RF techniques for enhancing tensor polarization in solid targets

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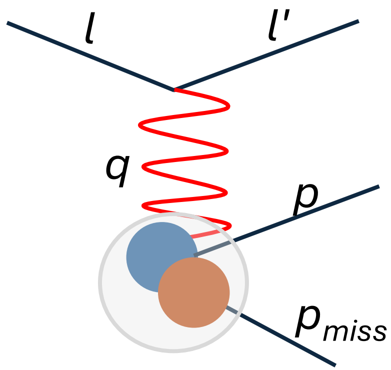
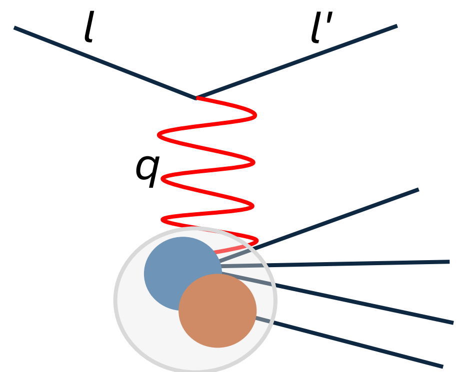
Physics Motivation: Tensor Measurements

Solid Targets = Spin-1 (ND_3)

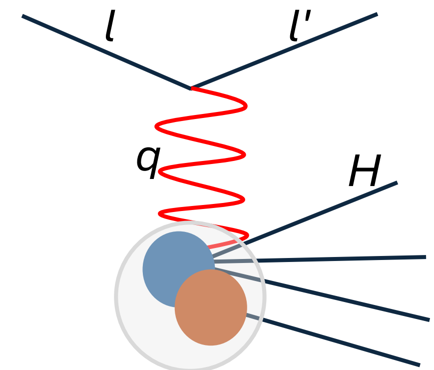


Quasielastic Scattering:
Understanding Nucleon-Nucleon repulsion



DIS: Tensor structure functions
QCD effects

Current cases of active study in UNH

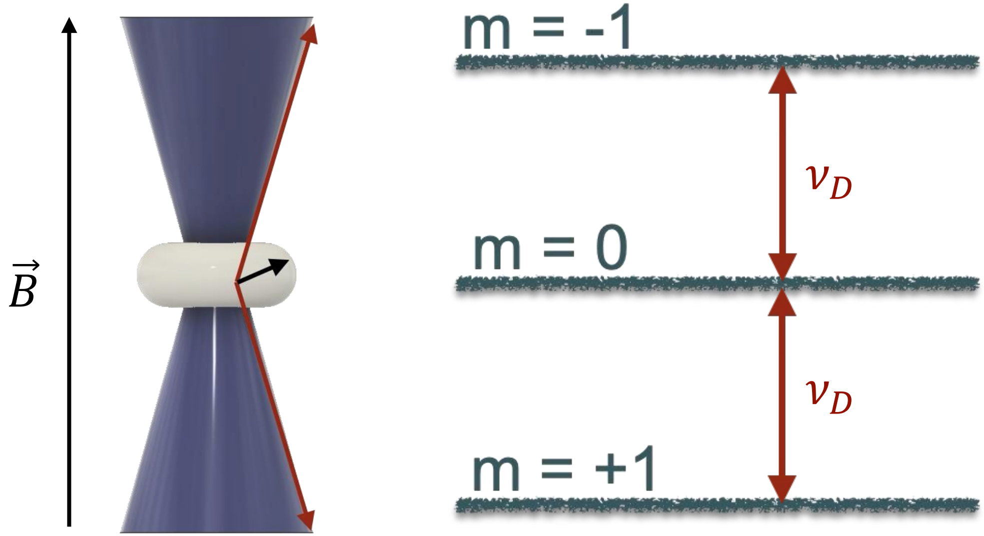


SIDIS: Tensor structure functions
Novel information about the interplay between QCD and nuclear structure.

- **Strong collaboration:** UNH, UVa, JLab, FIU, UCAM, U. Pavia, ORNL, Universidad Técnica Federico Santa María, among others.
- **Seeking more collaborators:** The Tensor program is a large project.
- More tensor physics could be possible (DVCS, real photons, etc)

What do we need? Large tensor polarization

Spin-1 Polarization



Spin-1 in a magnetic field

•3 sub-levels (+1, 0, 1) due to Zeeman interaction.

•Two energy transitions I_+(+1↔ 0) and I_- (0 ↔ -1).

