

Adiabatic Fast Passage Spin Manipulation Measurements in Solid Polarized Targets

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b1/Azz Tensor Collaboration Meeting



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Why AFP? Polarized Targets in Nuclear Physics

Motivations for AFP

Tensor polarization manipulations — spin-1

targets require controlled reversal of both vector and tensor polarization components

Reduce systematic uncertainty in asymmetry

extraction — frequent fast reversals keep beam conditions and detector acceptance matched between $+P$ and $-P$ data sets

AFP vs. DNP: the process

DNP polarization reversal: **hours** per flip

AFP coherent inversion: **0.1–0.5 s**

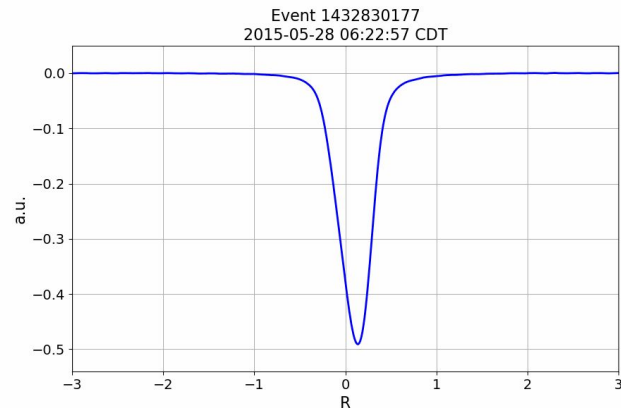
RF frequency swept through NMR resonance

[More About AFP in Devin's talk on Thursday](#)

This paper: [arXiv:2604.02365](https://arxiv.org/abs/2604.02365)

1. AFP efficiency **survey** – five materials
2. **New** joint spin-1 lineshape analysis

System: 5 T / 1 K polarized-target lab
University of Virginia



AFP: Rotating Frame and Adiabaticity

External field contains rf field

$$\vec{H} = H_0 \hat{z} + H_1 \cos(\omega t) \hat{x} + H_1 \sin(\omega t) \hat{y}$$

Effective field in rotating frame

$$\vec{H}_e = \left(H_0 + \frac{\omega}{\gamma} \right) \hat{z}_r + H_1 \hat{x}_r$$

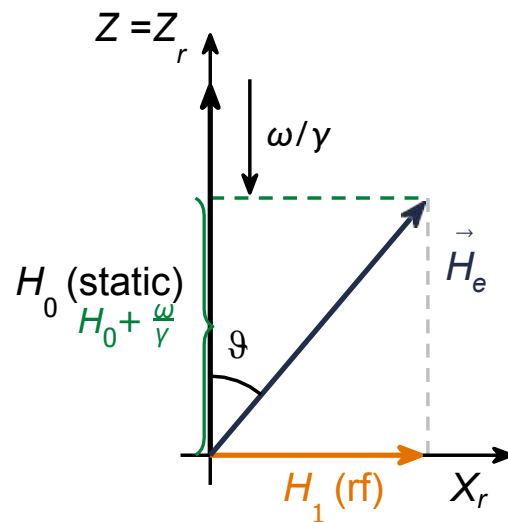
Larmor frequency: $\omega_0 = -\gamma H_0$

Adiabaticity [*Phys. Rev. B* **46**, 6596 (1992)]

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

Fast (faster than relaxation): $\tau \ll T_{1\rho}$

“the passage results in a reversal of the magnetization direction with little loss of its magnitude”



Hautle, ETH thesis (1993);
Abragam, *Principles of Nuclear Magnetism* (1961)

Experimental Apparatus: UVA 5 T / 1 K System

System components

Superconducting solenoid: $B_0 = 5$ T

^4He evaporation refrigerator: $T \approx 1$ K

Microwave system for DNP

Series-tuned LCR Q-meter NMR

NMR frequencies at 5 T

Nucleus	Frequency
^1H	≈ 213 MHz
^2H	≈ 32.7 MHz

Two target cups

Small cup (~ 1 g): reduced coupling,
precision studies

Large cup (~ 7 g): production scale;
radiation damping may appear

AFP RF chain

R&S generator \rightarrow LZY-1X+ amplifier
 \rightarrow directional coupler \rightarrow coil

