Polarized neutron birefringence in polarized ^{3}He and precision NMR measurements in ^{3}He SEOP cells for nuclear few body physics

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Theory Motivation and Experimental Goals

1. Three-nucleon (3N) interactions contribute ~5% of the binding energy of nuclei but are poorly constrained by experiment. This blocks nuclear theory from reliable computations of certain properties of stable nuclei and of the many new nuclei that radioactive beam facilities will create in the future. In particular, the spin dependence of 3N interactions is poorly understood.

2. We work to measure TWO new spin dependent observables in n-^{3}He s-wave scattering: the difference $\Delta b = b_{+} - b_{-}$ of the scattering amplitude in the two available spin channels (J=1/2+1/2=1, and J=1/2-1/2=0), AND the n-^{3}He spin-dependent total cross section σ_p.

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Calvin W Johnson et al 2020 J. Phys. G: Nucl. Part. Phys. 47 123001

Measurement of b_i in n-^{3}He

1. Define the "incoherent" scattering length b_i of a neutron on a nucleus of spin I as proportional to the difference $\Delta b = b_+ - b_-$ of the bound scattering lengths in spin channels J=I+/- 1/2.

$$b_i = \frac{I\sqrt{I+1}(b_+ - b_-)}{(2I+1)}$$

2. Δb measured in polarized neutron transmission through a polarized target from the phase shift $\boldsymbol{\phi}$* of the polarized neutron in the polarized medium, which is birefringent for neutrons (called "pseudomagnetic precession"):

$$\Delta b = \frac{2\phi^*}{\lambda P_3 N d} = \frac{\sigma_p}{\lambda_{th.}} \frac{2\phi^*}{\cosh^{-1} R}$$

where P_3 is the target polarization, N the target number density, d the target length, λ the neutron de Broglie wavelength (more later on last equation)

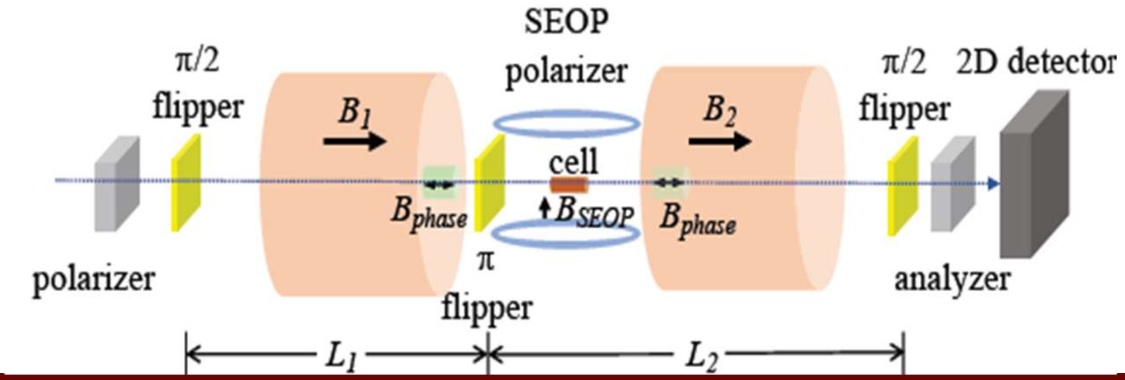
Method for b_i : Neutron Spin Echo 1

1. ^{3}He is polarized with spin-exchange optical pumping (SEOP) by polarizing an alkali vapor with circularly polarized laser light and then letting the alkali polarize the ^{3}He through hyperfine interactions.

2. Adiabatic fast passage (AFP) is used for population inversion of the ^{3}He spins. This isolates the spin-dependent phase shift due to the incoherent scattering length.

3. The neutrons are polarized by a supermirror polarizer and are rotated by 90 degrees to precess about the magnetic field of the first spectrometer arm and accumulate phase.

4. A 180-degree flip creates a coherent echo envelope downstream in the second arm. A 90-degree flip enables the phase shift from the sample to be read by polarization analysis

