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An Analysis of the Parity Violating Asymmetry of Polarized Neutron Capture in Hydrogen from the NPDGamma Experiment

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AN ANALYSIS OF THE PARITY VIOLATING ASYMMETRY OF POLARIZED NEUTRON CAPTURE IN HYDROGEN FROM THE NPDGAMMA EXPERIMENT

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at The University of Kentucky

By
Elise Tang
Lexington, Kentucky

Director: Dr. Christopher Crawford, Professor of Physics and Astronomy
Lexington, Kentucky
2015
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AN ANALYSIS OF THE PARITY VIOLATING ASYMMETRY OF POLARIZED NEUTRON CAPTURE IN HYDROGEN FROM THE NPDGAMMA EXPERIMENT

The NPDγ Experiment is used to study the $\vec{n} + p \rightarrow d + \gamma$ reaction for the purpose of examining the hadronic weak interaction. The nucleon-nucleon interaction is overwhelmingly mediated by the strong force, however, the weak part can be extracted by a study of its parity violating manifestations. When neutrons are incident on protons, deuterons and 2.2 MeV gamma rays are produced. If the incoming neutrons are polarized, the parity violating weak interaction gives rise to a measured spatial asymmetry, $A_\gamma$, in the outgoing gamma rays, as $\vec{\sigma}_n \cdot \vec{k}_\gamma$ is parity odd.

At low energies, the weak nucleon-nucleon interaction can be modeled as meson exchange and characterized with six parameters. NPDγ is sensitive to one of these parameters, $h_\pi$. Previous measurements that extrapolate $h_\pi$ from more complicated interactions disagree, and disagree with the theoretical reasonable range. Additionally, a previous iteration of the NPDγ Experiment performed at Los Alamos National Lab was statistics limited in its measurement of $A_\gamma$. For this reason, a new measurement was performed at the high neutron flux Spallation Neutron Source at Oak Ridge National Lab.

In the experiment, a high flux of cold neutrons was polarized to $\sim$95% by a supermirror polarizer, the spins flipped in a defined sequence by a radio-frequency spin rotator, and then the neutrons captured on a 16L liquid para-hydrogen target, which emits gamma-rays asymmetrically upon capture. The gamma-rays are detected in a $3\pi$ array of 48 CsI crystal
detectors. This thesis discusses the NPDγ Experiment in detail, and includes an analysis of subset of the NPDγ data that has unique timing and data acquisition properties that preclude it being analyzed with the combined data set. Aγ was extracted with a result of 

\[(6.254 \pm 37.694) \times 10^{-9}\].

Elise Tang

December 10, 2015
AN ANALYSIS OF THE PARITY VIOLATING ASYMMETRY OF POLARIZED NEUTRON CAPTURE IN HYDROGEN FROM THE NPDGAMMA EXPERIMENT

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This thesis is dedicated to my parents, for never doubting me, to my husband, for believing I could do it, and to my sweet baby, whose birth I cherish more than this, and who I hope to inspire with this work.
I would like to acknowledge the instruction and insight of my advisor, Chris Crawford, and his patience in teaching me. I would also like to acknowledge the hard work of the members of the NPDGamma collaboration, without whom there would be no experiment.

I would like to thank Seppo Pentillä for teaching me labwork, David Bowman and Geoff Greene for enlightening conversations about the physics of the experiment, and in particular Zhaowen Tang for many useful discussions and seeing this work to its end.
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Chapter 1

Introduction

1.1 Parity Violation and the Weak Force

The discrete symmetry groups charge-conjugation (C), parity (P), and time-reversal invariance (T) were historically considered to all be conserved, i.e. invariant under transformation of the operator. Parity transformation is inversion under spatial reflection, i.e. $P(\vec{x}) = -\vec{x}$.

In the 1950’s there arose an unexplainable feature in the decays of the $\tau$ and $\Theta$ strange mesons. The $\tau^+$ decays to 3 $\pi$ mesons, and the $\Theta^+$ decays to two $\pi$ mesons, and since $\pi$ mesons have intrinsic negative parity then $\tau$ and $\Theta$ have different parities, see Eq. 1.1.1. This is referred to as the tau-theta puzzle. However, the masses and lifetimes of the two particles were found to be the same, so Lee and Yang proposed that parity must be violated in the weak force, and that $\tau^+$ and $\Theta^+$ were manifestations of the same particle with different decay modes [1]. $\Theta$ and $\tau$ were later found to be the same particle, the positive kaon.