Sweep: $\Delta f = 400$ kHz, $\tau = 0.1\text{--}0.4$ s

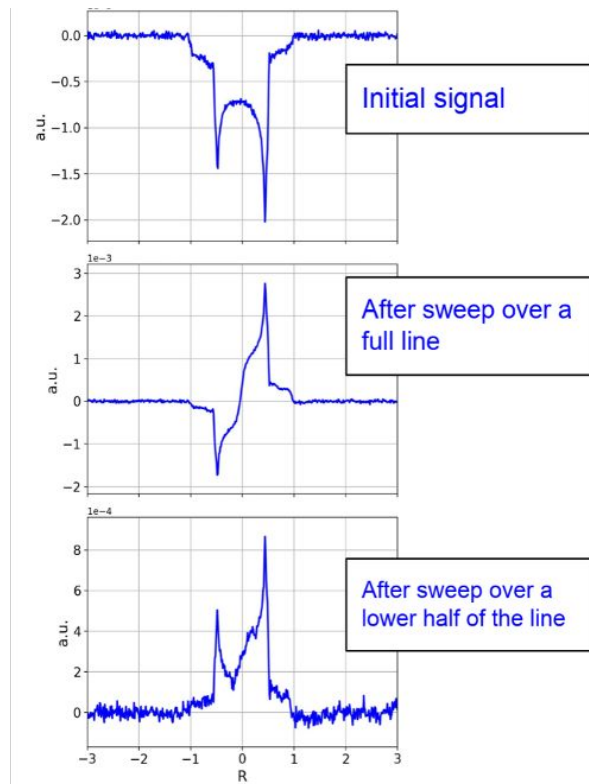
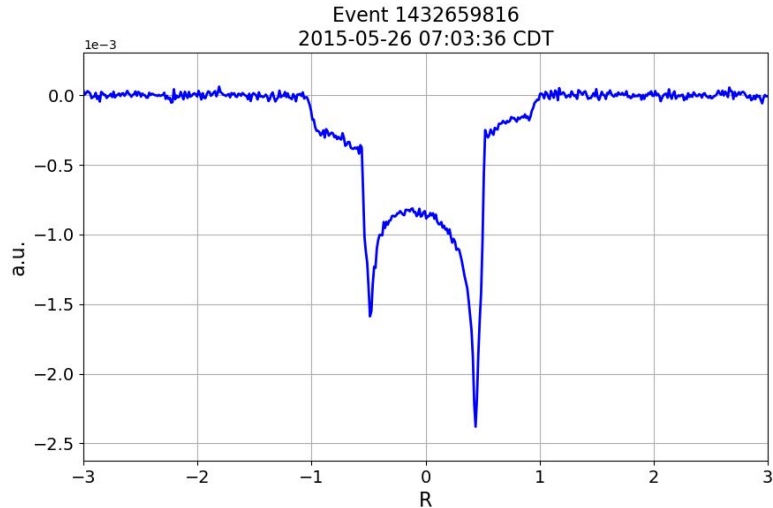
Required $Q \lesssim 80$

Three-Step Sweep: Required Sequence for Deuteron AFP

Required sequence (Hautle 1991)

1. **State 1:** initial $+P$
2. **Full sweep:** intermediate hole-burned state
3. **Half-sweep:** fully inverted $-P$

Total: **1.5 passes** through 400 kHz band



Target Materials

Irradiated $^{15}\text{NH}_3$ and $^{14}\text{ND}_3$

- ▶ Electron irradiation at NIST-MIRF (14 MeV, $10\ \mu\text{A}$, fluence $\sim 10^{17}\ \text{e}^-/\text{cm}^2$)
- ▶ Warm ($\sim 87\ \text{K}$) irradiation \rightarrow NH_2 radicals
- ▶ Radical density $\sim 10^{19}$ spins/g