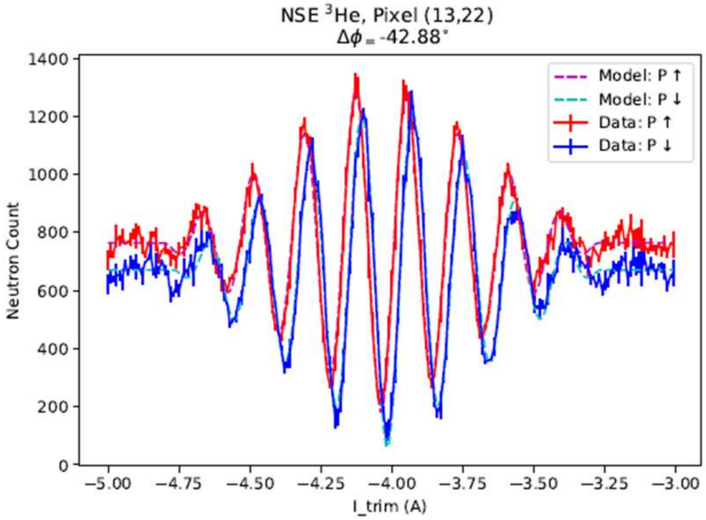


Method for b_i: Neutron Spin Echo 2

1. A phase coil is scanned in small steps around the point where the two NSE precession regions field integrals are balanced.

2. We have seen a clear spin echo envelope from our previous run.

3. This “test” measurement, done for another experiment, compares well to the two other measurements done on this before and yielded despite only several hours beam time: $\Delta b = [-5.27 \pm 0.05$ (stat.) -0.05 (syst.)] fm.



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Preliminary b_i Result: Limited by P_3 Precision

1. Neutron scattering length measurements in few-body systems are sensitive enough to probe small effects not yet adequately treated in present theoretical models.

2. Dominant error is NOT the phase shift $\boldsymbol{\phi}^*$: it is P_3

3. We have a trick to determine P_3, but the trick requires us to also measure the n-^{3}He spin-dependent total cross section σ_p.

"This work" added from: H. Lu, O. Holderer, A. Ioffe, S. Pasini, P. Pistel, Z. Salhi, B. M. Goodson, W. M. Snow, and E. Babcock, **A Complete Approach to Determine the ^{3}He neutron incoherent scattering length b_i,** Phys. Rev. C **108**, L031001 (2023). arXiv:2303.07031

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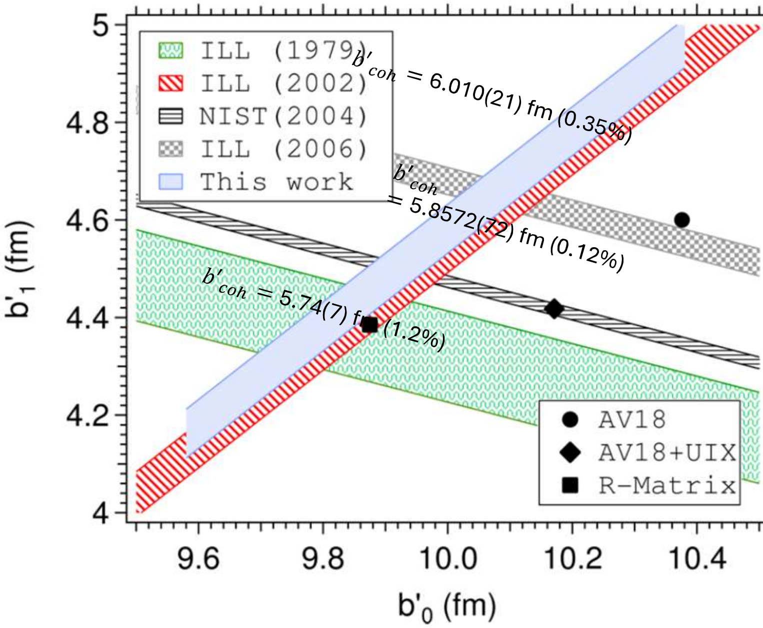

How to Determine both b_i and σ_p

- For b_i one must determine the product $P_3 Nd\lambda$ with high precision.

- The transmission ratio $T(P_3)/T(0)=\cosh[\sigma_p P_3 Nd\lambda/\lambda_{th}]$ can be measured very accurately and would give us what we need, IF σ_p was known well enough

- $\sigma_p = \sigma_p$ [J=0] + σ_p [J=1] . σ_p [J=0] is already known, but no one has measured σ_p [J=1] . If we can measure P_3 absolutely, then $T(P_3)/T(0)$ will give us σ_p [J=1]. For a uniformly magnetized medium one can calculate the relation between internal magnetization $M_3 = \mu_3 P_3 N$ and the magnetic field B_3 : $B_3 = \mu_0 M_3 (1-2/3)$ for our geometry