$$\Theta^+ = \pi^+ + \pi^0 \quad parity \ even \quad (1.1.1)$$

$$\tau^+ = \pi^+ + \pi^+ + \pi^- \quad parity \ odd \quad (1.1.2)$$

Following the seminal paper by Lee and Yang, Madame Wu, et al., conducted the first
experiment that proved parity violation in the weak force [2]. In the experiment, $^{60}\text{Co}$ nuclei were polarized and the $\beta$-decay electrons were detected in the polar and equatorial plane. If parity were conserved, the number of detected particles in each location would not be correlated with the $^{60}\text{Co}$ spin direction. But if parity is violated, then $\vec{p}_e \cdot \sigma_C^{\text{o}}$ is parity odd, and results in a parity-odd observable of the outgoing electron spatial distribution as shown in Eq. 1.1.3 [1].

$$I(\theta)d\theta = A(1 + \alpha \cos \theta) \sin \theta d\theta$$  \hspace{1cm} (1.1.3)

The non-zero measurement of $\alpha$ by Wu, et al, proved that parity is violated in the weak force, as numerous following experiments confirmed.

After parity violation in weak processes was discovered, the form of the weak current was changed to reflect this parity violation via a mixture of vector and axial-vector currents [3]

$$J^W_{\mu} = \bar{\psi} \gamma_{\mu} (1 - \gamma_5) \psi$$ \hspace{1cm} (1.1.4)

where $\bar{\psi} \gamma_{\mu} \psi$ is a vector, which is negative under parity, and $\bar{\psi} \gamma_5 \gamma_{\mu} \psi$ is an axial vector, which is positive under parity transformation. Since the weak force is measured experimentally to be maximally parity violating, the mathematical representation of the weak force must include this fact. Beginning with the massless Dirac equation, if $u_1$ and $u_2$ are two-component spinors with $u_1$ representing left-handed particles and right-handed antipar-
particles, and \( u_2 \) representing right-handed particles and left-handed antiparticles, then

\[
\begin{align*}
    u &= \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \\
    \frac{1}{2} (1 - \gamma^5) u &= \begin{pmatrix} u_1 \\ 0 \end{pmatrix}
\end{align*}
\]

(1.1.5)

Only the left-handed particles (right-handed antiparticles) are selected, which is maximally parity violating. If the particles have mass, then \( \frac{1}{2} (1 - \gamma^5) \) projects out the left-handed component of the particle \([4]\).

The weak interaction is well understood in the quark and leptonic sectors, however, due to complications from the strong force and nucleon structure, the hadronic weak interaction is not well understood. Many experiments have been performed in an attempt to gain an understanding of the hadronic weak interaction, however, due to complicated nuclear wavefunctions and problems achieving statistical significance these measurements are contradictory and insufficient to shed light on this interaction. It will be shown that the subject of this thesis, the NPDGamma experiment, is especially sensitive to the \( h_{\pi} \) coupling constant associated with the weak N-N interaction, due to the experiment’s inherent simplicity and lack of nuclear structure complications, as well as its statistical significance.

1.2 The Weak Nucleon Interaction

In nucleon-nucleon interactions, the weak nucleon interaction can be modeled as meson exchange between nucleons, where one coupling is via the strong force and the other coupling...
via the weak force, see Fig. 1.1. This mixture of the strong and weak forces creates parity violation in the nucleon interaction, whereas two strong or two weak couplings would both be parity conserving reactions.

![Figure 1.1: The meson exchange model of internucleon interactions involves both a strong and a weak vertex, with mesons exchanged between the two. $h$ is the coupling constant between the weak vertex and the meson, and must be determined by experiment for each meson.](image)

The strong coupling is parity conserving. However, the weak coupling occurs, at low energy, when there is an $S \to P$ transition, i.e. when $\Delta l = 1$. Since the two particles are fermions, we are limited to $S$ and $P$ states that have antisymmetric total wavefunctions, i.e. the wavefunction must be odd in the product of one of spin, angular momentum, or isospin, or in all three. Thus, in the notation $^{2S+1}L_J$, the available states are $^3S_1$ with $I=0$, $^1S_0$ with $I=1$, $^3P_0$ with $I=1$, $^3P_1$ with $I=1$, $^3P_2$ with $I=1$, and $^1P_1$ with $I=0$. Taking into account conservation of $J$ and $I$, the transitions that can occur are:

$^3S_1 \to ^3P_1$ with $\Delta I = 1$, 


\[ ^3S_1 \rightarrow ^1P_1 \text{ with } \Delta I = 0, \]

\[ ^1S_0 \rightarrow ^3P_0 \text{ with } \Delta I = 0, 1, 2. \]

There is no transition to \(^3P_2\), as there is no S-state with corresponding \(J=2\), and angular momentum must be conserved. See Fig. 1.2. These are parameterized by Danilov in [8].