Butanol-based materials

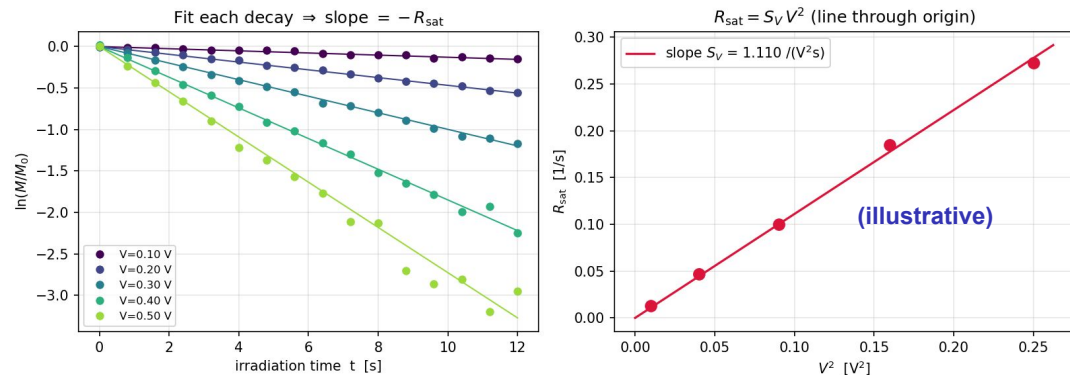
- ▶ TEMPO-doped n-butanol and deuterated butanol
- ▶ Irradiated deuterated butanol
- ▶ TEMPO density: 2.2×10^{19} spins/g

Five materials studied

Material	Nucleus
Irradiated $^{15}\text{NH}_3$	^1H
Irradiated $^{14}\text{ND}_3$	^2H
n-butanol + TEMPO	^1H
D-butanol + TEMPO	^2H
Irrad. D-butanol	^2H

From B₁ Calibration to AFP Efficiency Optimizations

[Goldman et al., 1968]



R_{sat} — from the semi-log slope (left)

$$\ln \frac{M(t)}{M_0} = -R_{\text{sat}} t \Rightarrow R_{\text{sat}} = -(\text{slope}).$$

One fit per drive voltage V .

B_1 — frequency sweep

Absolute (nuclei = probe, no coil constant):

$$B_1 = \sqrt{\frac{R_{\text{sat}} |f|}{2\pi^2 n \bar{\gamma}^2}} = \sqrt{\frac{R_{\text{sat}} \Delta f_{\text{pp}}}{2\pi^2 \bar{\gamma}^2}}$$

Estimate: Get initial B_1

Optimize: Fix df/dt + Vary B_1 vs A

[Hautle, ETH thesis (1993) §4.3.4]

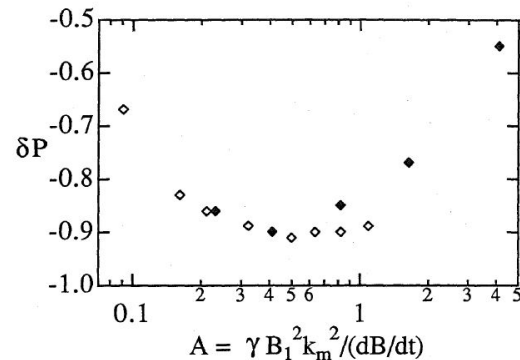


Figure 5.6: To achieve an optimum efficiency, it is favourable to keep the sweep rate constant and to adjust the rf field strength (open diamonds: $dB/dt = 0.23$ T/s, B_1 variable), rather than the opposite way (full diamonds: dB/dt variable, $B_1 = 0.32 \times 10^{-4}$ T).

