

Probing Pulse Structure at the Spallation Neutron Source via Polarimetry Measurements

A Thesis Presented for the

Master of Science

Degree

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For Tom E Miller, you are missed..

You are what you do. Choose again and change.

Abstract

The Fundamental Neutron Physics Beamline (FNPB) at Spallation Neutron Source is used to probe fundamental forces via cold neutrons. The beamline's latest experiment is probing the hadronic weak interaction through the capture of polarized cold neutrons on ${}^3\text{He}$ nuclei. While the strong nuclear force is dominant in this interaction, a weak signal can be observed in the parity violating momentum asymmetry in the reaction products. As the asymmetry measurement requires both neutron spin states, a means of controlling the neutron spin is required. In order to alternate the spins, a radio frequency spin rotator was installed for the experiment. The efficacy of this device is dependent on the time neutrons spend within it. In this thesis I attempt to use polarimetry measurements to probe the pulse structure of the SNS with the goal of facilitating future research. While this is unlikely to impact the results of the $n{}^3\text{He}$ experiment, it is a topic of considerations for future experiments at the FNPB.

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Chapter 1

Theory and Motivation

1.1 The n^3He interaction

The $n + ^3He \rightarrow p + T + 765KeV$ interaction is a useful test bed for the hadronic weak interaction. In the interaction, thermal neutrons capture on ^3He to form an excited ^4He intermediate state separated by about 20.6 MeV from being a stable alpha particle. Unable to decay via gamma emission due to parity and angular momentum the ^4He breaks down into a proton and a triton. The proton carries roughly 75 percent of the energy and leaves an ion trail approximately five times as long as that of the triton. By detecting the difference in the trails lengths we can measure the relationship between proton direction and the incoming neutrons spin. From a fundamental physics perspective the interesting part of this interaction is the parity violation manifest in the mixing of the lowest two excited states which, respectively are even and odd. The isospin=0 nature of these excited states makes the reaction particularly sensitive to the I=0 couplings h_ρ^0 and h_ω^1 of the DDH model. [7] These states carry no angular momentum, necessitating mixing with other resonances for spin dependence, and thus introducing a large dependence on the I=1 long range coupling f_π [3]

Table 1.1: DDH paper best estimates.

Coupling Constant	Reasonable Range	Best Value
h_{π}^1	$0 \rightarrow 30$	12
h_{ρ}^0	$-81 \rightarrow 30$	30
h_{ω}^0	$-27 \rightarrow 27$	-5

1.1.1 Theory and motivation

The standard model recognizes four fundamental forces that govern the interactions of matter. In order of descending strength these are: the Strong nuclear force, electromagnetism, the Weak nuclear force and gravity. As neutrons are composed of charged quarks with mass they are subject to all four of these forces. The neutron serves as an ideal testing ground for the interactions between these four. In the case of the n^3He experiment the hadronic weak interaction is the subject of our focus. The weak force is carried through the exchange of $W^{\pm}$ and Z^0 bosons. These particles are too short ranged (on the order of $10^{-18}m$) for a direct interaction between hadrons (which typically have femtometer spacing). Instead, the hadronic weak interaction arises from a weak coupling at one of the vertexes as either an emitter or absorber of mesons. This is displayed in the Feynman diagram below. Charge conservation dictates that the neutral Z^0 particle can only couple to virtual ρ^0 or ω^0 mesons while the $W^{\pm}$ can couple to similarly charged virtual π or ρ mesons. The Weak component of this diagram is 10^{-7} times weaker than the strong component. Despite this daunting difference a Weak signal can still be extracted by exploiting the parity violating property of the Weak force.^[7]

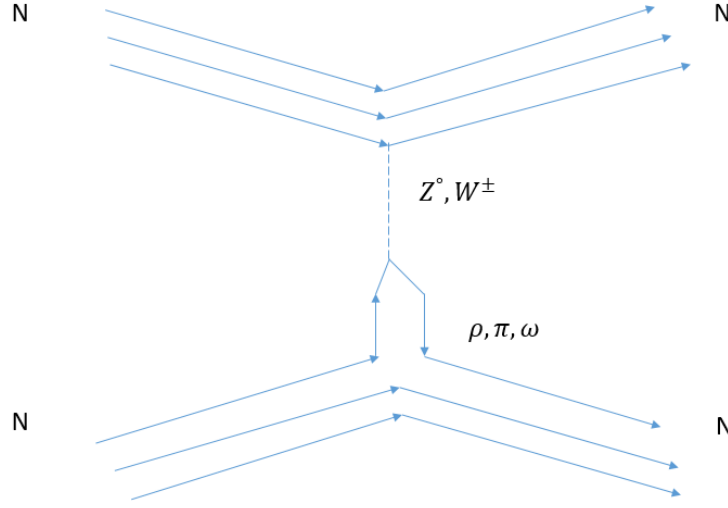


Figure 1.1: Hadronic weak interaction

Hadronic weak interaction

1.1.2 Parity

In physics parity is the operation of inverting the spatial dimensions. In terms of the ubiquitous right hand rule this can be thought of as a transition between a right handed and a left handed coordinate system. The measurement of a parity conserving phenomena is invariant under a parity transformation, while a non-conserving phenomenon will generate a sign change. It was long considered that parity invariance was a fundamental symmetry of the universe. The strong and electromagnetic forces are invariant under parity transformation, and from an philosophical level it doesn't make intuitive sense that reality should behave differently under a change of handedness. This assumption was challenged by observing the decay of the K^+ particle which was observed to have two distinct decay paths.[12]

$$K^+ \rightarrow \pi^+ + \pi^0$$

$$K^+ \rightarrow \pi^+ + \pi^+ + \pi^- \text{ [12]}$$

The intrinsic parity of the pion is negative one resulting in the two final states having opposite parities. It was initially believed that the K^+ was in fact two separate particles. However, experimental evidence indicated that this was not the case.

In 1956 Lee and Yang proposed that parity was not conserved in the weak interaction and suggested a number of experiments that could test this non-conservation.[18] Their hypothesis was confirmed the next year when C.S. Wu and her team confirmed a preferential emission of decay products opposite the direction of the nuclear spin of Cobalt 60 nuclei.[12]

In the $n^3\text{He}$ interaction the parity violating component is the relationship between the neutron spin and the momentum of the outgoing proton. The DDH model predicts that the asymmetry is dependent on four coupling constants as described below.

$$A_p^{n^3\text{He}} = -0.1892(86)f_\pi - 0.0364(40)h_\rho^0 - 0.0334(29)h_\omega^0 \approx 1.147 \times 10^{-7} \text{ [3]}$$

