Investigation into Polarization Uncertainty Minimization of Solid Polarized Targets

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September 9, 2013

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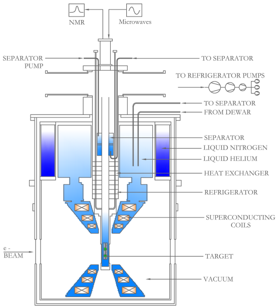
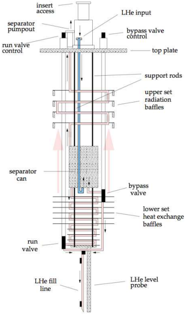
Solid Polarized Target



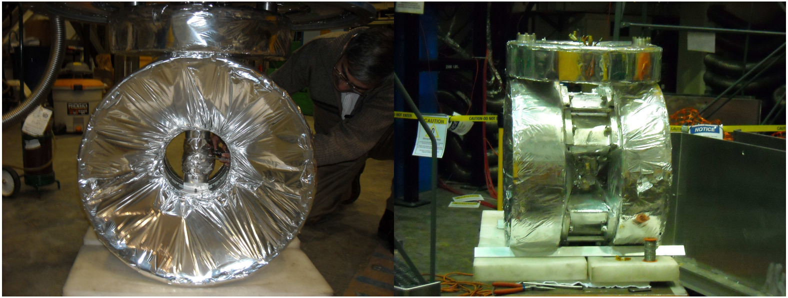


A. Rijal

- (A) ∼100 nA
- (B) $10^{35}\text{cm}^{-2}\text{s}^{-1}$
- (C) dilution factor f<50%

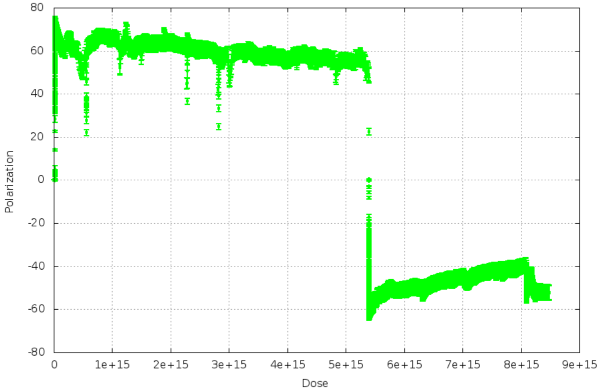
- DNP using Microwave Stronge B-Field
- Cryogenic System (1.5-0.03 K)
- Materials Specific to Experiment
- NMR (Yale/Q-meter)
- Proton/Deuteron

Relevant Experiments



- E93-026(Gen01), E01-006(RSS), E06-014(d2n), E07-003(SANE), E08-027(G2P), E08-007(Gep), (FROST)
- E143, E155, E155x
- Upcoming: E12-13-011(b1), E12-07-107, E12-09-009, E12-06-109, E12-09-007, E12-11-108(solid), (HiFROST, DY)

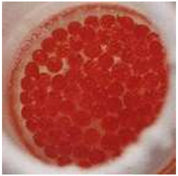
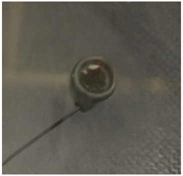
The Need for Error Reduction



- Polarization Observables for Kinematic Range
- Largest Error in Asymmetry Measurement
- Pushing Frontier on Precision

Material Performance



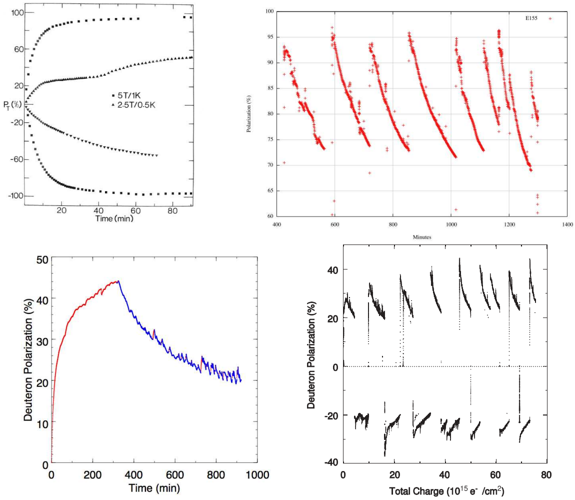



Errors from Material

- (A) Density Variation (Multiple Stresses)
- (B) Tolerate High Intensity Beam
- (C) Homogeneity
- Optimal Irradiation (Field/Experiment)