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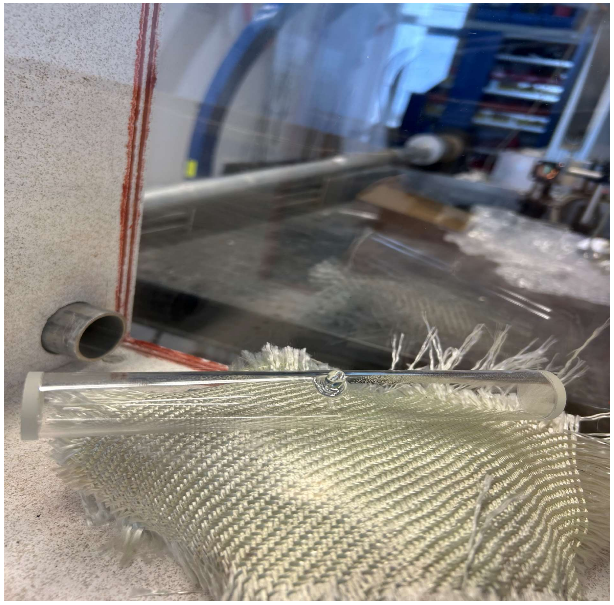
- The problem is then measuring B_3 by NMR in a cell with this calculable geometry.



B_3 Measurement

The field experienced by the ^{3}He nuclei in our particular cell geometry: $B_3 = \mu_0 M_3 (1-2/3)$

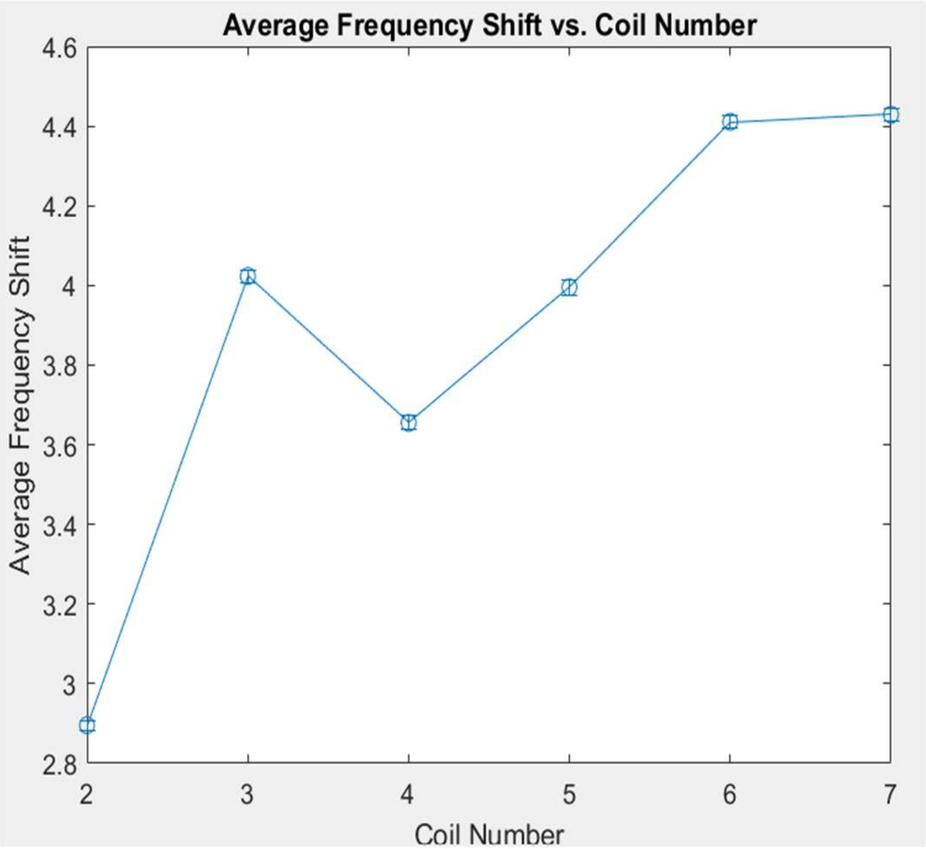
This is the field of the scalar contact subtracted from the field of a uniformly magnetized cylinder. 2% correction is made for a finite cylinder.

D/L ratio is calculable

This corresponds to a 6 Hz shift in FID frequency when the cell is 100% polarized.

B_3 Measurement

- We had 6 coils fixed across the length of the cell, and about 5000 Free Induction Decay (FID) signals were measured in the neutron run.
- The signal to noise ratio is high enough for good fits to FID pulses.
- But our frequency shifts are not the right size for the 50% ^{3}He polarization.
- We observe frequency "pulling" effects from masing.