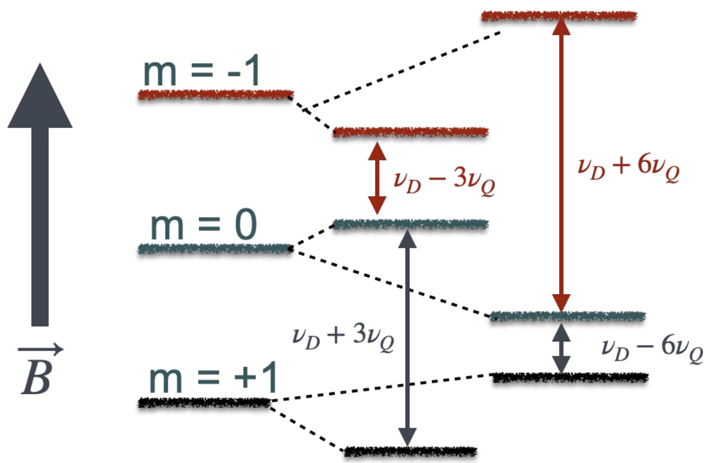
$$\nu_D = \frac{\mu_D B}{h}$$

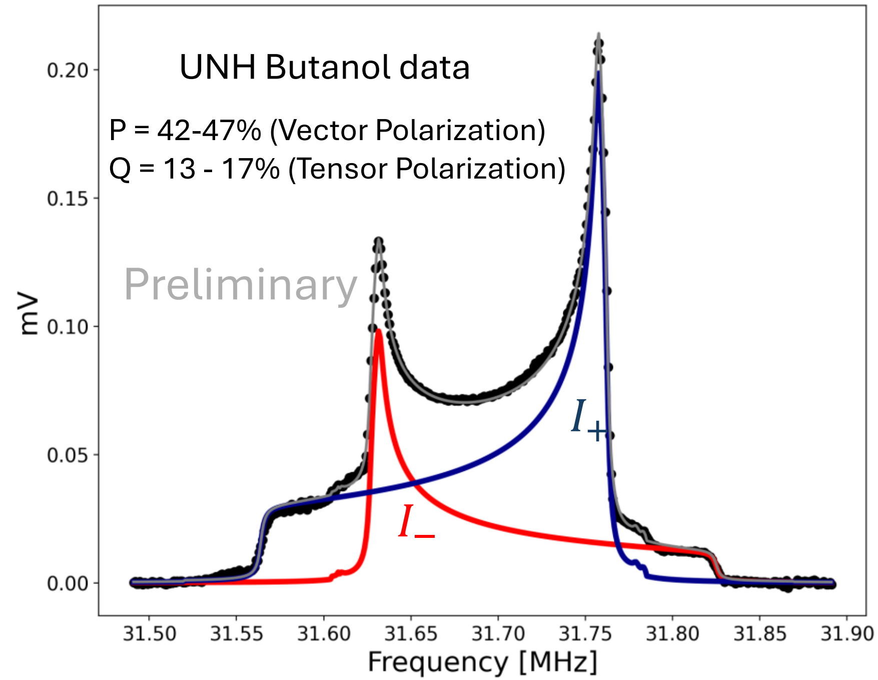
$$\nu_D = 6.54 \text{ MHz/T}$$

Spin-1 Polarization

$$E_m = -h\nu_D m + h\nu_Q(cos^2\theta - 1)(3m^2 - 2)$$

eQ:	Electric quadrupole interaction (shifts the energy levels)
eq:	Electric field gradient
θ:	angle between eq and eQ





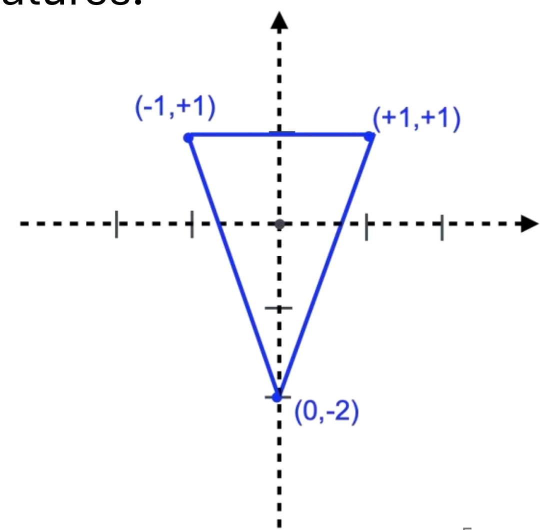
Enhancing Vector Polarization with DNP

- At thermal equilibrium (B = 5 T and T = 1 K), the vector polarization is P ~0.1%
- Dynamic Nuclear Polarization (DNP) enhances the vector polarization to up to 50% in deuterated butanol and deuterated ammonia. In short, paramagnetic centers in the material, either chemically doped or irradiated, induce spin transitions through the application of microwaves to the sample, which is already in a magnetic field at very low temperatures.