1.2 Experiment and Analysis

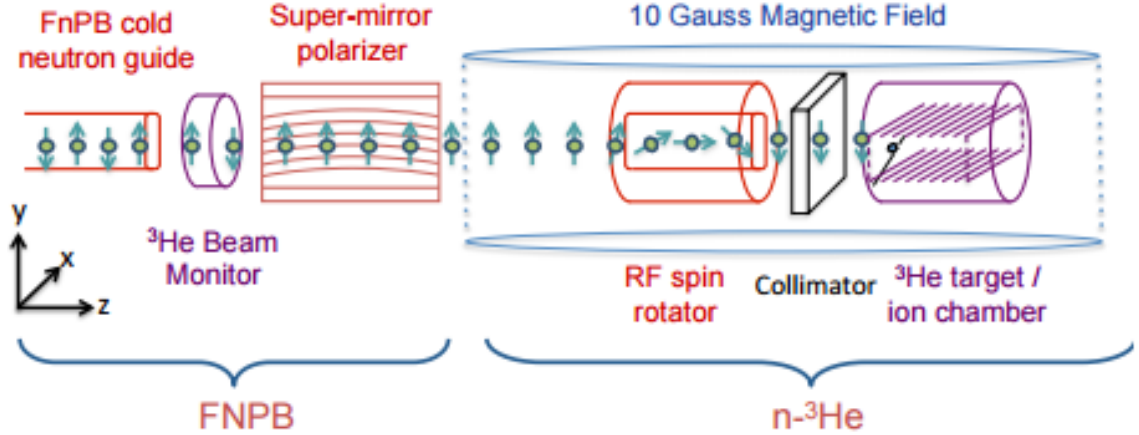


Figure 1.2: Experiment schematic courtesy of Mark McCrea[15]

1.2.1 Spallation Neutron Source

The n^3He experiment took place at beamline 13B of the Spallation Neutron Source in ORNL. The SNS functions by spalling neutrons off a liquid mercury target using high energy protons provided by a linear accelerator. These protons are grouped into $1\mu s$ pulses that impinge on the target with a frequency of 60Hz. During the operation of n^3He , power supplied to the target was slowly increased from 1-1.4MW. This corresponds to protons per pulse on the order of 10^{14} and neutrons production an order of magnitude higher, as each incident proton will spall 20 to 30 protons. As the statistical sensitivity of the n^3He experiment is dependent on the number of neutrons measured, higher neutron flux is desirable. After being generated at the mercury target the neutrons have a range of kinetic energies varying between zero and the energy of the incident protons. As I will discuss in a later chapter, the ability of the spin flipper and other components to function is dependent on a specific set of neutron energies. In order to obtain a useful beam spectrum the neutrons are moderated by scattering within unpoisoned liquid para hydrogen (due to its small cross section for low energy neutrons[11]) at 20 K. After the moderator the neutrons are channeled with a curved beam guide in order to reduce background from fast neutrons and gamma rays. Due to the well ordered time structure of the neutron pulses the beam profile can be further refined by the use of choppers. The choppers are rotating disks of neutron absorbent ^{10}B with an opening for the selected wavelength. The FnPB includes two choppers at 5.5 m and 7.5 meters downstream of the moderator. After the spectrum of the neutrons is refined by the chopper it is passed through a set of multilayer beam guides to be polarized through interaction with a supermirror.[8]

After being tuned by the choppers the neutron pulse is directed to the cave.

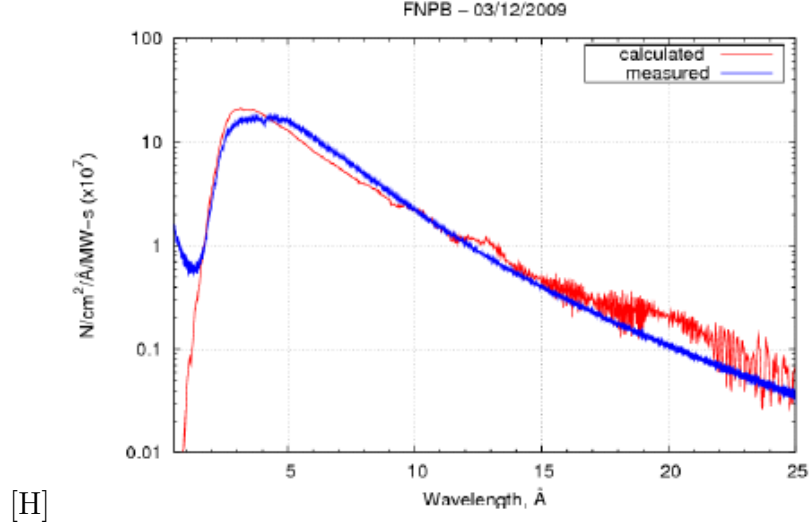


Figure 1.3: Calculated and measured spectra provided by the SNS[8]
 Calculated and measured spectra provided by the SNS[8]

1.2.2 n^3He

For the purposes of n^3He neutrons of wavelength 2.5-6.5 angstroms (1600 m/s to 608 m/s) were used. The experimental set up of n^3He involves a polarized beam of neutrons being transmitted through a spin flipper and into an ion tank. Within the tank is ^3He gas and a series of wire planes. Each plane is capable of detecting the protons generated in the $n + ^3He \rightarrow p + T + 765KeV$ interaction This current is then transmitted to a DAQ computer. The SNS operates at a 60 hz pulse rate and a pulse length of roughly 16.67ms.

Chapter 2

Polarimetry Overview

2.1 Definitions

The observable of interest in the n^3He experiment is the parity violating correlation between the neutron' spin and the momentum of the outgoing proton. The physics based asymmetry (A_p) is related to the polarization of the neutron beam and the spin flipper efficiency as follows.

$$A_p = \frac{A_{obs}}{\langle P_n \rangle \cdot \langle \epsilon_{sf} \rangle}$$

Here P_n is the beam polarization, A_{obs} is the observed asymmetry, and ϵ_{sf} is the spin flipper efficiency. As a result a precise measurement of the polarization and of the spin flippers efficiency is required. Neutrons are fermions and therefore have two spin states, spin up, which indicates that the neutron spin is aligned with the axis of measurement (in this case the static field) and spin down in which the particle spins are anti-aligned with the axis of measurement. Polarization measurements are a measure of the average orientation of the spin states as given by $P = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$. There are two polarization measurements of interest, in the n^3He experiment: the beam polarization and the efficiency of the spin flipper.

2.1.1 Impact on Analysis

While the experiment as a whole can reach 10^{-8} precision there are a number of factors that affect the sensitivity of polarimetry measurements. These range from the structure and behavior of the analyzing cell, to the signal passed to the spin flipper. In order to obtain meaningful information about the DDH coupling constants we must extract the physics based asymmetry from the experimental asymmetry. Experimental asymmetry is represented by the following equation.

$$A_{exp} = \frac{(A_b + PA_{phy})}{(1 + A_p P A_{phy})}$$

Here A_b represents the beam false asymmetry, A_p represents the spin flip asymmetry and finally A_{phy} denotes the physics asymmetry the experiment is intended to measure[10]. The factors P and A_p act solely as a dilution. Consequentially, we are able to enhance n^3He 's sensitivity by reducing their impact.