Joint Manipulated-Lineshape Analysis

Fitting procedure

- ▶ **Dulya-type lineshape** fitted independently to the I^+ and I^- transitions
- ▶ I^+ and I^- extracted from **separate fits**
⇒ avoids coupling between components
- ▶ **Linear background** ($B + B_1 x$) included in each fit
- ▶ Noise σ : select tail points $|R| > 4$, subtract linear baseline, compute RMSD; assign uniformly to **all** data points

Calibration constant C

Determined from the **final ten pre-AFP** thermal-equilibrium spectra; each gives C_k :

$$C = \frac{\sum_k C_k / \sigma_k^2}{\sum_k 1 / \sigma_k^2}$$

$$P = C(I^+ + I^-), \quad Q = C(I^+ - I^-)$$

Reference: Hautle *et al.* [*NIM A* **356**, 108 (1995)] at 2.5 T

Table 1
Results from AFP experiments with various nuclei in different target materials

Nuclei	Substance dopant	e^- conc. (spins/g)	δP^{\max}
^1H	1-butanol EHBA-Cr(V)	2.0×10^{19}	-0.76
^7Li	^7LiH	low	-0.90
^1H	(irradiated)		-0.90
^{19}F	8-fluoro-1-pentanol	1×10^{20}	-0.37
^1H	TEMPO		-0.40
^2H	1-butanol- d_{10} EHBA-Cr(V)- d_{22}	2.36×10^{19} 6.35×10^{19}	-0.92 -0.90

Hautle *et al.*: Key observations

^2H reaches $|\delta P|^{\max} = 0.90\text{--}0.92$ at much lower A than ^1H

^1H (TEMPO): $|\delta P|^{\max} = 0.40$

UVA vs. Hautle

Hautle: 2.5 T, field sweep

UVA: **5 T**, frequency sweep

UVA adds NH_3 and extends to larger (7 g) targets (**First AFP study of NH_3**)

AFP Efficiency Survey Across Materials at UVA

Material	Nucleus	Paramagnetic centers	Spins/g	ϵ	$\delta\epsilon$	Cup	$P_i(\%)$
Deuterated butanol + TEMPO	^2H	TEMPO	2.2×10^{19}	0.77	0.03	7 g	0.35
n-butanol + TEMPO	^1H	TEMPO	2.2×10^{19}	0.38	0.04	1 g	0.82
Irradiated deuterated butanol	^2H	Irradiation	warm dose	0.80	0.03	7 g	0.36
Irradiated $^{14}\text{ND}_3$	^2H	Irradiation	warm dose	0.88	0.02	1 g	0.22
Irradiated $^{15}\text{NH}_3$	^1H	Irradiation	warm dose	0.48	0.04	7 g	0.92

Clear trend

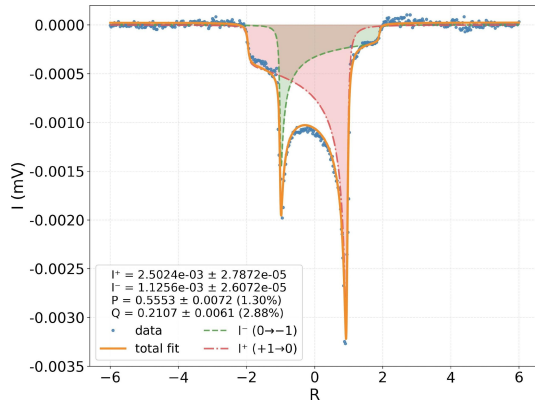
Deuteron materials: $\epsilon \sim 0.77\text{--}0.88$

Proton materials: $\epsilon \sim 0.38\text{--}0.48$

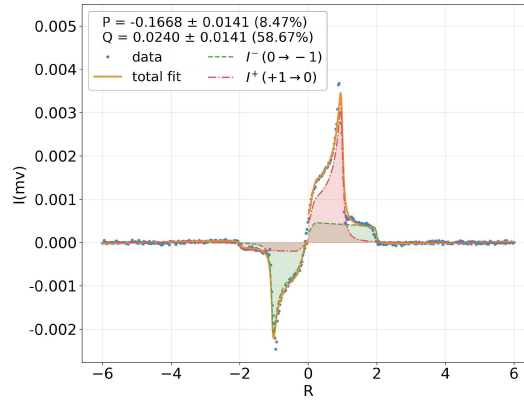
ND_3 best performer ($\epsilon = 0.88$, 1 g cup)