Vector Polarization:
$$P = N_+ - N_-$$
$$-1 < P < +1$$

Tensor Polarization:
$$\mathrm{Q} = N_+ + N_- - 2N_0$$
$$-2 < Q < +1$$

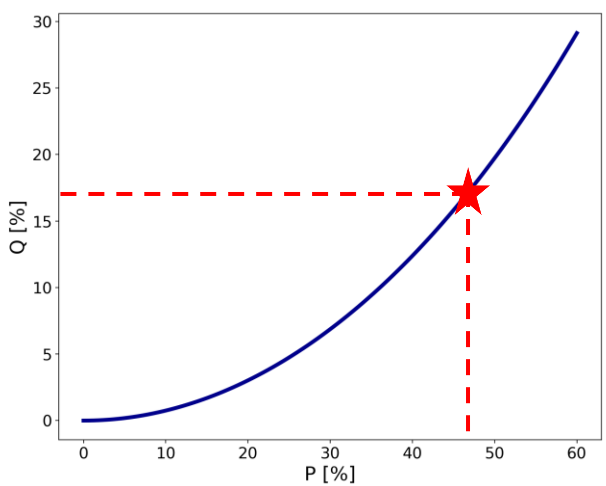
Normalization:
$$1 = N_+ + N_- + N_0$$



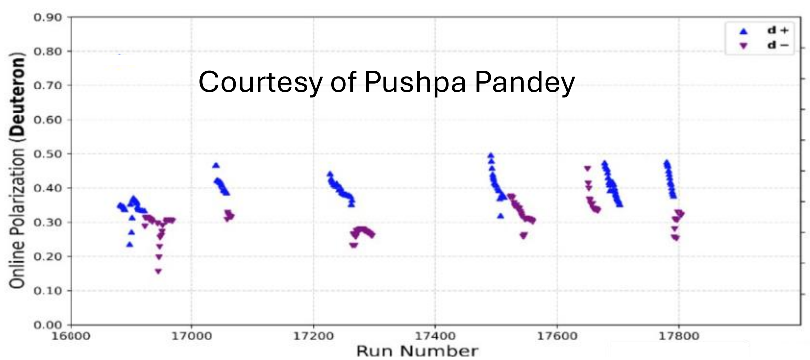
Can we perform an experiment with this technique?

- Target material used in tensor polarized techniques: deuterated ammonia (ND_3)

- After DNP, Vector and tensor polarizations are related as: $Q = 2 - \sqrt{4 - 3P^2}$

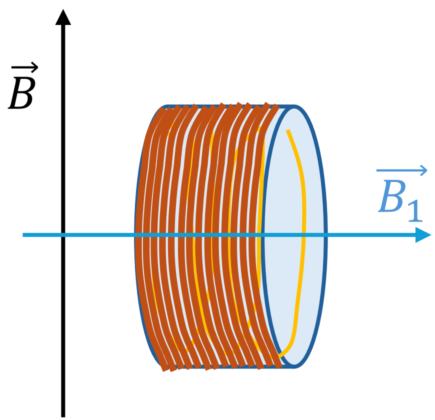


Tensor polarization with DNP is at best 15 – 20% and decays with dose (under electron beam).



Need additional techniques to enhance the tensor polarization

Enhancing tensor polarization: RF "hole burning"



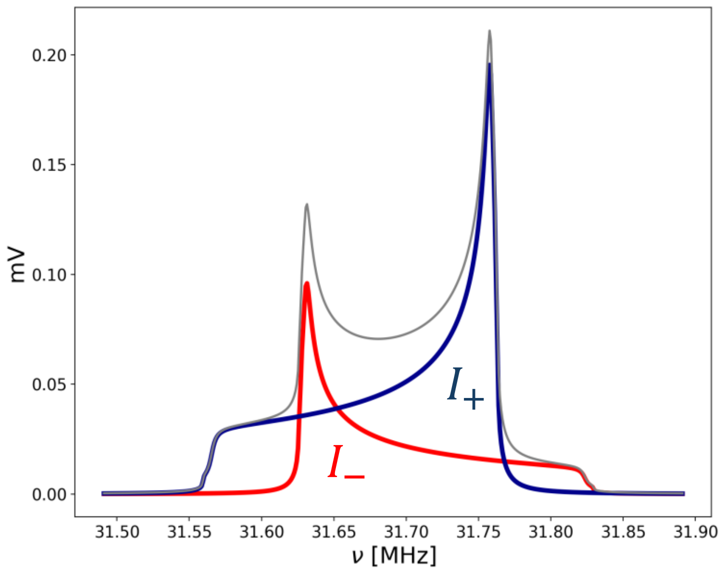
- $\vec{B}$: Holding field
- $\overrightarrow{B_1}$: RF field perpendicular to the holding field.
- ν_{RF}: RF frequency
- $h\nu_{RF}$ energy levels will be in saturation.
- The intensity of the NMR around ν_{RF} will decrease.
- If $P > 0$:
  - burning a hole in the (0↔-1) transition decreases the m = 0 population, which increases Q.
  - burning the (1 ↔ 0) transition increases the m = 0 population , which decreases Q.

it is not possible to saturate one deuteron transition without also saturating the other, which dilutes the effect. The only exception to this is the pedestal regions of the NMR line (shoulders).

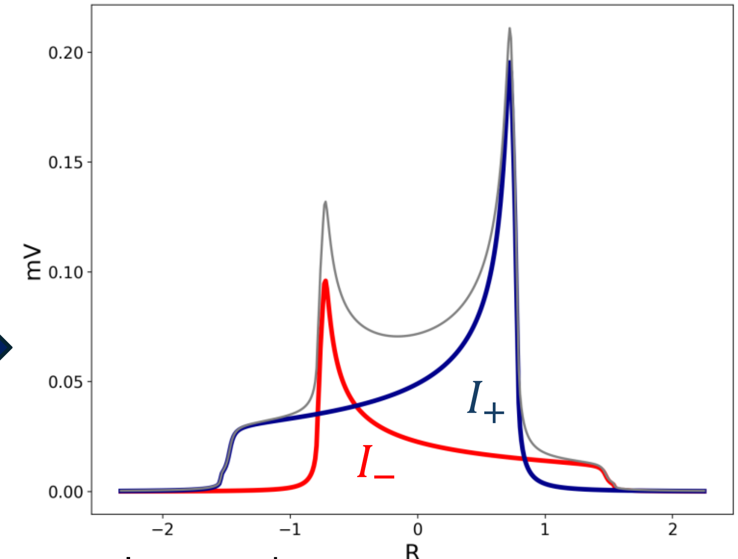
Assume we start from:

$P = 0.45$ and $Q = 0.16$

$N_+ = 0.585, N_- = 0.135, N_0 = 0.28$



$$R = \frac{\nu - \nu_D}{\nu_Q}$$



Simulation

Note UNH data with Butanol has two bonds.