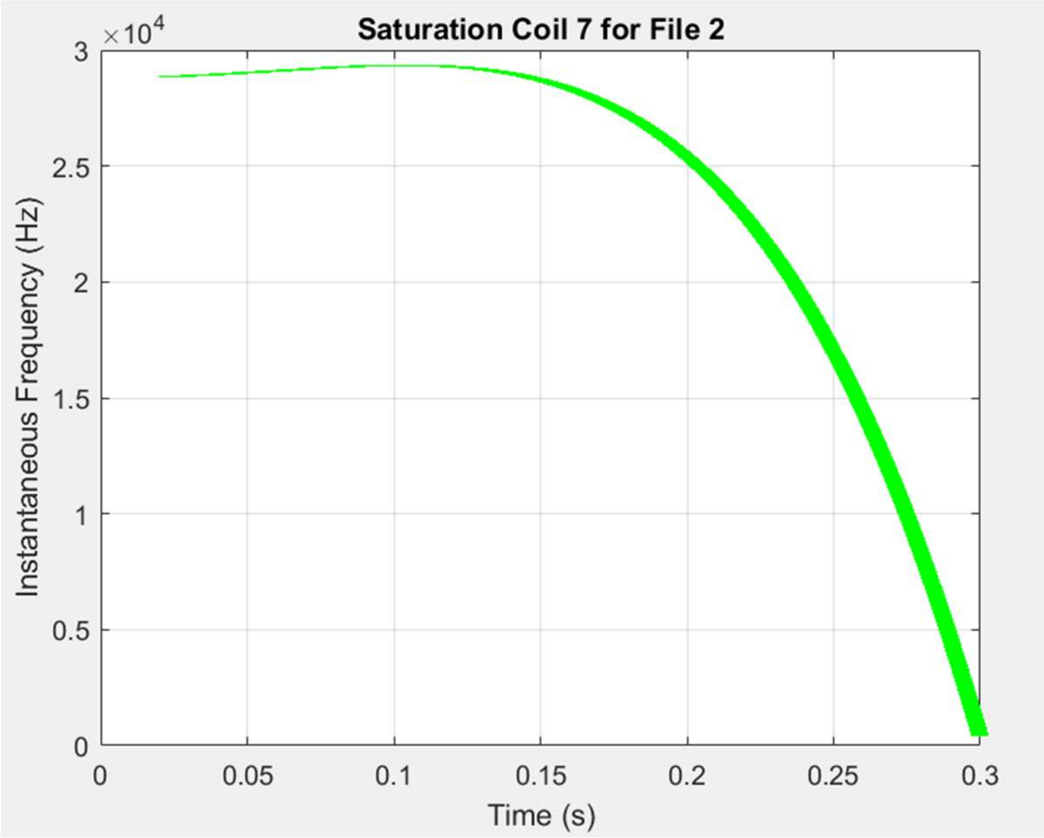


Radiation Damping (RD) Correction

- The feedback from the field of the precessing FID creates eddy currents in the FID probe, which creates an opposing oscillating magnetic field to the motion of the decaying magnetization.
- In the higher Zeeman splitting energy (masing state) the polarized helium can be treated as an impedance load coupled to the resonating circuit.
- This creates a phenomenon called “frequency pulling”.

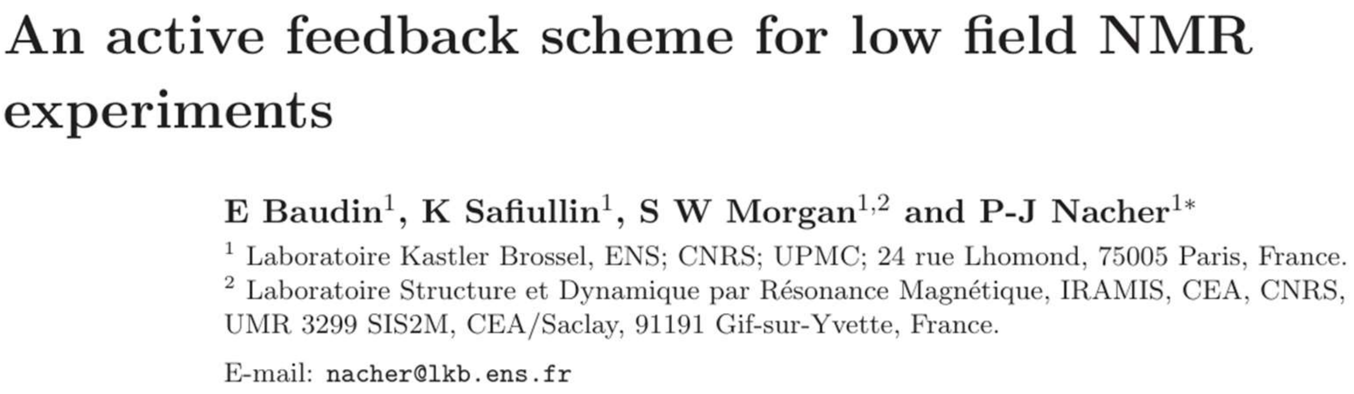
Correction for Frequency Pulling

- By carefully simulating the spin coil interaction we can correct for the effect.
- But we first need the damping parameters and initial conditions.
- We must construct an additional coil which is RD proof to check the validity of the model.
- This in turn requires active feedback, which we can do for all coils to get rid of the systematic effect once and for all and repeat the measurement.