![Diagram](image)

Figure 1.2: Possible transitions for the weak part of the N-N interaction. S-P mixtures ensure parity violation.

In 1980 Desplanques, Donoghue and Holstein calculated the parity nonconserving weak Hamiltonian in the meson exchange picture using meson-nucleon couplings, Eq. 1.2.1 [5, 6]

\[
H^{PNC} = \frac{h_\pi}{2} \bar{N}(\tau \times \phi_\pi)N
+ \bar{N}(h_\rho^0 \phi_\rho^0 + h_\rho^1 \phi_\rho^1 + \frac{h_\rho^2}{2\sqrt{6}} (3\tau_z \phi_\rho^0))\gamma_\mu \gamma_5 N
+ \bar{N}(h_\omega^0 \phi_\omega^0 + h_\omega^1 \phi_\omega^1)\gamma_\mu \gamma_5 N - h_\rho^t \bar{N}(\tau \times \phi_\rho^t) \frac{\sigma_\mu \nu k^\nu}{2M} \gamma_5 N. \tag{1.2.1}
\]

The weak N-N interaction is here studied at low energies, where direct quark-quark interactions are not possible due to the nucleon separation. At such low energies light mesons
dominate the interaction. Neutral scalar mesons, including $\pi_0$, $\eta$, $\eta'$ and $\delta^0$, are disallowed due to Barton’s Theorem, which forbids couplings between neutral, zero angular momentum mesons and on-shell nucleons due to CP invariance [5]. The remaining light mesons include $\pi_\pm, \rho_\pm, \rho_0$ and $\omega_0$.

Desplanques, Donahue, and Holstein calculated theoretical “best values” and “reasonable ranges” for each of the meson-nucleon coupling constants, shown in Table 1.1. These theoretical values are compared to experimental results to test the validity of both theory and experiment.

Table 1.1: DDH Theoretical Best Values and Reasonable Ranges

<table>
<thead>
<tr>
<th>Coupling Constant</th>
<th>Best Value</th>
<th>Reasonable Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{\pi}$</td>
<td>0.45</td>
<td>0 – 1.14</td>
</tr>
<tr>
<td>$h_{\rho}^0$</td>
<td>-1.14</td>
<td>-3.08 – 1.14</td>
</tr>
<tr>
<td>$h_{\rho}^1$</td>
<td>-0.019</td>
<td>-0.038 – 0</td>
</tr>
<tr>
<td>$h_{\rho}^2$</td>
<td>-0.95</td>
<td>-1.1 – 0.75</td>
</tr>
<tr>
<td>$h_{\omega}^0$</td>
<td>-0.19</td>
<td>-1.03 – 0.57</td>
</tr>
<tr>
<td>$h_{\omega}^1$</td>
<td>-0.11</td>
<td>-0.076 – -0.19</td>
</tr>
</tbody>
</table>

The pion coupling is of particular interest as it is the long-range meson coupling. The parity violating spatial gamma ray asymmetry, $A_\gamma$, in the capture of polarized neutrons on protons ($\bar{n}+p\rightarrow d+\gamma$) is primarily sensitive to the pion coupling constant, with only small contributions from other mesons. This work describes the NPDGamma experiment, which
measured:

\[ A_\gamma = -0.11 h_\pi - 0.001 h_\rho^1 - 0.003 h_\omega^1 \]  \hspace{1cm} (1.2.2)

The first term in Eq. 1.2.1 is the pion term. The pion field is given by:

\[ \phi_\pi = \begin{pmatrix} \frac{\sqrt{2}}{2} (\phi_+ + \phi_-) \\ \frac{\sqrt{2}}{2} (\phi_+ - \phi_-) \\ \phi_0 \end{pmatrix} \]  \hspace{1cm} (1.2.3)

and \( \tau \) is the normal set of isospin matrices. The third term of the cross product between these excludes the neutral pion, as required by Barton’s theorem, but includes the \( \pi_+, \pi_- \), which has \( I=1,-1 \). This shows that the pion is involved only in \( \Delta I=1 \) transitions. In the case of \( \bar{n}+p \rightarrow d+\gamma \), the bound n-p system is an isoscalar, while the pion is an isovector. Therefore this interaction is \( \Delta I=1 \). Danilov [7] shows that \( A_\gamma \) occurs from the isovector part of the weak interaction. Therefore a measurement of \( A_\gamma \) can be used to extract \( h_\pi \).