See M. McClellan talk

In general:

$I_+ \propto [1 - R]^{-\frac{1}{2}}$ where $-2 \le R \le 1$

$I_- \propto [1 + R]^{-\frac{1}{2}}$ where $-1 \le R \le 2$

$$N_+ - N_0 = C \int_{-2}^{1} [1 - R]^{-\frac{1}{2}} \mathrm{dR}$$

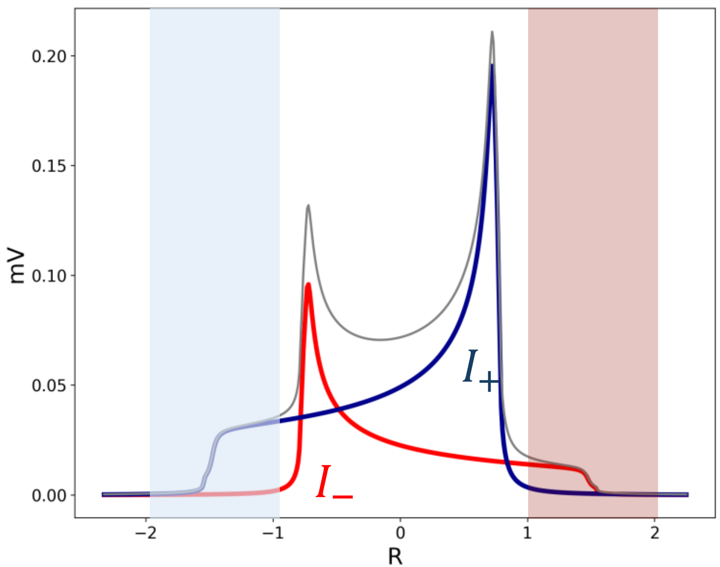
$$N_0 - N_- = C \int_{-1}^{2} [1 + R]^{-\frac{1}{2}} \mathrm{dR}$$

Assume we start from:

$P = 0.45$ and $Q = 0.16$

$N_+ = 0.585, N_- = 0.135, N_0 = 0.28$

If we burn the pedestal:



Burning any of the two pedestals will decrease P

Burning the pedestal of I_- has an increment of Q

I_- pedestal (from $1 \le R \le -2$):

Almost no effect in I_+

The fraction of burned signal would be:

$$f_- = \frac{\int_1^2 [1+R]^{-\frac{1}{2}} \mathrm{dR}}{\int_{-1}^2 [1+R]^{-\frac{1}{2}} \mathrm{dR}} = 0.184$$

$$N'_0 = N_0 - f_- \frac{N_0 - N_-}{2}$$

$$N'_- = N_- + f_- \frac{N_0 - N_-}{2}$$

$P' = 0.42$ and $Q' = 0.20$

I_+ pedestal (from $-2 \le R \le -1$):

Almost no effect in I_-

The fraction of burned signal would be:

$$f_+ = \frac{\int_{-2}^{-1} [1-R]^{-\frac{1}{2}} \mathrm{dR}}{\int_{-2}^{1} [1-R]^{-\frac{1}{2}} \mathrm{dR}} = 0.184$$

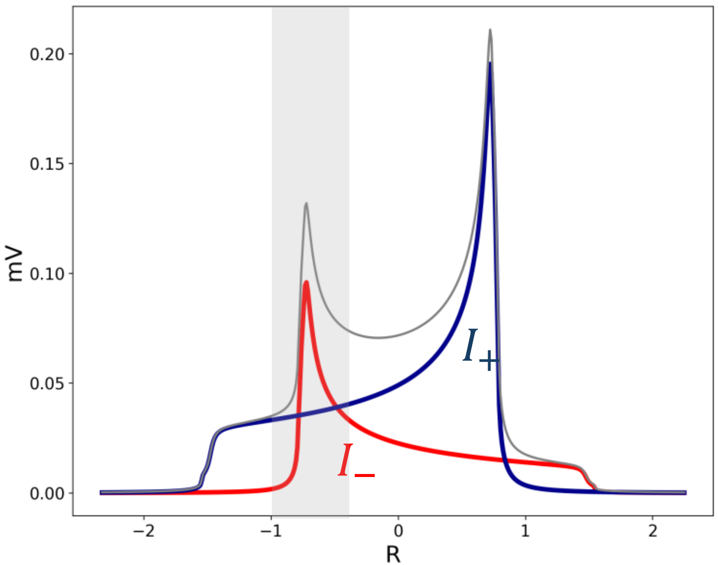
$$N'_+ = N_+ - f_+ \frac{N_+ - N_0}{2}$$

$$N'_0 = N_0 + f_+ \frac{N_+ - N_0}{2}$$

$P' = 0.42$ and $Q' = 0.076$

Assume we start from:
$P = 0.45$ and $Q = 0.16$
$N_+ = 0.585, N_- = 0.135, N_0 = 0.28$

If we burn the peak:



