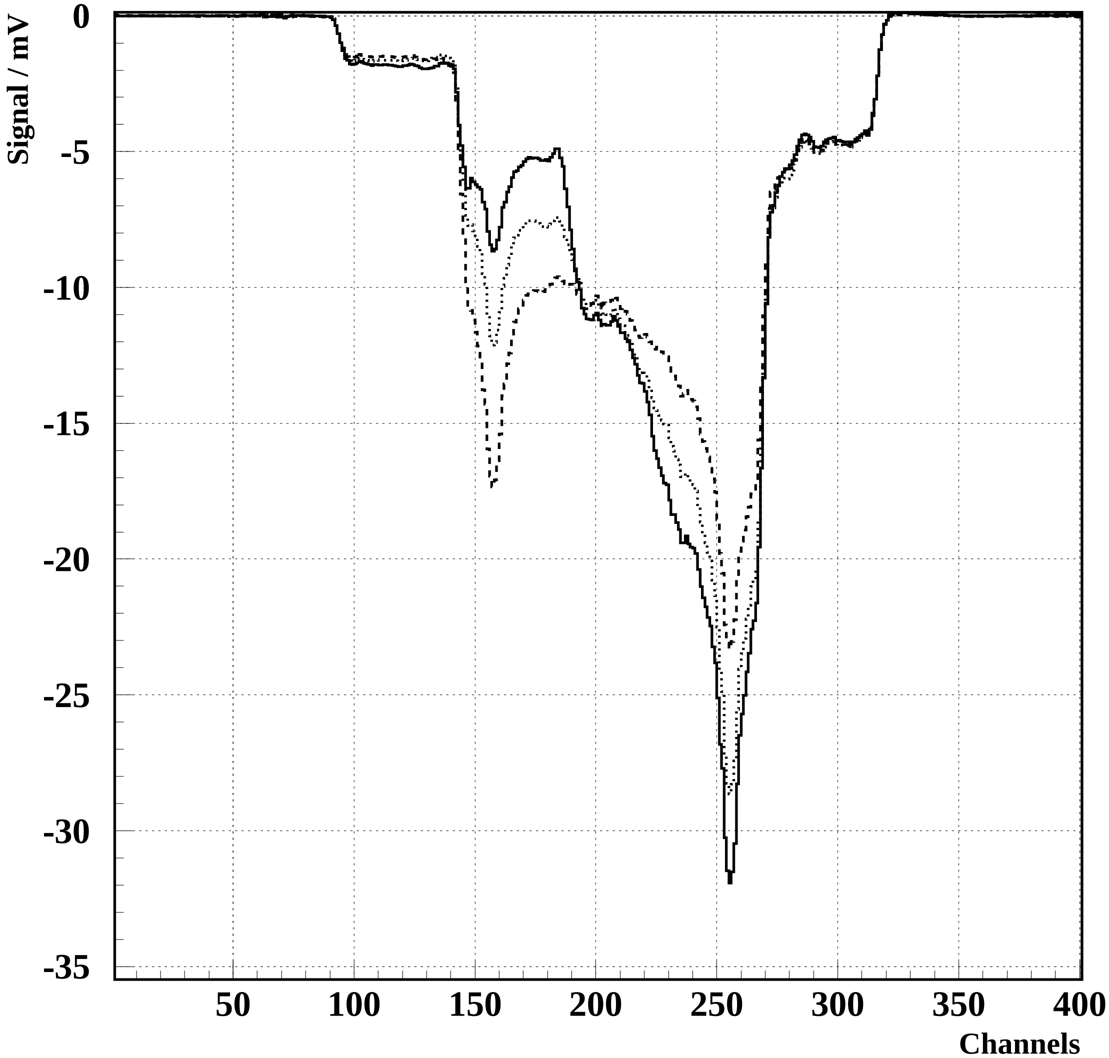

Figure 7: Initial RF saturated deuteron signal (solid line), and changing under microwave irradiation (dashed lines).

4 Conclusions

The proton polarization in ammonia was $\gtrapprox$90% with material that had been cold irradiated but kept under LN_2 for more than one year. The purple color had disappeared leaving the granules with a greyish tinge. This has been noted previously by us and other experimenters and indicates that after the initial radiation the color has little to do with the polarization performance.

The proton polarization in CH_2 was 10%, about the same as seen previously under similar polarization conditions. The only question is the dose that the material received, though it is likely that the polarization saturates with dose as was seen with irradiated butanol. Perhaps it is worth confirming this point in a future experiment.

The measurement of the ammonia proton polarization at 2.5 T and 5 T of 25% and 90% respectively shows a strong relation with doping density. This has been noted previously, except that the doping has been optimized for operation at 2.5 T, though at lower temperatures. Here presumably we are optimized for 5 T. There was no polarization measurement made at 7.55 T, though the NMR was tuned at the appropriate frequency (321.88 MHz) and a TE signal observed and measured. However the extreme sensitivity of the tune to length of $\lambda/2$ cable has led to a re-evaluation of the now standard technique. The first tests of a prototype circuit, as mentioned in Section 2.4, took place after this run and will be reported separately. However, they were very encouraging and will have an impact on the measurement of both proton and deuteron polarizations.

The polarization of the deuteron in ammonia provided the main surprise. Material that had been accidentally 'tempered' and had lost its purple color to become yellowish, gave polarizations of >40%. This has to be compared with a more standard material, which had been cold irradiated and was purple and polarized to 30%. The effect of tempering was confirmed when this purple material was itself tempered and polarizations of 50% obtained. Together with the experience obtained with protons in ammonia, it would appear that the color has very little to do with polarization performance and may in fact be deleterious.

Polarization of the deuteron in LiD confirmed the standard 25% that is achieved at 5 T and 1 K.

The measurement of the ammonia deuteron polarization at 2.5 T, 5 T, and 7.55 T again indicated a strong dependence on doping, although the 7.55 T measurement is inconclusive because of microwave power starvation. With the LiD, where power is not so big a consideration, the polarization achieved at the three fields improved with field value, in line with that observed by Abragam.

Attempts to improve the deuteron vector polarization by operating two EIO tubes at slightly different frequencies (instead of 'FMing') were inconclusive as were the attempts to enhance the tensor polarization by a similar technique. We should probably revisit the vector polarization enhancement, but we believe the tensor polarization will not improve by differential frequency irradiation as there are faulty assumptions in the method.

However we believe that the tensor polarization was improved by RF saturating one line and that this is a technique that will be pursued. A sign change of the deuteron tensor polarization was obtained which is a significant step forward. The maximum vector polarization we achieved, +50%, gives a tensor polarization of +20%, while our RF saturation technique gave a value, estimated from the residual NMR enhancement of the other peak, of about -30%.

Overall, the indications from this run are that if we want better understanding of the polarization process more EPR measurements are vital.

5 Acknowledgements

We indebted to D. Day, C. Harris, C. Keith (Jefferson Lab), D. McNulty, J. Pierce, and A. Tobias for their help and support during this period of measurements.

6 Bibliography

[**1**] A. Abragam et al., J. Phys. 41 (1980) 309.

[**2**] T. D. Averett et al., Nucl. Instr. and Meth. A 427 (1999) 440.

[**3**] P. Hautle et al., Nucl. Instr. and Meth. A 356 (1995) 108.