Quantify Characteristics

- Maximum Polarization
- Dilution Factor
- Material Performance
- Spin-Lattic Relaxation
- $m = 0$ Cross Relaxation


100
60
20
P_T (%)
-20
-60
-100
20
40
60
80
Time (min)
5T/1K
2.5T/0.5K
E155
Polarization (%)
Minutes
Deuteron Polarization (%)
Time (min)
Deuteron Polarization (%)
Total Charge (10^{15} e⁻ /cm²)

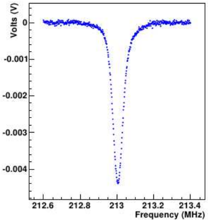
Analysis General Approach

- TE Events Selection
- Quality of Baseline
- Reintegration of Signle
- Extract Calibration Constant
- Extract Enhanced Area
- Errors from Each Contribution

Resolving/Reintegration TE Signal

1. Baseline/background Subtraction Quality Baseline and Fit
2. Integrate Area Riemann Sum

Complete Set of Contributions



$$P_{TE} = \tanh\left(\frac{\mu B}{kT}\right)$$

$$P_E = G\frac{\int S_E(\omega)d\omega}{\int S_{TE}(\omega)d\omega} = GC_{TE}A_E$$

$$\left(\frac{\delta C_{TE}}{C_{TE}}\right)^2 = \left(\frac{\delta P_{TE}}{P_{TE}}\right)^2 + \left(\frac{\delta A_{TE}}{A_{TE}}\right)^2$$

$$\frac{\delta P_E}{P_E} = \left[\left(\frac{\delta P_{TE}}{P_{TE}}\right)^2 + \left(\frac{\delta A_{TE}}{A_{TE}}\right)^2 + \left(\frac{\delta S_{TE}}{S_{TE}}\right)^2 + \left(\frac{\delta A_E}{A_E}\right)^2 + \left(\frac{\delta S_E}{S_E}\right)^2 + \left(\frac{\delta G}{G}\right)^2\right]^{1/2}$$

1. A_{TE} - Relative uncertainties in area acquired during TE
2. S_{TE} - Measurement limitation during TE
3. S_E - Systematic variation in enhanced signal
4. G - Error from gain

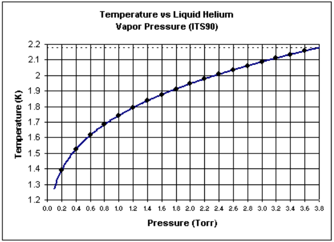
TE Polarization Uncertainties

$$T = \sum_{i=0}^{9} a_i \left(\frac{\ln p - b}{c} \right)^i$$

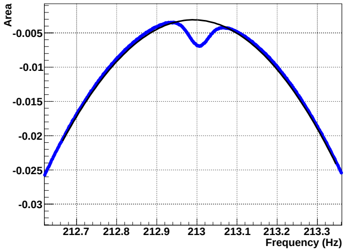
$$\delta T = \sum_{i=1}^{8} a_i \left(\frac{\ln p - b}{c} \right)^i \frac{\delta p}{\delta c}$$

$$\delta P_{TE} = \frac{\mu B}{KT} \sqrt{\left(\frac{\delta B}{B} \right)^2 + \left(\frac{\delta T}{T} \right)^2} \mathrm{sech}^2 \left(\frac{\mu B}{KT} \right)$$

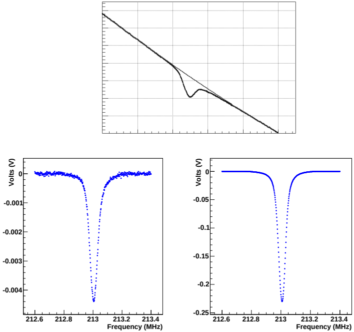
- (A) Error in Pressure Measurement
- (B) Calibrations
- (C) Tempurature Fluctuations
- (D) Magnet Setability