2.2 Spin Rotation

In general, changing spin orientation is a quantum mechanical operation. In the case of the ^3He experiment this can be treated classically via the Bloch equations as they return the expectation value of the quantum mechanical description of a Rabi flip.

$$\frac{d\vec{M}(t)}{dt} = \vec{M}(t) \times \gamma \vec{B}(t) - R(\vec{M}(t) - \vec{M}_0)$$

Here M is the nucleons magnetic moment, B is the magnetic field, γ is the gyromagnetic ratio, and R is the relaxation matrix. This can be unpacked into a set of three equations one for each component as follows.[2]

$$\begin{aligned} \frac{d\vec{M}_x(t)}{dt} &= \gamma[\vec{M}_y(t)\vec{B}_z(t) - \vec{M}_z(t)\vec{B}_y(t)] - \frac{\vec{M}_x(t)}{T_2} \\ \frac{d\vec{M}_y(t)}{dt} &= \gamma[\vec{M}_z(t)\vec{B}_x(t) - \vec{M}_x(t)\vec{B}_z(t)] - \frac{\vec{M}_y(t)}{T_2} \\ \frac{d\vec{M}_z(t)}{dt} &= \gamma[\vec{M}_x(t)\vec{B}_y(t) - \vec{M}_y(t)\vec{B}_x(t)] - \frac{\vec{M}_z(t) - \vec{M}_0}{T_1} \end{aligned}$$

By convention the initial magnetization is in the $\hat{z}$ direction. T_1 refers to the spin lattice relaxation time, while T_2 is the spin-spin relaxation time. For the purposes of this paper two simplifications can be made to these equations. First, rather than the

laboratory frame of reference, a rotating frame can be constructed in which the x and y-axis rotate about the z-axis at the Larmor frequency. Second, as both relaxation times approach infinity we can simplify the equations to.

$$\frac{d\vec{M}_z(t)}{dt} = -\vec{M}_y(t)\gamma\vec{B}_x(t) \quad \frac{d\vec{M}_x(t)}{dt} = 0 \quad \frac{d\vec{M}_y(t)}{dt} = -\vec{M}_z(t)\gamma\vec{B}_x(t).$$

At this point the magnetization along the z axis can be solved as

$\vec{M}_z(t) = \vec{M}_0 \cos(\omega_x t)$ where ω_x is the gyromagnetic ratio of the nucleus/nucleon multiplied by the transverse field. As a result by tuning the strength of and duration of the transverse field we can generate a π rotation. The spin flip efficiency can therefore be viewed as a rotation of the spin vector from being aligned with the field to anti-aligned with the spin flip probability being equal to the projection of the vector on the axis of the guide field.

For a quantum mechanical treatment of spin rotation via Rabi pulses please refer to Jim Byrne's book *Neutrons Nuclei and Matter* [5].

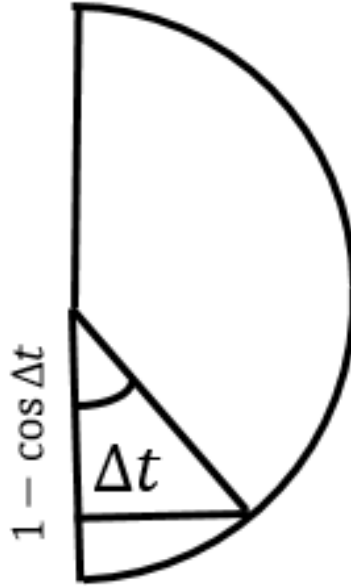


Figure 2.1: Visualization of spin rotation

Visualization of spin rotation

2.3 Polarization measurement

Polarimetry measurements are taken by observing the transmission of neutrons through a polarized ^3He spin filter. The $n^3\text{He}$ experiment uses an ion chamber of ^3He gas both as the principle detector for the experiment and as a neutron detector for polarimetry measurements.

The neutron polarization is calculated from three transmission measurements, one for each neutron spin state (T_+, T_-) and transmission through an unpolarized cell (T_0).

The transmission ratios with the radio frequency spin flipper (RFSF) on and off can respectively be described by R1 and R2.

$$R1 = \frac{T_+}{T_0} = \cosh(\chi\lambda P_{He})[1 + P_n \tanh(\chi\lambda P_{He})]$$

$$R2 = \frac{T_-}{T_0} = \cosh(\chi\lambda P_{He})[1 + (1 - 2\epsilon_{sf})P_n \tanh(\chi\lambda P_{He})]$$

Here λ is the neutron wavelength, and P_{He} is the polarization of the ^3He cell. The value χ is slightly more complicated. Known as the cell optical thickness, χ is an intrinsic property of the cell incorporating the number density of ^3He in the cell, the capture cross-section for a reference wavelength and the cell's length. Mathematically χ is represented by the following equation.

$$\chi \equiv \frac{n\sigma_0 l}{\lambda_0}$$

In this equation n is the number density of the ^3He and l is the cell length, while λ_0 and σ_0 are the wavelength and capture cross section for a given reference wavelength[16].

The hyperbolic identity $1 - \tanh^2(\chi\lambda P_{He}) = \frac{1}{\cosh(\chi\lambda P_{He})} \sqrt{\cosh^2(\chi\lambda P_{He}) - 1}$ results in the ratios $R1$ and $R2$ only depending on $\cosh(\chi\lambda P_{He})$.

$$\text{Given } \cosh(\chi\lambda P_{He}) = \frac{1}{2\epsilon_{sf}}[R_2 - (1 - 2\epsilon_{sf})R_1]$$

We can use this substitution to write the two transmission ratios as

$$R1 = \frac{1}{2\epsilon_{sf}}[R_2 - (1 - 2\epsilon_{sf})R_1] + P_n \sqrt{\left[\frac{1}{2\epsilon_{sf}}[R_2 - (1 - 2\epsilon_{sf})R_1]\right]}$$

$$R2 = \frac{1}{2\epsilon_{sf}}[R_2 - (1 - 2\epsilon_{sf})R_1] + (1 - 2\epsilon_{sf})P_n \sqrt{\left[\frac{1}{2\epsilon_{sf}}[R_2 - (1 - 2\epsilon_{sf})R_1]\right]}$$

Solving for P_n we recover.

$$P_n = \frac{R_1 - R_2}{\sqrt{[(2\epsilon_{sf} - 1)R_1 + R_2]^2 - 4\epsilon_{sf}^2}}$$

This result does not directly depend on the polarization or other properties of the ^3He cell allowing for measurements of the beam polarization to be made purely via the ion chamber's signal[16].

2.4 Spin Flipper Efficiency

Throughout section 2.3 the calculation of neutron polarization has depended on the quantity ϵ_{sf} , the spin flipper's efficiency. The spin flipper efficiency can be determined from a sequence of four transmission measurements. A measurement made with the RFSF off and one with it on, followed by the same measurements after an adiabatic fast passage (AFP) flip.

Two ratios can be constructed from these measurements

$$R_{sf} = \frac{T_{sf}^{afp} - T_{sf}}{T_{sf}^{afp} + T_{sf}} = (1 - 2\epsilon_{sf})P_n \tanh(\chi\lambda P_{He})$$

for when the Spin flipper is on, and

$$R_{off} = \frac{T^{afp} - T}{T^{afp} + T} = P_n \tanh(\chi\lambda P_{He})$$

for the unaltered spin orientation.

Using these values we can calculate the spin flipper efficiency $\epsilon_{sf} = \frac{1}{2}(1 - \frac{R_{sf}}{R_{off}})$. The use of AFP flips poses a potential concern as there is always an element of depolarization in this process. This effect can be mediated by taking three transmission measurements and using an AFP flip after the first and second measurements. The first and third measurements can then be averaged producing a transmission measurement that approximates the same ^3He polarization as only one AFP flip[10].