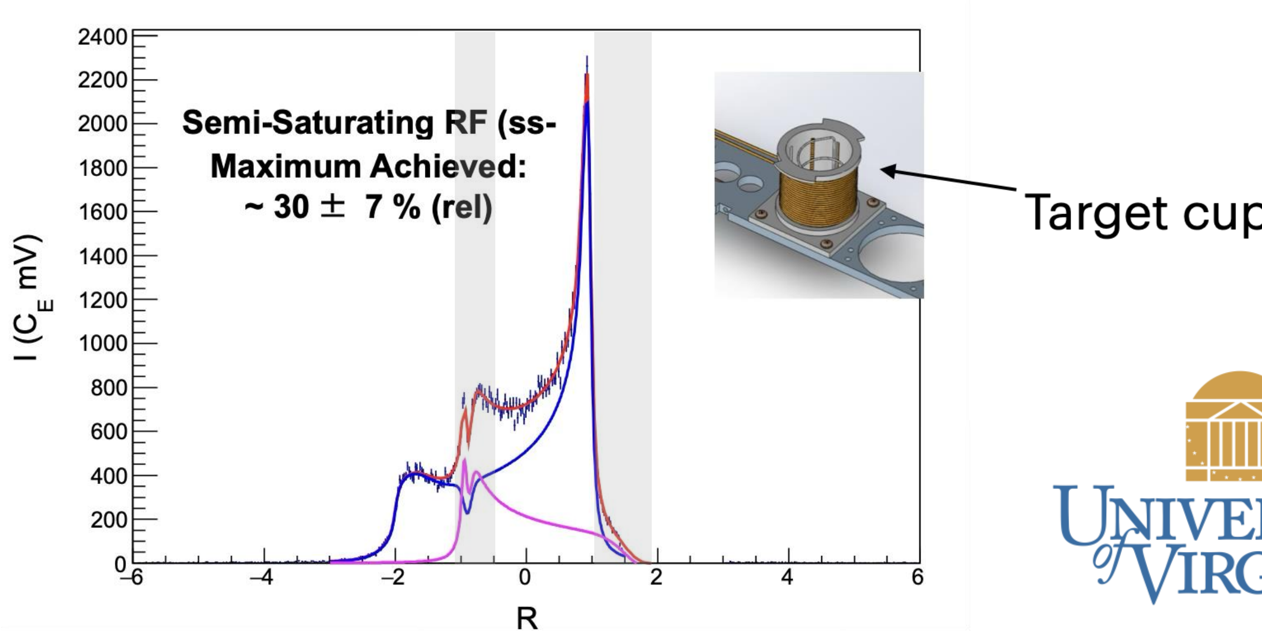
It will have an effect in both I_+ and I_-

To understand the effect:

- Estimate the fractions of burned signal f_+ and f_-
- Estimate the new populations: N'_+, N'_- and N'_0
- Estimate P' and Q'

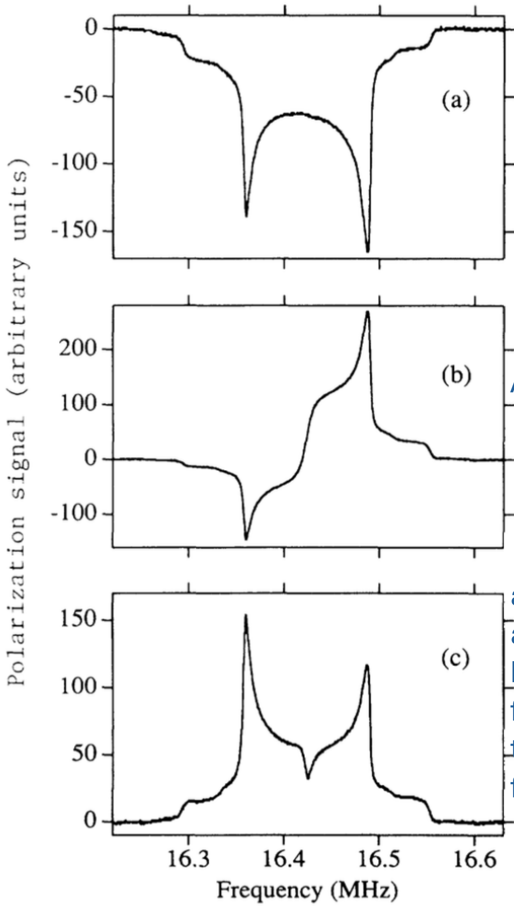
Typically, the vector polarization decreases and the tensor polarization increases up to 20 -22% depending on the initial polarization.

Other Techniques: semi-selective RF (ss-RF)



D. Keller Eur. Phys. J. A53 (2017)

Adiabatic fast passage (AFP)