Singal Integration and Errors

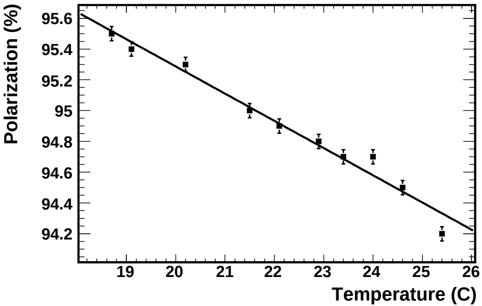


- (1) Center the Signal & High Sweeps
- (2) Baseline Subtraction
- (3) Fit Quadratic Around Peak
- (4) BG (DC-vertical offset) Subtraction
- (5) Variation in Area in the χ^2 Min-Steps



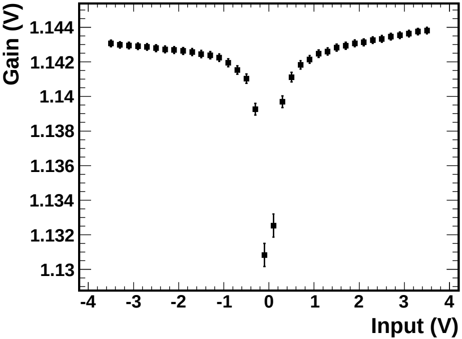
- (A) Riemann sum
- (B) Strong Correlation to Polynomial
- (C) On-line Minimization by Centering
- (D) ~2% for TE

Q-meter



1. Variation in temperature with output voltage
2. Only relevant for data taking (need temp monitor)
3. Less then 1% but much smaller with temperature control

Yale Card Characteristics



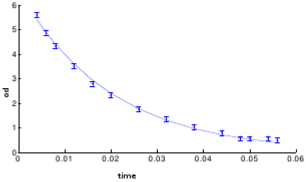
1. Actual operative voltage 3 ± 0.3V
2. Input voltage in a function of polarization
3. Small effective error ~0.1-0.5%

Contributing Uncertainties

(#)	Type	Source	Error (%)
(1)	S_{TE}	ΔT	1.45
(2)	A_{TE}	ΔA_{TE}	1.61
(3)	A_{TE}	ΔA_{fit}	0.75
(4)	S_E	R_B	0.50
(5)	S_E	ΔV_Q	0.75
(6)	S_E	NMR-tune	0.47
(7)	S_E	ΔB_{drift}	0.25
(8)	G	ΔV_{Yale}	0.10
(9)	-	$\Delta \bar{P}_{run}$	0.50

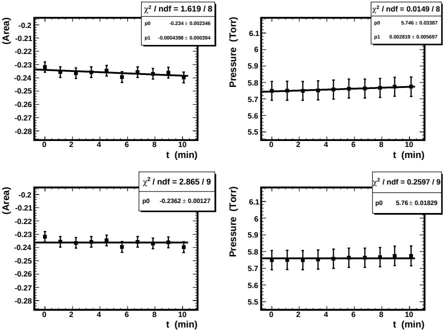
1. A_{TE}: Uncertainties in area acquired during TE
2. S_{TE}: Measurement Limitation during TE
3. S_E: Systematic variation in time of enhanced signal
4. G: Error from conditioning card

Systematic Steps to Extract Maximal Information



- (A) Thermalize to TE (fit to get t_1)
- (B) Quantify Thermal Fluctuations (20 min: 2%)
- (C) Set of Constraints area (pressure) data quality
- (D) Maximize area (pressure) data points
- (F) Minimize area (pressure) data Uncertainty