2.4.1 Spin Flip Ratio

The SFR is simply the ratio of transmission through the analyzing cell for the spin flipper being on vs the spin flipper being off.

$$T_{off} = T_0(\lambda) \cdot e^{-\chi^\lambda} [\cosh(\chi\lambda P) + P_n(\lambda) \sinh(\chi\lambda P)]$$

$$T_{on} = T_0(\lambda) \cdot e^{-\chi^\lambda} [\cosh(\chi\lambda P) + \alpha P_n(\lambda) \sinh(\chi\lambda P)]$$

for $\alpha = 1 - 2\epsilon_{SF}$ which produces a spin flip ratio of

$$SFR = \frac{1 + P_n(\lambda) \tanh(\chi\lambda P)}{1 + \alpha P_n(\lambda) \tanh(\chi\lambda P)}$$

This equation is can be reduced by recalling that $\tanh(x)$ approaches one for large values of which is a valid approximation given the large arguments used. As a result

$$SFR \approx \frac{1 + P_n(\lambda)}{1 + \alpha P_n(\lambda)}$$

For a spin flipper in good operation this will result in SFR values in a range of 35-40 for any given wavelength. Higher SFR values correspond to a greater spin flipper efficiency. Therefore the guide field can be tuned based on optimization of this quantity.

Chapter 3

Polarimetry Components

3.1 Overview

The purpose of this chapter is to outline the physical components of the polarimetry apparatus and to discuss their structure and underpinnings.



Figure 3.1: A schematic of the Polarimetry configuration[17]

3.2 Supermirror

The neutron flux provided by the SNS is initially unpolarized. In order to provide a polarized beam for the n^3He experiment a supermirror polarizer is installed immediately before the end of the neutron guide[13]. The mirror is comprised of 45 channels made of glass panes coated with alternating layers of silicon and nickel. Physically the mirror is 43 cm long and is curved in order to ensure that all neutrons provided to the beamline bounce off the mirror to maximize polarization. The

polarizing properties of the mirror depend on exploiting the spin dependence of the nickel's index of refraction when in a magnetic field[8].

$$n = \sqrt{\frac{E - V_{nuc} \pm \mu \cdot B}{E}} \text{ for } E = \frac{h^2}{2m\lambda^2}$$

Here n is the index of refraction while E is the neutron's energy, V_{nuc} is the Fermi pseudopotential, μ is the neutron's magnetic moment, and B is the guide field. This results in one spin state encountering alternating layers with indexes of refraction resulting in reflection while the other spin state is confronted with homogeneous indexes resulting in transmission and eventual absorption in the silicon. This results in a beam polarization of 93% at the cost of a factor of three in neutron intensity.

3.3 Guide Field

The n^3He experiment is contained within a uniform guide field that preserves the neutron polarization from the supermirror to the target and is integral to the function of the spin flipper. This field is generated by four rectangular coils that are connected in series to a primary power supply. The inner coils contain 18 wire windings each while the outer coils each have 39. Additionally each of the four coils have 12 wire windings with their own power supplies that allow for fine tuning of the field. Finally shim coils with their own power supplies are used to reduce transverse non-uniformities within the experiment. During polarimetry measurements the guide field is tuned by adjusting the main power supply in order to match the Larmor frequency to the frequency of the RFSSF. The field is monitored by a pair of magnetometers that are connected to the DAQ electronics. Over the course of the experiment a general upwards trend was noted in the guide field, but it remained between 9 and 9.2 Gauss.

3.4 Collimation

The neutron beam supplied to the experiment is collimated by a four jaw collimator designed by Christopher Hayes[10]. The collimator is made of four bars of neutron

absorbent ${}^6\text{Li}$ mounted on rails, two of which are oriented horizontally and two vertically as detailed in the figure below. These bars absorb 100% of the beam barring the rectangular space left between the doors.

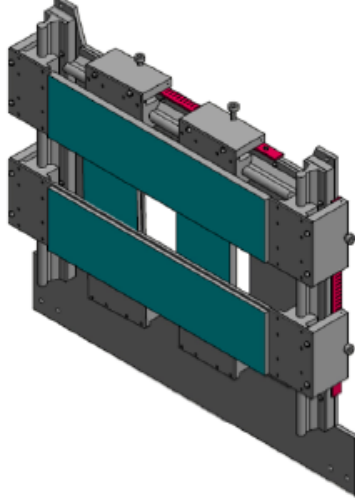


Figure 3.2: A schematic of the collimator

The jaws are adjusted with the aid of integrated straightedge rulers that allow the width and position of the window to be set within 0.1 mm. For the majority of data acquisition the jaws were unchanged. The exception to this is polarimetry measurements, which necessitated the window being reduced to a $3.5 \times 3.5 \text{ cm}^2$ in order to restrict the beam to the neutrons that would pass through the analyzing cell. After polarimetry measurements were completed the jaws were returned to their original configuration.

3.5 Spin Flipper

As an asymmetry measurement, the $n^3\text{He}$ experiment requires the ability to alternate spin states. To achieve this, the experiment utilizes a beam of polarized cold neutrons from a supermirror that are then passed through a radio frequency spin flipper before reaching the target. The spin flipper rotates alternating pulses from the SNS using a

combination of magnetic fields. First is a guide field enclosing the experiment. This field is kept homogeneous to ensure that neutrons maintain their polarization after leaving the supermirror; it is tuned to resonance with the spin flipper. By matching the rate of precession to the spin flipper's efficiency we obtain a resonance condition for the spin state transition. The second field is the RF magnetic field generated by the spin flipper. In order to ensure a rotation of π radians the strength of this field must be tuned to the spectrum of the incoming neutrons. The total probability of transition is dependent on the strength of the field and the time spent within the spin flipper. This is described in the following equation $e_{sf} = \frac{\omega_1}{a^2} \sin^2(\frac{at_{sf}}{2})$, where ω_1 is the resonant frequency for the neutron's oscillations, a is defined as $\sqrt{(\omega_0 - \omega_{RF})^2 + \omega_1^2}$ and t_{sf} is the time the neutron spends within the spin flipper.

3.5.1 Spin flipper signal

The signal passed to the spin flipper was created using the ArbExpress Ver2.1 waveform editing tool from Tektronix[10]. Using this a sinusoidal waveform was created with an amplitude that decreases in accordance with $1/t$ across the neutron pulse duration of $\Delta T = 16.6667ms$. The signal utilized 444.25 oscillations during this interval in order to generate a frequency close to the Larmor frequency of the neutrons which as stated in section 2.2 is a requirement for spin flipping. Each oscillation within the wave function is composed of roughly 146 individual voltage points separated by approximately $25\mu s$. This waveform is then sent from the generator to an amplifier and finally routed to the double cosine theta coil.

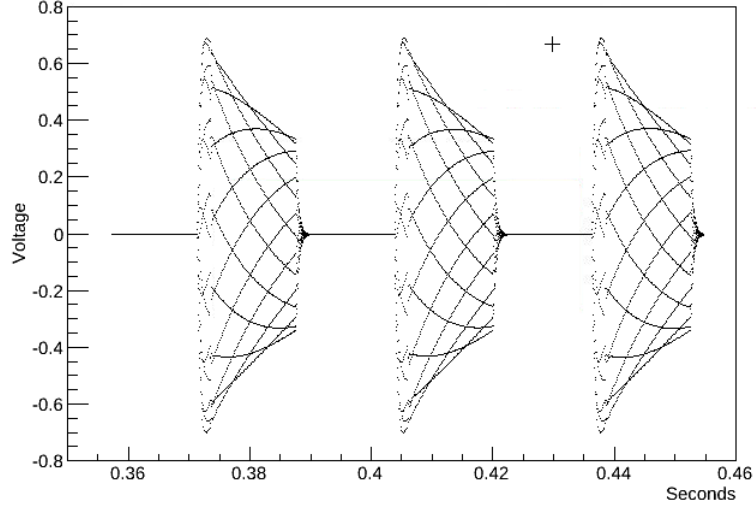


Figure 3.3: The RFSF signal as recorded by the daq

The amplitude of the pulse must be tuned to the length of time that the neutrons remain within the spin flipper. The $n^3\text{He}$ experiment as a whole requires spin flipper efficiencies of $> 98\%$. If a set voltage was used for all time bins, then outside of a relatively small range the spin flipper's efficiency would fall below 98% as seen in Figure 3.4.