Initial State

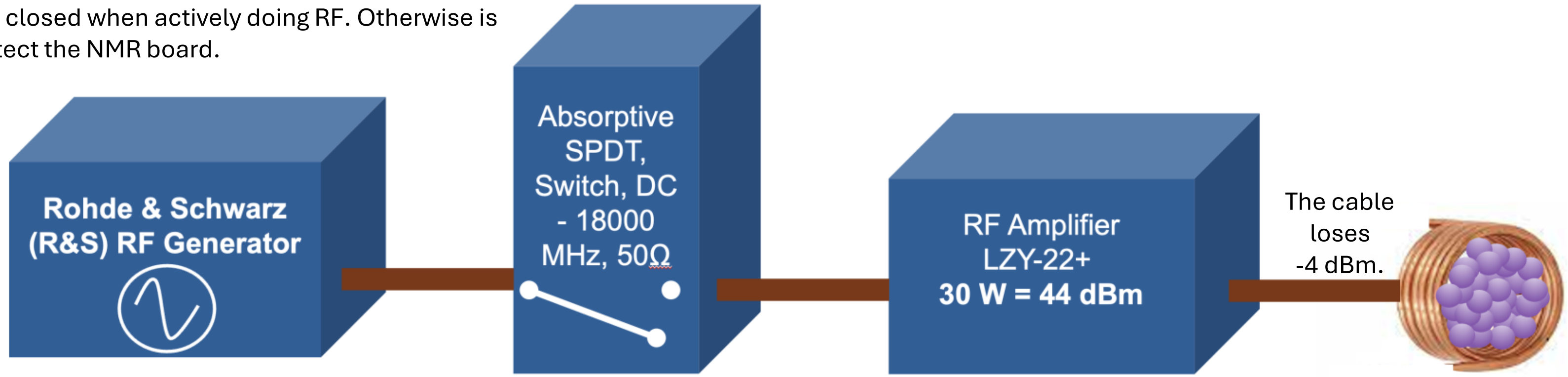
After one sweep

after an additional half-sweep from the low to the center frequency

- Polarization direction of nuclear spins can be rapidly reversed
- B_1 is swept one and a half through the resonance frequency of the nuclear spins
- sweep rate should be faster than the longitudinal relaxation rate T_1, but slower than the transverse relaxation rate T_2.
- Not yet tested in UNH.

RF Configuration at UNH

Switch is only closed when actively doing RF. Otherwise is closed to protect the NMR board.

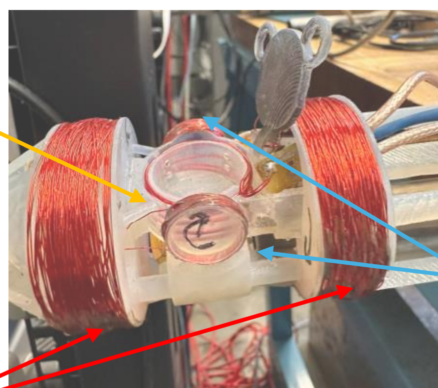


The cable loses -4 dBm.

The switch loses -1 dBm.