Active feedback

- In order to combat RD we have decided to implement a well-known addition to the FID circuit.



An active feedback scheme for low field NMR experiments

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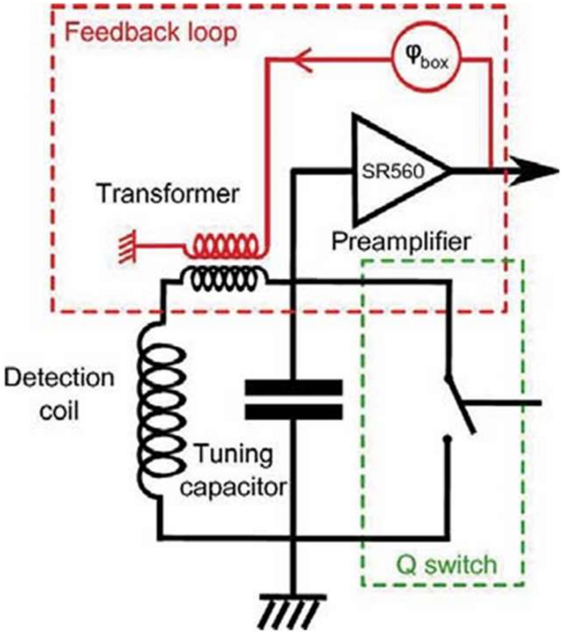
Active feedback

- The paper presents an active feedback circuit for improving low field NMR and MRI experiments, particularly for frequencies below 100 kHz.
- Reduces radiation damping without sacrificing signal-to-noise ratio (SNR)
- The scheme uses a feedback control box to adjust the phase and amplitude of the feedback signal. This is coupled to the NMR tank circuit via a small transformer.



Conclusion

1. We have shown that we can get the statistical accuracy required on ∅.
2. We have a new idea for σ_p with promising data from ISIS. The σ_p data is the dominant error in previous b_i measurements and will reduce their stated errors. σ_p is a second new few body measurement (in addition to b_i that can be the subject of theory calculation).
3. With the incorporation of active feedback system, we should be able to get rid of frequency pulling.
4. With σ_p and ∅ determined to high precision we can get b_i to 0.1% precision.
5. A proposal for repeating this measurement at ISIS in the spring will be submitted.

References

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2. H. Lu, O. Holderer, A. Ioffe, S. Pasini, P. Pistel, Z. Salhi, B. M. Goodson, W. M. Snow, and E. Babcock, **A Complete Approach to Determine the ^{3}He neutron incoherent scattering length b_i,** Phys. Rev. C **108**, L031001 (2023). arXiv:2303.07031

Thanks!

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$\boldsymbol{\sigma_p}$ & b_i

1. The σ_p data is the main cause of error in previous b_i measurements and will reduce their stated errors.

$$\Delta b = \frac{2\phi^*}{\lambda P_3 N d} = \frac{\sigma_p}{\lambda_{th.}} \frac{2\phi^*}{\cosh^{-1} R}$$

2. The intent is to perform a measurement that can determine the value for σ_p to the uncertainty of 0.1%.

$\boldsymbol{\sigma_p}$

1. The reaction channel for the determining σ_p is dependent on the triplet absorption (σ_1). Where σ_{un} is the unpolarized helium and neutron absorption cross-section. σ_p is the polarized ^{3}He neutron cross section absorption.

$$\sigma_p = (\sigma_{un} - \sigma_1)$$

The error on σ_p is on the order of several percent and limits how well we can determine Δb. σ_{un} is known very well (~ 0.1%).

$\sigma_p = \sigma_p$ [J=0] + σ_p [J=1]
$\sigma_p = \sigma_{un}$ [J=0] is already known
,so we will ALSO determine σ_p [J=1] for the
first time in this work!

Magnetometry

1. In muon g-2 and other absolute NMR measurement standards, they use spherical polarized cells to measure the absolute magnetic field from the Larmor precession frequency.
2. We do the same thing, but we measure the Larmor frequency shift in a cylindrical cell between the higher and lower Zeeman energies to determine the polarization.
3. We had 6 coils fixed across the length of the cell.
4. About 5000 FID signals were taken.