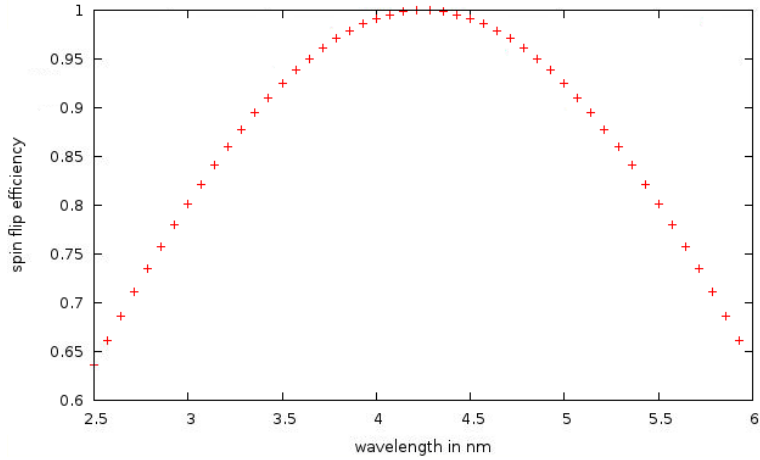


Figure 3.4: Illustration of a "flat" voltage being provided to the RFSF

In order to generate a signal which accounts for this, voltage supplied to the spin flipper is determined by two values, V_a which controls the amplitude of the signal, and

the ratio $\frac{a}{b}$ which determines the factor by which the voltage decreases over the $1/t$ curve. For the data production runs at the n^3He experiment the values $V_a = 486mV$ and $a/b=2.370$ were used. These values were set by evaluating the spin flipper ratio at six different a/b ratios and then utilizing a calculated optimum value.

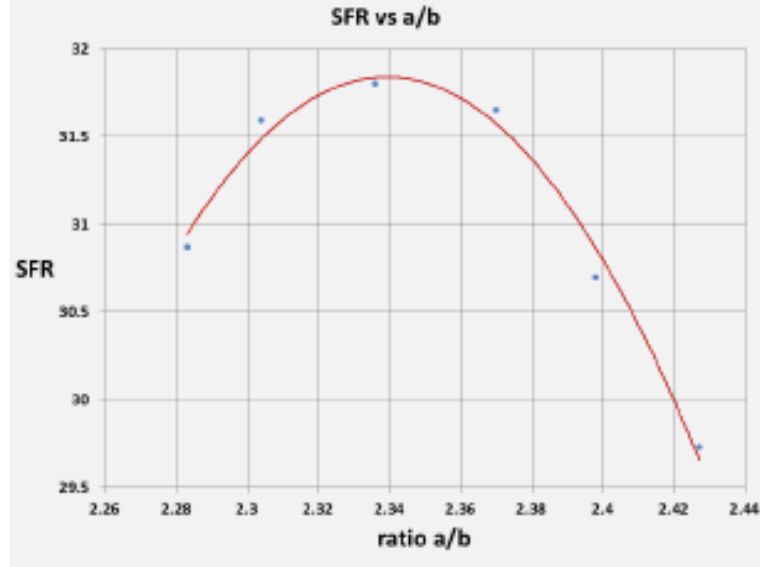


Figure 3.5: Spin Flip Ratio utilizing different "slopes" fit to a parabola[10]

While the a/b ratio was not adjusted during data taking out of concern of disrupting the experiment at two different points the voltage V_a was shifted across a series of fifteen values and analysis of this data comprises the bulk of chapter 4.

3.6 Adiabatic Fast Passage

3.6.1 Theory

Adiabatic fast passage is a nuclear magnetic resonance technique for generating a population inversion in the spins of particles held within a magnetic field with high efficiency independent of the uniformity of the holding field.

Adiabatic fast passage is dependent on two magnetic fields, a holding field B_0 and a rotating radio frequency field. Visualizing AFP can be simplified by working in a

reference frame that rotates at the instantaneous frequency of the RF field. Within this rotating frame there is an effective magnetic field with amplitude $\Delta\omega/\gamma$ along the $\hat{z}$ axis where $\Delta\omega = \omega_0 - \omega_{RF}$. By sweeping RF from a very low value, $\omega_{RF} \ll \omega_0$ to a high value, $\omega_{RF} \gg \omega_0$ in a short time the effective field and magnetization are rotated by π [9].

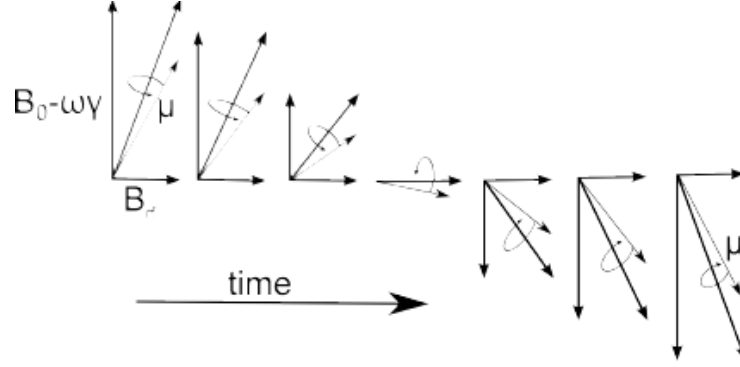


Figure 3.6: A vector representation of the AFP fields[16]

Due to the RF field sweeping across a range of frequencies all of the ^3He spins are rotated regardless of variations in the magnetic fields leading to a high afp flip efficiency independent of experimental imperfections in the field.

Each time the filtering cell is subjected to an AFP flip it suffers a partial depolarization. This makes measuring the efficiency of an AFP flip in the experiment a priority. The AFP flip efficiency can be calculated using the relationship $\epsilon = (P_n/P_0)^n$. Where ϵ is the AFP efficiency and P_n is the polarization of the ^3He cell after n flips. The net polarization can either be found by comparison of measurements of the cells polarization taken at the beamline.

In previous experiments it was determined that the efficiency of the AFP flip procedure came out to 0.972 ± 0.004 [16].

3.6.2 Implementation

The physical apparatus for polarization was composed of a ^3He filter cell, two magnetic coils and, a ^6Li Collimator. The coils are a pair of Helmholtz coils with a diameter of 9.5 inches made of 25 windings of 16 gauge copper. During an AFP flip a function generator is triggered to create an oscillating signal that sweeps from 20 to 60 kHz in 2 seconds with a peak to peak amplitude of 0.8V. This signal is passed to an RF amplifier that boosts the function generator's signal by a factor of 100 and is then passed to the AFP coils.