Procedural Usability Constraints



TE Usability Criteria

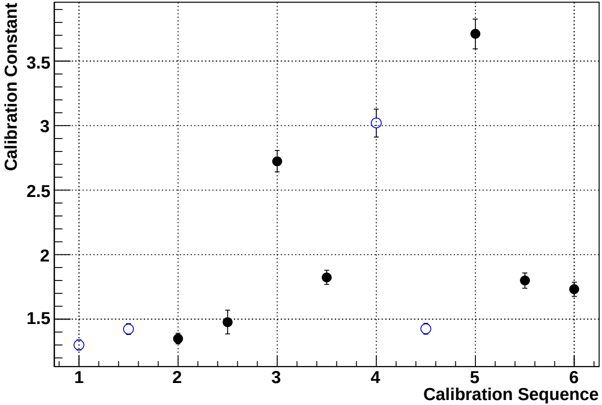
- (1) 2% limit in thermal fluctuations at 1.5 K
- (2) At least 6 points (in flattest region)
- (3) 2-parm: Slope less than 0.0035 area/min (Torr/min)
- 1-parm: Increase contiguous points without increasing error (still ‘Usable’)

Quality Area and Pressure within Procedural Constraints

- (A) Final One Parameter Line Fit for Final Set (Fit Error)
- (B) Compare Initial Set with Final Set (Systematic Error)
- (C) Find δP_{TE} and δA_{TE}
- (D) Add TE errors up and obtain CC

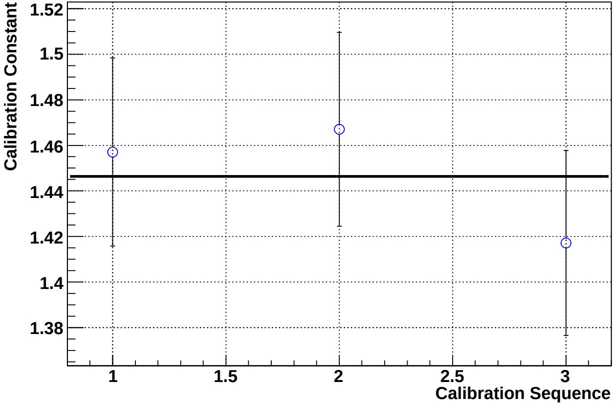
$$\delta T = \sum_{i=1}^{8} a_i \left(\frac{\ln p - b}{c}\right)^i \frac{\delta p}{\delta c}$$

$$\delta P_{TE} = \frac{\mu B}{KT}\sqrt{\left(\frac{\delta B}{B}\right)^2 + \left(\frac{\delta T}{T}\right)^2} \mathrm{sech}^2\left(\frac{\mu B}{KT}\right)$$



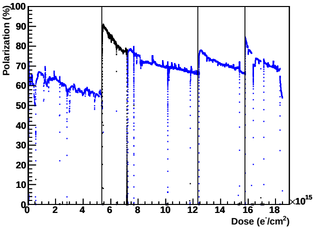
- - CC set and uncertainty
- - Showing top (open) and bottom (closed) cups

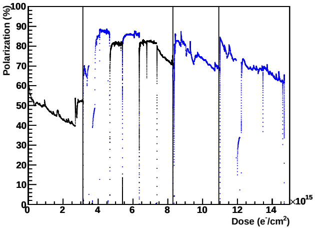
Final Calibration Fit



- (a) Only CC for ‘Usable’ TE
- (b) Consecutively Used Material (Undisturbed between TE)
- (c) Each within Error Bars (1σ)
- Final Fit Leads to Error Reduction ($3\% \rightarrow 2.4\%$)

Charge Averaging Error





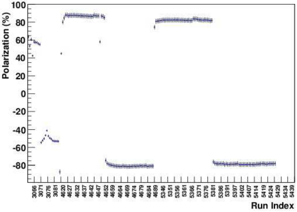
$$\bar{P}_{run} = \sum_i^n Q_i P_i$$

$$\Delta\bar{P}_{run} = \sqrt{\sum_i^n Q_i^2 (\bar{P}_{run} - P_i)^2}$$

- (a) Charge Average For Each Run
- (b) Error In Charge Average
- (c) Set Quality Constraint $\Delta\bar{P}_{run}/\bar{P}_{run} < 0.5\%$