Current configuration

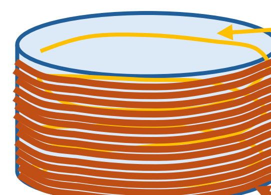
NMR coils



RF coils

EPR coils
Currently not in use

Next configuration

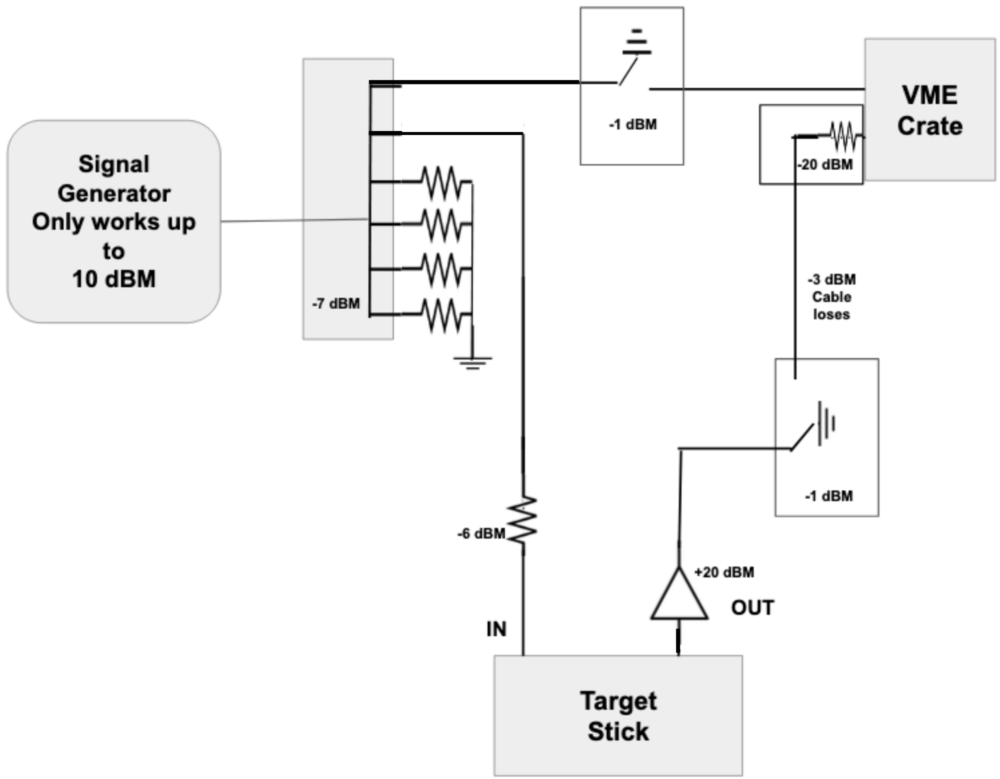


NMR coils inside the cup

See A. Zec talk

- Uniform RF around the target cup
- Test AFP

A few words about our NMR system

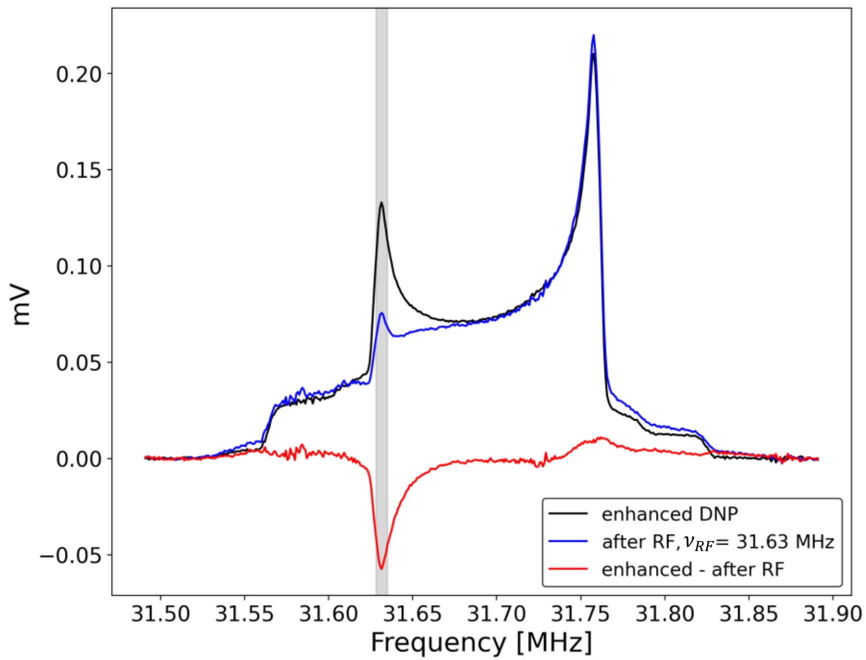


P. Mcgaughey, NIM Volume 995, 11 April 2021, 165045

- NMR system is LANL developed Q-Meter equivalent
- Shown are the losses or gains in the line due to the different components.
- The VME and the signal generator can be very sensitive to the power of the RF.
- Switches are opened when actively performing RF manipulation.
- The DAQ process is still quite manual when switching between RF and NMR; it requires just a click.

Most recent results

(less than a week ago)



The plots show the lineshape of the NMR after subtracting the baseline and the wing fit, with no further manipulation.

- Maintained high (> 40%) vector pol. while holeburning!
- RF applied to a central frequency 31.63 MHz, on the peak
- Power estimated on target 30 dBm
- Red Area (enhanced – after RF)

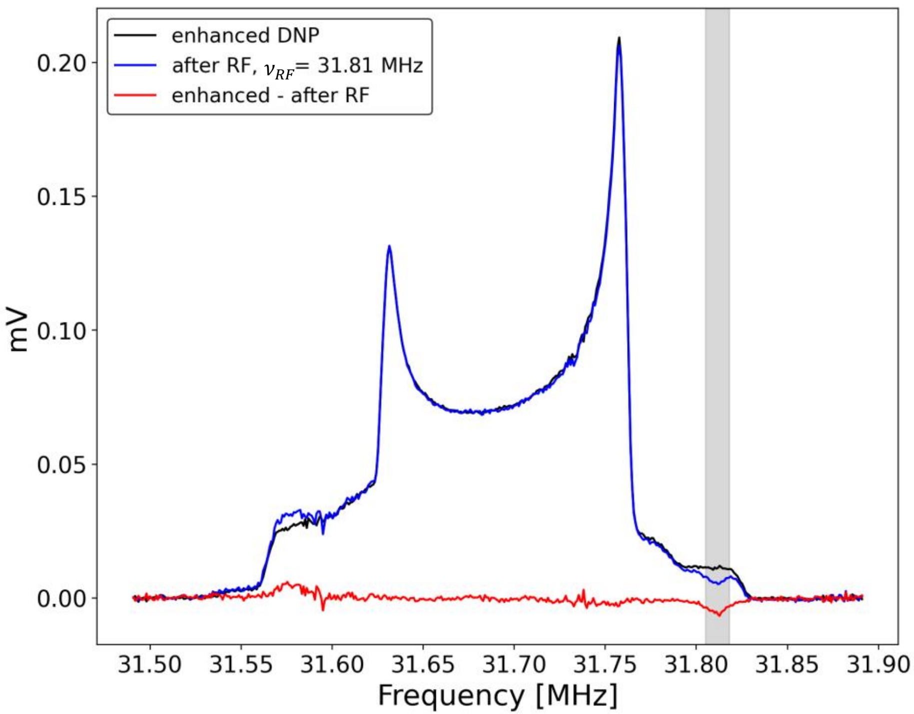
Preliminary

$$A_- = 0.55\, A_+$$

What is the Tensor polarization?
Analysis is ongoing

Most recent results

(less than a week ago)



The plots show the lineshape of the NMR after subtracting the baseline and the wing fit, with no further manipulation.

- Maintained high (> 40%) vector pol. while holeburning!
- RF applied to a central frequency 31.81 MHz, on the shoulder
- Power estimated on target 30 dBm
- Red Area (enhanced – after RF)