(First AFP study of $^{15}\text{NH}_3$)

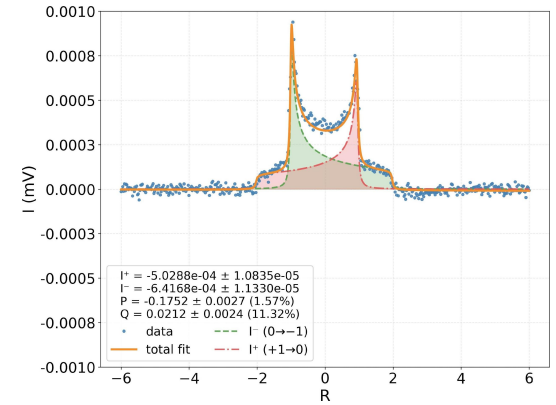
AFP Lineshape Evolution: Irradiated Deuterated Butanol



(a) **Initial equilibrium.**
Calibration constant C set here.

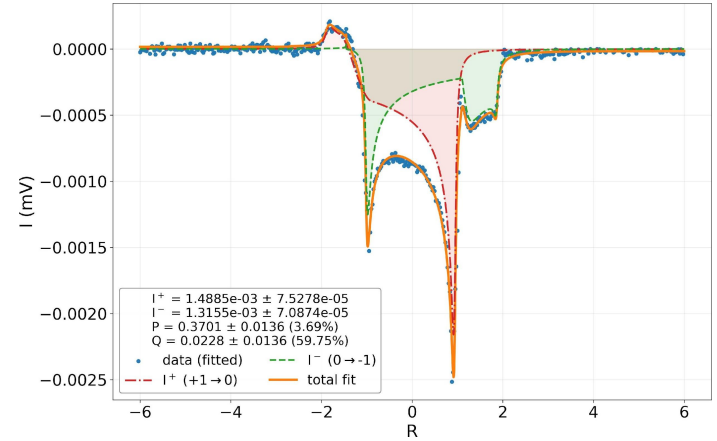
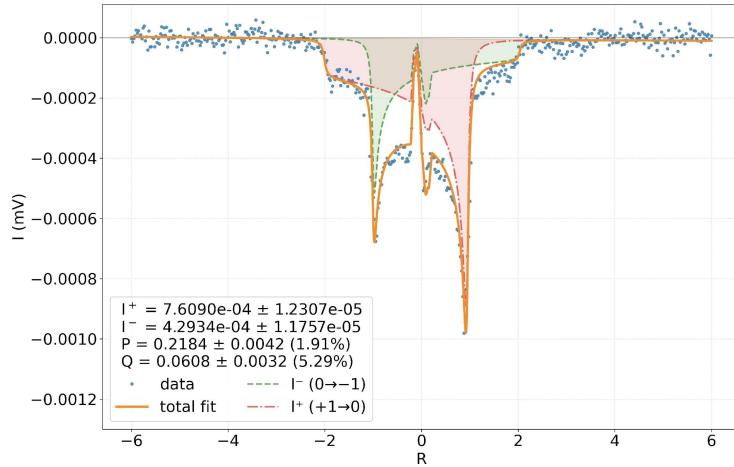


(b) **Intermediate state** after full sweep.



(c) **Fully inverted** after subsequent half-sweep.