Uncertainty by CC and Run

Run Range	Arm	Cup	C_{TE}
3061–3070	Left	T	– 1.299 (3.05%)
3071–3084	Left	B	– 1.371 (3.76%)
3085–3130	Left	T	– 1.299 (3.05%)
4599–4695	Left	B	– 1.823 (3.01%)
5339–5344	Left	T	– 1.424 (2.87%)
5345–5346	Left	B	– 1.799 (3.28%)
5347–5484	Left	B	– 1.731 (3.18%)
22146–22155	Right	T	– 1.299 (3.05%)
22156–22172	Right	B	– 1.371 (3.76%)
22173–22217	Right	T	– 1.299 (3.05%)
23540–23618	Right	B	– 1.823 (3.01%)
24113–24118	Right	T	– 1.424 (2.87%)
24120–24121	Right	B	– 1.799 (3.28%)
24122–24258	Right	B	– 1.731 (3.18%)



(#)	Type	Source	Error (%)
(4)	S_E	R_B	0.50
(5)	S_E	ΔV_Q	0.75
(6)	S_E	NMR-tune	0.47
(7)	S_E	ΔB_{drift}	0.25
(8)	G	ΔV_{Yale}	0.10
(9)	-	$\Delta \bar{P}_{run}$	0.50
		$\Delta P/P$	~1.00

- (4) Magnetoresistance (R_B)
- (5) Q-meter Temp (ΔV_Q)
- (6) NMR Tune Drift (NMR-tune)
- (7) B-field Drift (ΔB_{drift})
- (8) Gain Error (ΔV_{Yale})
- (9) Charge Average ($\Delta \bar{P}_{run}$)

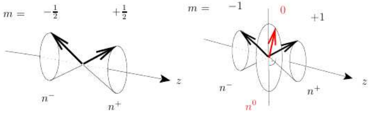
- (A) Proton (NH_3) ~3-4%
- (B) Deuteron (ND_3) ~4-5%

Summary of Offline Uncertainty Minimization

- (A) Collect Instrumental, Systematic, Statistical
- (B) Fit Area and Pressure (max points/min error)
- (C) Set Usability Criteria on TE points
- (D) Set Quality Constraints on CC
- (E) Fit Calibration Constant
- (F) Add in Time Dependant Effects

Summary of Online Uncertainty Minimization

- (A) Center TE Signal Before TE
- (B) No B-field Drifts
- (C) Q-meter Temperature
- (D) Multiple TE per Set



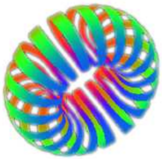
$$P = \frac{n_+ - n_-}{n_+ + n_- + n_0} \quad (-1 < P_z < 1)$$

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

(A) positive and negative

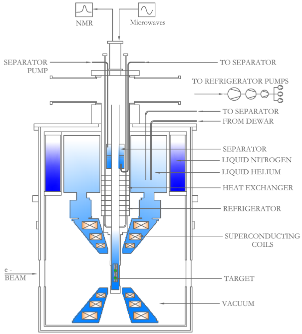
(B) negative and unpolarized

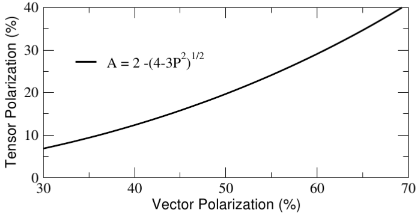
(C) positive and unpolarized



- (a) b_1, A_{zz}
- (b) T_{20}, T_{21}, T_{22}
- (c) photo/electro disintegration
- (d) photoproduction

Spin-1 Polarization



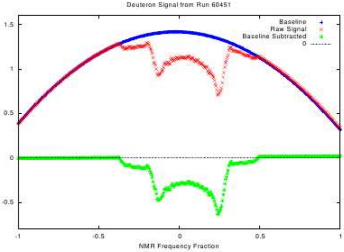


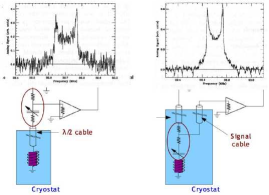
- Solid Polarized Target (ND_3):
  - ✔ Standard Polarized Target
  - ✘ Standard Field 5T Strength P_{zz}=10%