Spin Exchange Optical Pumping

In order to polarize the ^3He cell the process of spin exchange optical pumping is used. In SEOP, ^3He is polarized via interaction with polarized Rubidium and Potassium. While Potassium is considerably more efficient at transferring polarization to the ^3He it is much harder to directly polarize as it requires a higher temperature cell and a more powerful laser. Polarizing the Rubidium allows us to operate at a relatively low temperature of 190-200°C and an infrared laser operating at 785nm. Circularly polarized photons of this energy can excite the electrons in Rubidium from its ground state of $5s_{1/2}m_j = -1/2$ to the excited $5p_{1/2}m_j = +1/2$. These excited electrons then decay back to the ground state with an even distribution between the two spin states. Electrons that end in the $+1/2$ state will remain there both because an additional $\delta + 1$ transition is prohibited by selection rules and because N₂ doping quenches radiative decays. Due to the fact that the laser will continually excite the ground state the atom becomes polarized via depopulation pumping. As previously stated the more effective Potassium atoms are polarized via spin exchange collisions between the two species of atom in the alkali vapor[6].

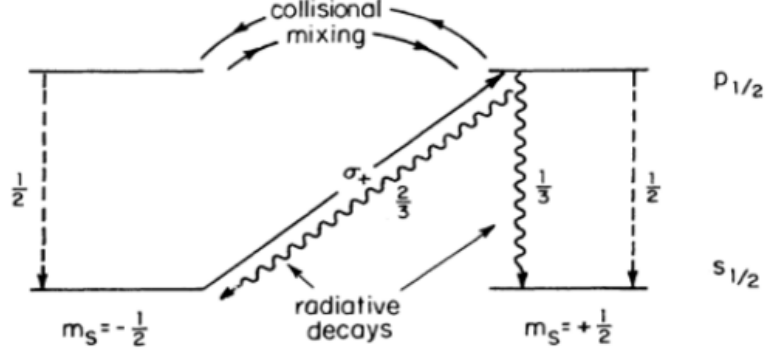


Figure 3.7: Polarization of an alkali metal by optical pumping[6]

Polarization of an alkali metal by optical pumping[6]

In polarizing ^3He the polarization of the gas is achieved through binary collisions. The spin exchange rate for this process γ_{SE} is $\gamma_{SE} = \langle \sigma_{SE} v \rangle [A]$, where the σv factor is the velocity averaged rate constant and A is the alkali number density. The final ^3He polarization during pumping is given by

$$P_{He} = \frac{\gamma_{SE} P_A}{\gamma_{SE} + \chi} (1 - e^{-(\gamma_{SE} + \chi)t}).$$

In the above equation P_A is the alkali vapor polarization and χ is the relaxation rate of the helium polarization sans the contributions from alkali vapor collisions.

Depolarization of the helium via collisions with the alkali is negligible during pumping as the alkali polarization remains near saturation during pumping. Allowing the cell to cool and the alkali to precipitate prior to turning off the laser prevents depolarization of the helium via collision with the alkali prior to transport.

During polarimetry measurements at the $n^3\text{He}$ experiment a sequence of three measurements were utilized: an initial run with the polarized cell, by a post AFP flip measurement and then a final flip and measurement. This results in having the same statistical effect on measurements as a signal flip.

3.7 Detector

The n^3He experiment produces free protons as a result of the interaction. While the main experiment is focused on measuring asymmetries in the momentum of the protons there is still a one to one relationship between incident neutrons and generated protons. As a result we do not require an additional neutron detector for polarimetry. Instead the experiments primary detector can also serve this role.



Figure 3.8: Ion Chamber[14]

The tritons and protons generated in the n^3He reaction have ranges between 1 and 10 cm. These charged particles can, in turn, ionize ^3He atoms resulting in currents in the signal wires which is amplified and digitized before being sent to the DAQ.

The ion chamber is comprised of 16 vertical signal planes of 9 wires each. These planes are alternated with 17 vertical high voltage wire planes each of which has 8 wires maintained at 350 volts. The signal wires are grouped into four sets of 36 wires which connect to pre-amplifier circuit board housed inside four square enclosures arranged around the perimeter of the ion chamber. These boxes each receive a steady flux of nitrogen gas to act as coolant during operation. The signal from the wire

panes is analog in nature and is sent to an ADC converter prior to being sent to the data acquisition computer.

The ion chamber has two gas feed valves used to fill the target with ^3He gas prior to the beginning of data acquisition. The density of the ^3He gas affects the mean free path for the decay products. Additionally, the density places a limit on the voltage supplied to the HV panes. Higher densities effectively necessitate a lower voltage in order to prevent arcing when the breakdown potential of the gas is exceeded.

In the $n^3\text{He}$ experiment the density of the gas is not directly measured, instead the temperature and pressure are set at $P = 7.0$ psi and $T = 21.33$ °C. Knowing this, the density of the gas, ρ , can be derived from the ideal gas law.

$$P = \frac{R}{M}\rho T$$

By inputting the above temperature and pressure and using the accepted molar mass of ^3He a density of $\rho = 5.945 \times 10^{-5} \frac{\text{g}}{\text{cm}^3}$ can be obtained[16].

3.8 Procedure

During a polarimetry run at the $n^3\text{He}$ experiment the first order of business is polarizing the ^3He analyzing cell. Polarization takes place at the main SNS building in the optics lab, and is started at least a full day prior to the polarimetry measurements. Technically full polarization of the cell is not required as measurement of the spin flipper efficiency and the beam polarization does not depend on a high polarization. However cell polarization was still measured as it is a diagnostic tool and because it does not require additional data to be taken. On the day of measurement the beamline's collimator is re-calibrated for polarimetry ensuring that the full measured flux passes through the analyzing cell. Afterwards a sequence of runs is implemented measuring the spin flip ratio with the intention of bracketing the ideal magnetic field for the resonant condition in spin flipping. During polarimetry two variables are used to ensure ideal operation, the magnitude of the holding field and the magnitude of the transverse field supplied by the spin flipper. The guide field's strength is manipulated

by adjusting the current provided to the coils while the transverse field's strength is controlled by varying the potential provided to the RFSF.

Chapter 4

Polarimetry Analysis

4.1 Analysis Introduction

During the operational period I performed analysis of the spin flipper performance with two primary goals. First, to ensure the proper function of the spin flipper for the experiment, and second, to use the spin flipper's efficiency as a function of time to probe the structure of the neutron pulse. Generally polarimetry runs could be completed within a sequence of as few as twelve short runs, of 30 seconds duration. This ensured a quick return to data taking without interfering with the experiment. These were deemed short polarimetry runs and were completed on a roughly monthly basis. In order to obtain data for studying the pulse, significantly more runs were required. These long polarimetry runs, necessary for optimizing the input voltage of the spin flipper, were performed in February and August of 2015.

4.2 Guide Field Tuning

In order to tune the guide field to the resonance case a simple run plan involving a pedestal run and array of guide field values was used. By using three different settings for the guide field we can bracket the optimal value and calculate it via curve fitting algorithms. Ideally a Rabi curve would be used however near resonance the spin flip

ratio's sensitivity to variation in B_0 is inverse parabolic. This allows the optimal value to be selected by fitting to an inverse parabola with fewer runs taken. While in the ideal case only three runs were required that were dependent on good initial guesses regarding the optimal value. As can be seen from table 4.1 there is a small upwards trend in the ideal guide field over the course of the experiment. The other principal insight from monthly polarimetry measurements was that the spin flipper efficiency was uniformly high barring the first and last four bins which were excluded from calculations due to the onset of the chopper. This is shown in figure 4.2.