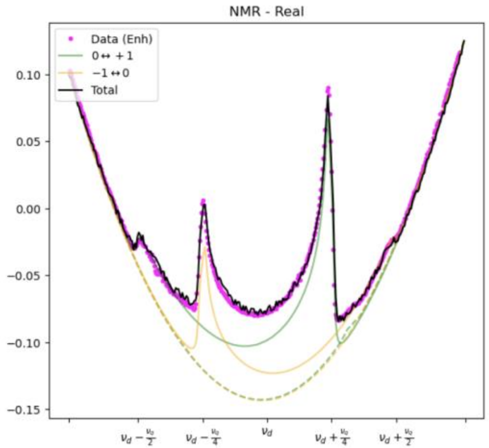
Preliminary

$$A_- = 0.6\, A_+$$

What is the Tensor polarization? Analysis is ongoing

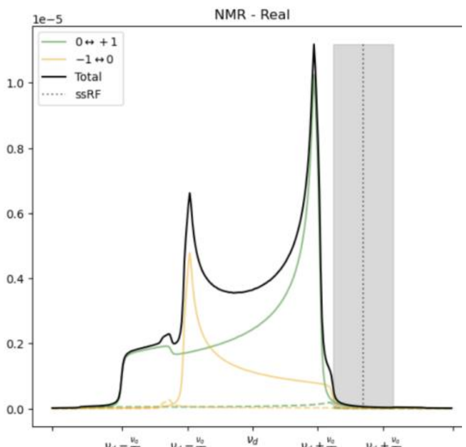
Simulation of Hole-Burned Signal

UNH Data vs. Simulation

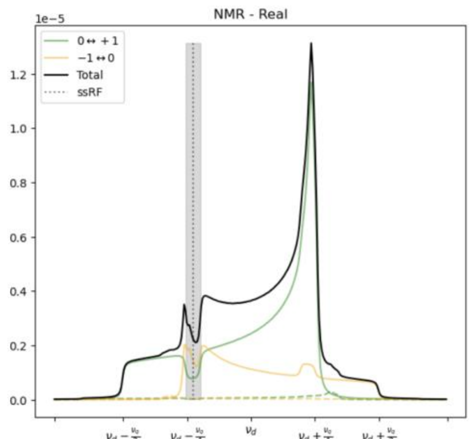


- Simulation of deuteron spin-flips seems to replicate our data very well
- Elena Long working to model hole burning effects with simulation

See E. Long talk

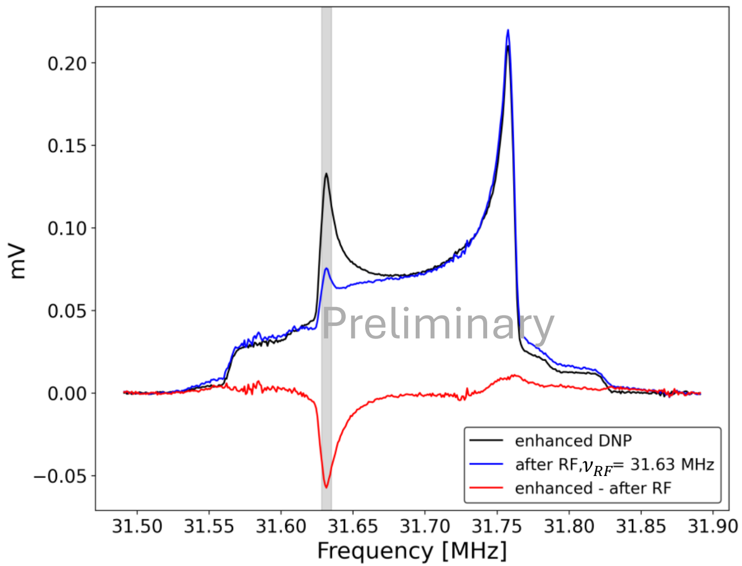


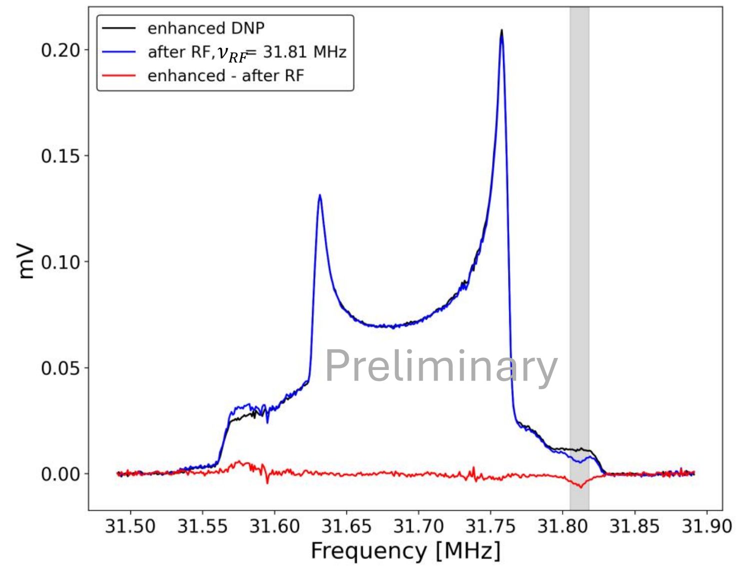
Shoulder Burn



Peak Burn

Next Steps





- Continue the data analysis to determine the tensor and vector polarization of the collected data.
- Utilize a more uniform coil configuration in the cup.
- Develop a more automated DAQ controller to simultaneously RF the shoulder and the peak, while also enabling NMR checks.
- AFP manipulation.

Professors

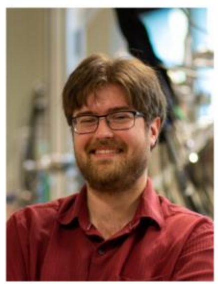

Karl Slifer


Elena Long


Nathaly Santiesteban

Postdocs


Allison Zec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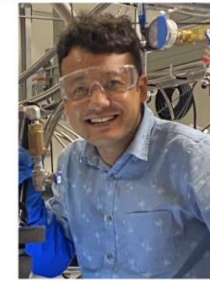
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