Spin-1 Polarization

Measurement from Area

- Previous Steps for TE
- Calibration Constant
- Min Inst Error (Cold NMR)
- Additional Ratio Fit
- ∼4

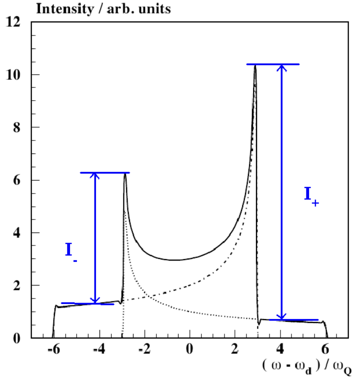




$$P = \frac{n_+ - n_-}{n_+ + n_- + n_0}$$

Measurement from Ratio

$$P = (r^2 - 1)/(r^2 + r + 1)$$



Assume Boltzmann Distribution

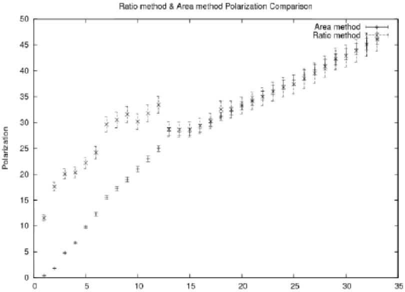
- $E_0 \Leftrightarrow E_1$, $\Delta E_+ = E_0 - E_1$, I_+
- $E_{-1} \Leftrightarrow E_0$, $\Delta E_- = E_{-1} - E_0$, I_-
- $r^2 = I_+/I_- = n_+/n_-$
- $r \approx n_0/n_-$

Tensor Polarization Measurement

$$P = \frac{n_+ - n_-}{n_+ + n_- + n_0}$$

Measurement from Fits

$$P = (r^2 - 1)/(r^2 + r + 1)$$



Assume Boltzmann Distribution

- $E_0 \Leftrightarrow E_1,\ \Delta E_+ = E_0 - E_1,\ I_+$
- $E_{-1} \Leftrightarrow E_0,\ \Delta E_- = E_{-1} - E_0,\ I_-$
- $r = I_+/I_- = n_+/n_-$
- $r \approx n_0/n_-$

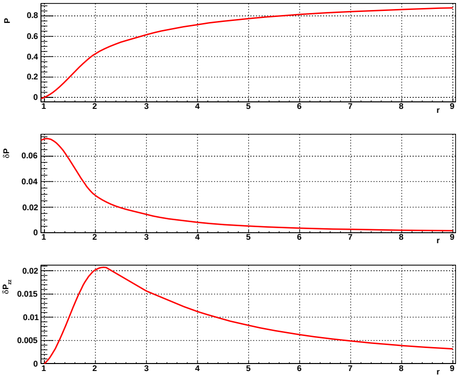
Tensor Polarization Measurement

$$P_{zz} = \frac{n_+ - 2n_0 + n_-}{n_+ + n_- + n_0}$$

Measurement from Fits

$$P = (r^2 - 1)/(r^2 + r + 1)$$

$$P_{zz} = (r^2 - 2r + 1)/(r^2 + r + 1)$$

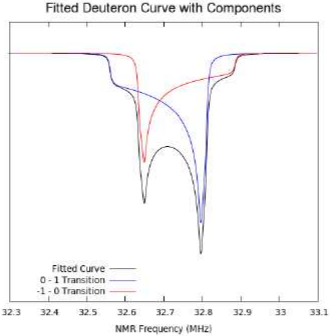


Uncertainties

- For $r = 2.5$ ($P = 50\%$) $\sim$same for fixed δr
- $\delta P_{zz}/P_{zz} \sim 7.5\%$ Vector Enhanced
- $4\% \leq \delta P_{zz} \leq 12\%$ Tensor Enhanced