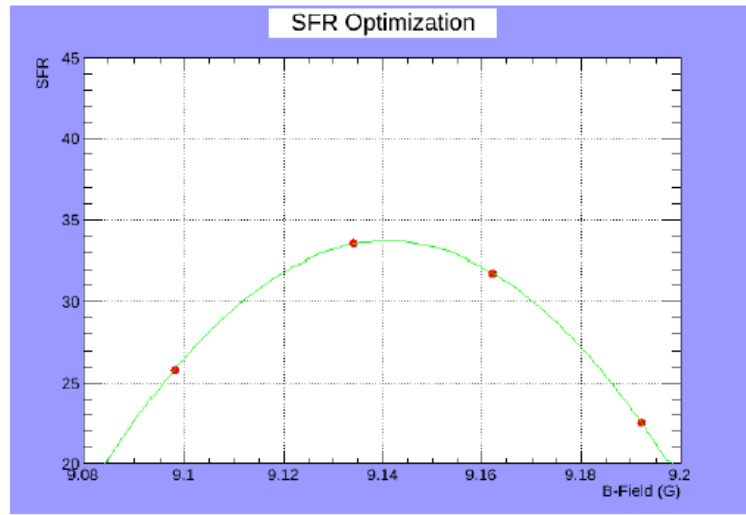
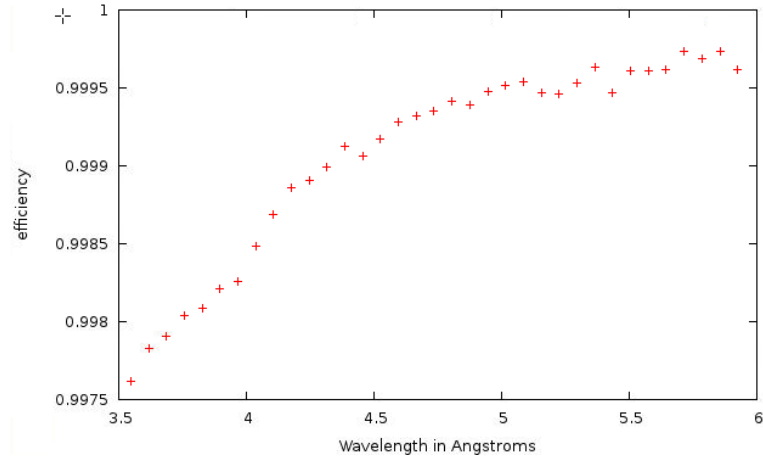


Figure 4.1: An optimization curve generated during monthly tuning fit to a parabola

Table 4.1: polarimetry results throughout the n^3He experiment

date	Optimal Magnetic Field	SFR
1/28/2015	9.09G	37.79
2/17/2015	9.06G	37.92
2/25/2015	9.09G	34.04
3/25/2015	9.12G	34.17
4/21/2015	9.12G	40.432
5/20/2015	9.14G	33.68
6/23/2015	9.15G	35.58
8/17/2015	9.16G	36.02
8/24/2015	9.106G	35.76
9/23/2015	9.15G	23.479
10/22/2015	9.16G	36.9
11/30/2015	9.177G	29.68

**Figure 4.2:** Spin Flipper efficiency vs wavelength

4.3 Voltage Tuning

Once the guide field is tuned to resonance, the field generated by the spin flipper must be tuned to rotate the spin of the neutrons by π radians while they are within the confines of the RFSF. As discussed in chapter three the spin flipper's signal is set using two constants: an initial magnitude V_0 and the ratio between the initial and final voltage $\frac{a}{b}$.

As the voltage tuning requires a full spin flip efficiency measurement, four runs must be used per voltage setting. An initial polarized run, two runs after afp flips, and an unpolarized run.

The ratio was set during the initial polarimetry runs in January 2015 using several preprogrammed values and, after an optimal value was selected, held constant throughout the data taking period, so as not to vary the experimental parameters. The initial magnitude V_0 was scanned over fifteen values during February and August of 2015, allowing the selection of an optimal value for V_0 and generating data necessary for analyzing variations in time of flight in the neutron spectrum.

4.3.1 Efficiency map

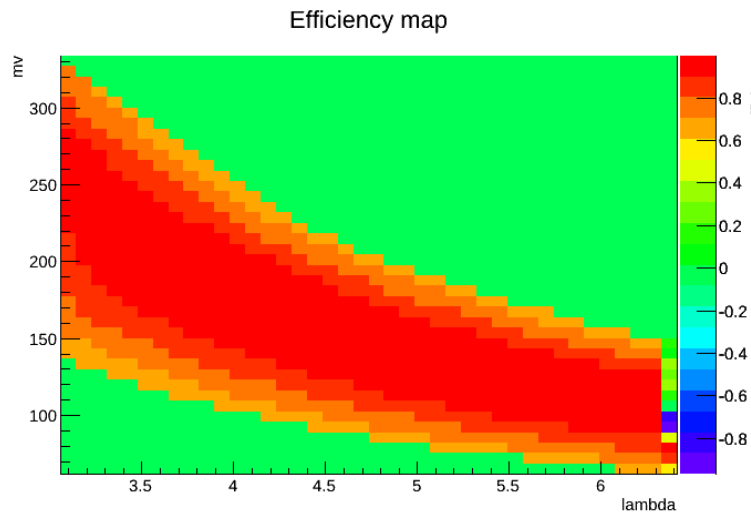


Figure 4.3: Spin Flipper efficiency as a function of voltage and time

Spin Flipper efficiency as a function of voltage and time

Given the initial values for V_0 and the ratio $\frac{a}{b}$, I calculated the voltage delivered to the RFSF throughout a pulse and created a two dimensional map of spin flipper efficiency as a function of voltage and wavelength. As discussed in section 2.2 variations in the voltage provided for the transverse field is proportional to $1 - \cos(\delta t)$ By fitting voltage vs time per bin to $1 - \cos(a * x + b)$ allows the extraction of an optimal voltage per time bin as shown in figure 4.6.

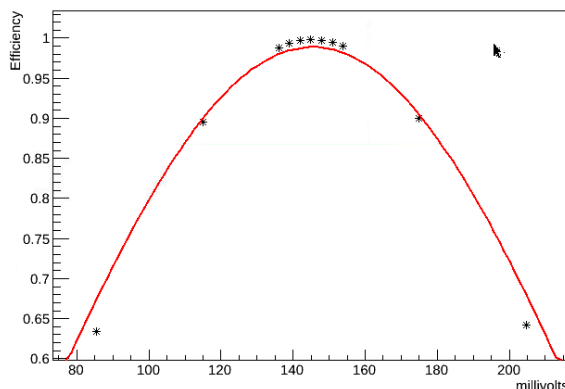


Figure 4.4: Example 1-cosine fit

Example 1-cosine fit

4.3.2 Residuals

I used the ideal fit voltages in gnuplot to generate a best fit $\frac{1}{t}$ curve. Once an ideal curve has been generated the next step in analyzing the signal is to measure the difference between the curve generated voltages and the optimal voltages per bin. These residual values are a measure of how poorly a $\frac{1}{t}$ signal fits the neutron spectrum seen by the n^3He experiment.