Hole Burning and Rates-Response Mechanism



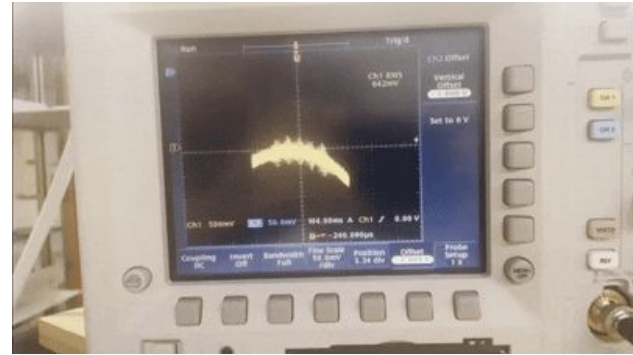
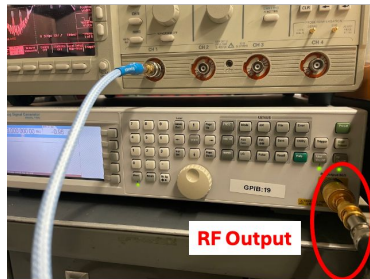
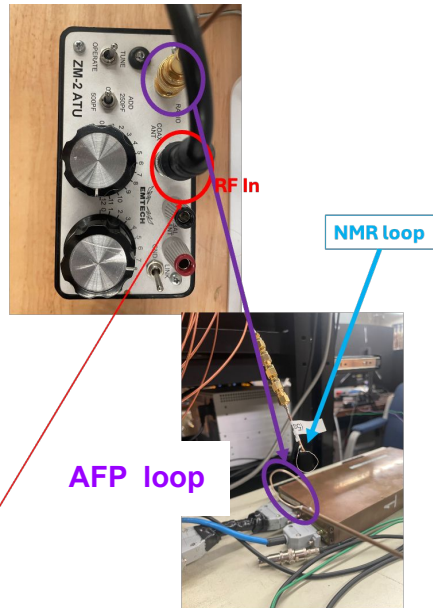
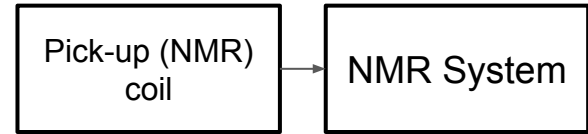
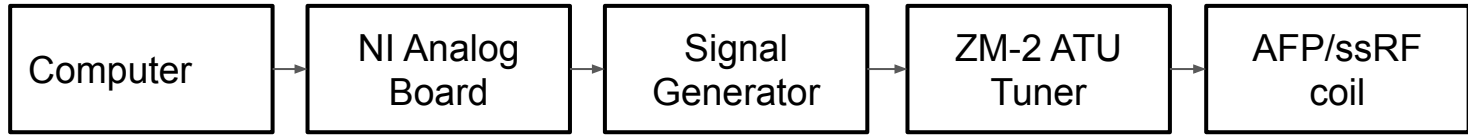
Hole burning in irradiated D-butanol. Narrow dip near $R \lesssim 0$ from unintended RF irradiation after sweep end (generator spur).

Pedestal AFP with hole burning on left pedestal. Demonstrates the rates-response equation.

Rates-response confirmed [Clement & Keller, *NIM A* **1050**, 168177 (2023)]

Depletion of one transition \Rightarrow compensating enhancement in the other at mirrored frequency with **half** the depleted area

RF modulations on NH3 Baseline (A crude modulation Example)



With AFP mod frequency 400 kHz
sweep time: 1 sec; total seeps =5

Conclusions and Ongoing Work

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Summary [arXiv:2604.02365 \(2026\)](https://arxiv.org/abs/2604.02365)

1. **Efficiency survey:** AFP efficiency
 - a. $\epsilon \sim 0.77\text{--}0.88$ for ^2H
 - b. and $\epsilon \sim 0.38\text{--}0.48$ for ^1H
2. **Joint lineshape analysis:** extracts P and Q from AFP-manipulated spin-1 spectra without Boltzmann assumption
3. Hole burning and rates-response mechanism quantitatively confirmed

Ongoing work

Repeat and optimize AFP measurements at the UVA lab

AI-based polarization extraction: Seay, Fernando & Keller, arXiv:2603.10146 (2026)

Contribute to JLab and Fermilab experiments regarding AFP, alongside continued AFP studies at UVA

Thank you!

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