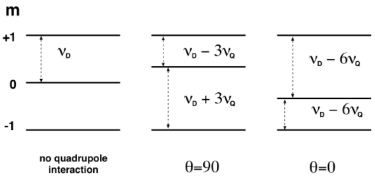
$$H = \omega_{0s} S_z + 2\omega_{1s} S_x cos\omega t + \omega_{2s} S_z k f(\phi, t)$$

$$P_{zz} = \frac{n_+ - 2n_0 + n_-}{n_+ + n_- + n_0}$$



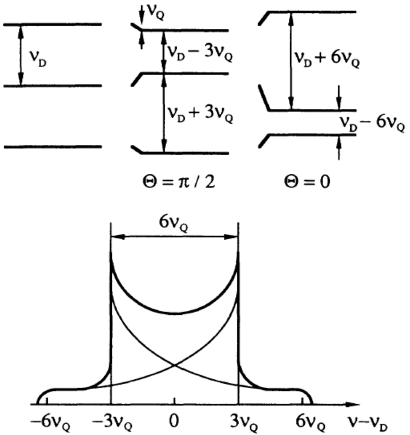
Measurement Capacity

1. Material Dependent
2. Enhancement Technique
3. Limitations with NMR
4. Error Propagation



Deuteron RF Modulation (center 32.7 MHz):

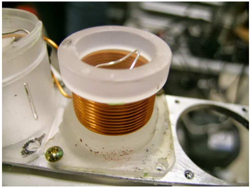
1. 32.6-32.65 MHz pedestal
2. 32.76 MHz peak
3. 24 kHz modulation
4. 10000 Steps/Second
5. Triangle Waveform

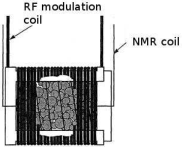


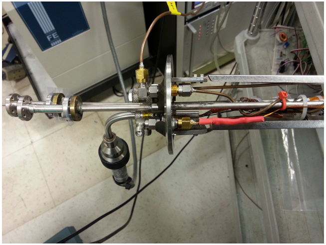
Optimization Research

1. Modulation Optimization For Experimental Use
2. Sustain and Measure with an NMR System
3. Measurement Method and Uncertainty Minimization
4. Relaxation Rate in Various Tensor Enhanced Modes (temp dep)

Deuteron RF Modulation

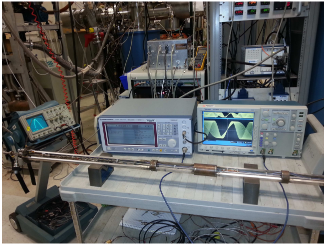






First Look

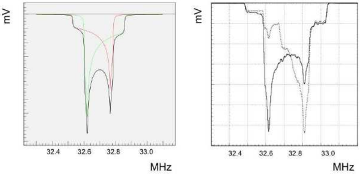
1. Secondary Coil (2 mT/A)
2. Translate NMR Area
3. Only Estimates
4. Intermittent NMR

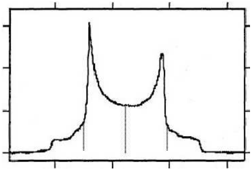


Enhanced Tensor Polarization Measurement

Enhancement Method

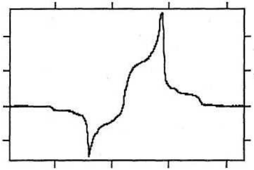
1. $P_{zz} = (r^2 - 2r + 1)/(r^2 + r + 1)$
2. $P_{zz} = \frac{n^i_{\pm} + dn_0 - 2(n^i_0 - dn_0)}{N} = P^i_{zz} + f(A^i, A^f, r)$
3. $P_{zz} = \frac{|\Delta IP|}{I_+ + I_-}\Delta\nu_{rf} - \delta a$
4. $P_{zz} = 1 - 3\frac{n_0}{N} = C(I_+ - I_-)$





Error Estimates

- (a) Natural distribution (4%)
- (b) RF Saturation (9-12%)
- (c) Proton RF (4-6%)



Summary

Uncertainty Minimization

- (a) Systematic Minimization Procedure
- (b) Quality Constraints
- (c) Linear Hypothesis Fitting
- (d) Account for all errors (1 TE)

Uncertainty in Tensor Polarization

- (a) Measurement Capacity
- (b) Uncertainty Large But Real (Set a Range)
- (c) Tests to Come