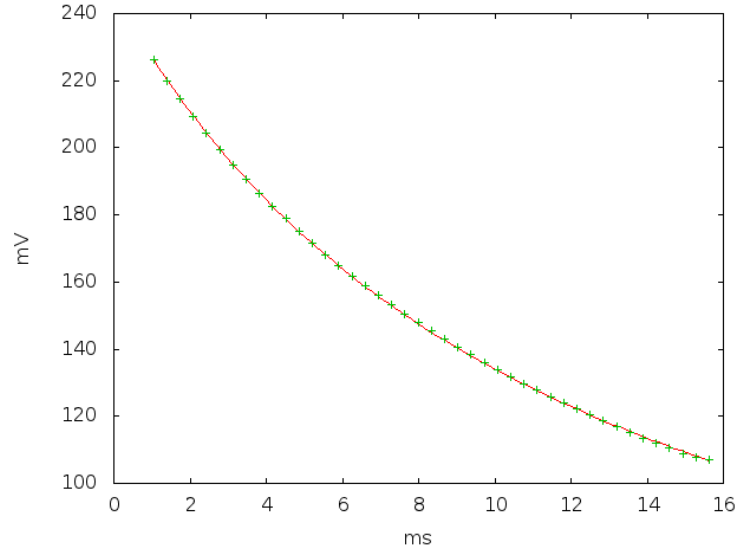


Figure 4.5: Best fit curve

Voltage as a function of time

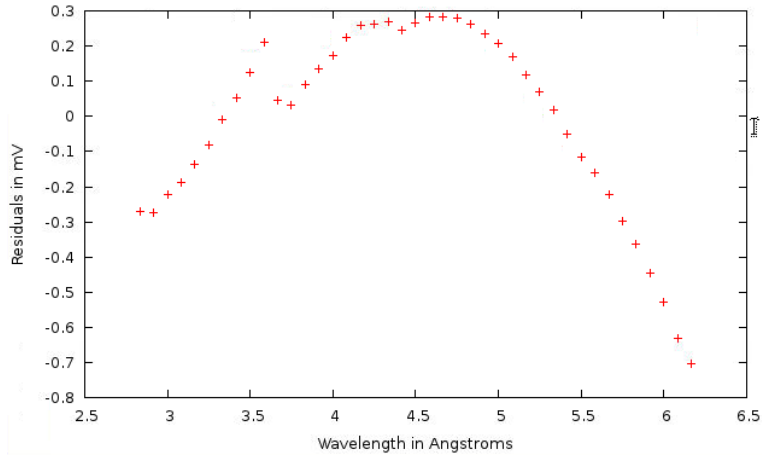


Figure 4.6: residuals vs wavelength

residuals vs wavelength

4.3.3 Implications

As can be seen in Chapter 3 the rotation of the neutron's spin in the RFSF can be visualized as the projection of a unit vector undergoing a rotation of π radians. This leaves the potential offset due to an uncertainty in time of flight equal to $1 - \cos(\delta t)$.

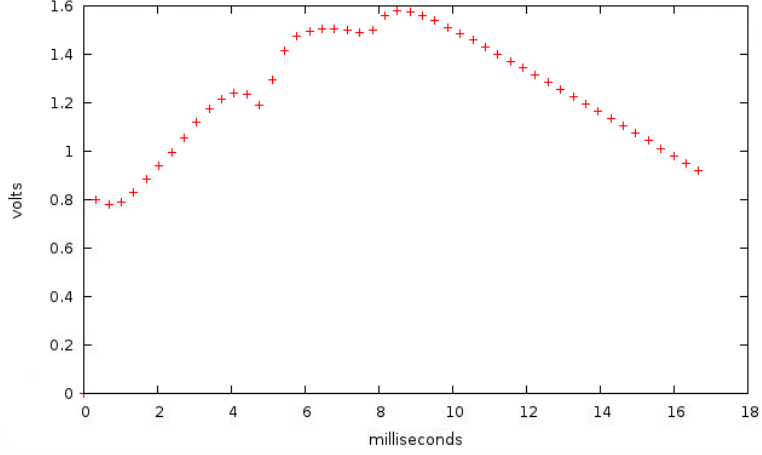


Figure 4.7: Example of raw beam spectra including Bragg peaks

By taking the Taylor expansion of cosine $1 - \frac{x^2}{2} \dots$ we can evaluate the maximum possible offset due to a deviation in time of flight. The neutron pulse is on the order of 10^{-2} seconds in length. As the contribution is of second order that means that the largest possible effect that a deviation in time of flight can have would be on the order of 10^{-4} of the total signal. Despite this we see residuals an order of magnitude higher at a thousandth of the total signal indicating that the spin flipper cannot be used to measure deviations from an ideal pulsed source in the SNS. Furthermore, rather than being random shifts due to moderation the residual plot has a consistent structure reproducing the Bragg peaks noted by Matthew Musgrave[16]. This indicates that there is an uncanceled background impacting measurements. If a later experiment could account for this signal it is possible that more precise measurements of the deviations from an pulsed velocity spectrum could be made.

Chapter 5

Conclusions

5.1 Implications for n^3He

The most immediate conclusion of this thesis is that any deviation from a simple instantaneous emission of neutrons from the moderator will have no effect on the outcome of the n^3He experiment. While the experiment is sensitive to variations in spin flipper efficiency the recorded residuals from the $\frac{1}{t}$ fitting were on the order of a thousandth of the total signal and the spin flipper efficiency derived from SFR measurements recorded during data acquisition had an average value of $\langle e_{sf} \rangle = 0.9979 \pm 0.00091$ well within the accepted 2% required for reaching the desired precision of physics asymmetry of 10^{-8} .

5.1.1 Expectations

By envisioning the spin flip as a rotation of a vector as discussed in section 2.2, one would expect signal broadening from the moderator to result in deviations from a best fit $1/t$ curve to occur on the scale of a ten thousandth of the voltage signal. Instead residuals between an ideal fit curve and experimental data consistently returned variations an order of magnitude higher. Moreover these residuals appeared to have structure rather than being random noise about a best fit curve.

5.2 Implications for FNPB

Given the difficulty of arranging different operating conditions during data acquisition, a conclusive cause for this signal was not determined. Suggestions for the source include an un-cancelled side channel background or scattered neutrons from the experimental apparatus depolarizing and shifting best fit models. The next experiment at the FNPB, Nab, is not dependent on a polarized neutron flux[1]. The Nab experiment is a precise measurement of a, the electron-neutrino correlation parameter and b, the Fierz interference term in neutron beta decay. As the analysis of the experiment is dependent on the isotropic emission of protons in beta decay beam polarization is unwanted.

However the proposed to abBA experiment, which is intended to simultaneously measure the four T-even neutron beta decay coefficients, depends on a clearly measured neutron spin flip efficiency in order to extract the physics based asymmetry from the experimental asymmetry. [4]

5.3 n^3He

Data analysis for the n^3He experiment is currently underway after a successful data acquisition period. By combining the physics based asymmetry from the n^3He experiment with the value of h_π^1 will provide a new range of values for the coupling constants h_p^0 and h_ω^0 from the DDH model of the hadronic weak interaction.

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Vita

Connor Gautam was born in Plantation, Florida on September 5th 1991 to Diana Gautam. He spent most of his childhood in central Illinois before moving to Tennessee. He received a Bachelor of Science from UTK in 2013 Since then he has been pursuing his graduate studies with a focus in fundamental nuclear physics.