This is seen by noticing that the \( ^3S_1 \rightarrow ^3P_1 \) transition is \( \Delta I=1 \) as in Fig. 1.4.

The weak Hamiltonian has both a charged current part and a neutral current part, which is Eqns. 1.2.4 and 1.2.5 [9], where \( \theta_c \) is the Cabibbo angle, \( G_F \) is the Fermi coupling constant, and \( \Delta S \) is the change in strangeness.

\[
H^c = \frac{G_F}{\sqrt{2}} \{ \cos^2 \theta_c J^{h\mu}_\mu (\Delta S = 0) J^{h\mu\dagger}_\mu (\Delta S = 0) + \sin^2 \theta_c J^{h\mu}_\mu (\Delta S = \pm 1) J^{h\mu\dagger}_\mu (\Delta S = \pm 1) \}  \hspace{1cm} (1.2.4)
\]

\[
H^n = \frac{G_F}{\sqrt{2}} \rho 2 J^{h\mu}_\mu (\Delta S = 0) J^{h\mu\dagger}_\mu (\Delta S = 0)  \hspace{1cm} (1.2.5)
\]

The \( \cos^2 \theta_c \) term is an isovector, with \( \Delta I = 0,1,2 \). The \( \sin^2 \theta_c \) term is an isospinor, with \( \Delta I = 0,1 \). For the \( \cos^2 \theta_c \) term, when \( I=1 \), the \( \Delta I = 1 \) disappears in the chiral limit.
Conversely, the $\sin^2 \theta_c$ is strangeness nonconserving, therefore the chiral limit does not apply and the $I=1$ remains.

Since the pion is associated with the $\Delta I=1$ transition (shown above), and since this transition is not allowed in the $\cos^2 \theta_c$ term in Eq. 1.2.4, the $\sin^2 \theta_c$ and the neutral current terms remain. Compared to the $\sin^2 \theta_c$ term, the neutral current term can be enhanced on the order of 40, while the $\cos^2 \theta_c$, with $\Delta I=0,2$, is only enhanced by neutral currents on order 2. The conclusion is that the pion-nucleon interaction is primarily a neutral current interaction, and measurement of the pion coupling gives insight into the neutral current N-N interaction [9].

Neutral current flavor changing weak interactions are suppressed by the GIM mechanism, which means that weak neutral current interactions can only be studied when flavor is conserved, which can only be done via the N-N weak interaction [5]. Since the pion coupling has been shown to be neutral current dominant, and since single nucleon interactions eliminate complications from complex nuclei, this mean that the NPDGamma experiment is uniquely favorable for studying quark neutral current weak interactions, in addition to information gained about the hadronic weak interaction.

To know the actual values of the coupling constants at least the same number of experiments must be done as couplings. Most possible experiments measure results that are linear combinations of several meson-nucleon coupling constants. Some different parity-violating
observables sensitive to the weak N-N interaction include:

1. Circular gamma polarization, $P_\gamma$
2. Asymmetry in decay products, $A_d$
3. Neutron spin rotation, $\phi_n$
4. Elastic $\vec{p}$-N scattering, $A_L$

Circular polarization in gamma-rays can be produced during decays from excited nuclear states. For parity to be conserved, total circular polarization must be zero, i.e. the amount of left-handed and right-handed emitted circularly polarized radiation must be equal. Parity violation in circular polarization is created by a linear combination of E1 and M1 emissions, where E1 is given by

$$\hat{\epsilon}_\gamma \cdot \mathbf{p}$$  (1.2.6)

and M1 is

$$i\hat{\epsilon}_\gamma \times \mathbf{q} \cdot \mathbf{L}$$  (1.2.7)

where $\hat{\epsilon}_\gamma$ is the polarization of the gamma ray and $\mathbf{q}$ is momentum transfer.

The momentum, $\mathbf{p}$, is a vector, with negative parity, and the angular momentum, $\mathbf{L}$, is a pseudovector with positive parity. Since $\hat{\epsilon}_\gamma \perp \mathbf{q}$, then E1 is negative parity and M1 is positive parity, which mix to create parity violation in circularly polarized radiation [3].

Measurements of parity violation in circular gamma-rays have been done in the $\vec{n}+p \rightarrow \text{d}+\gamma$ reaction, in decays of $^{18}\text{F}$, and in decays of $^{21}\text{Ne}$. The most sensitive experiment was
in $^{18}$F, which will be described later.

Parity violation in gamma-ray distributions is described in detail in this work, particularly the $\vec{n}+p \rightarrow d+\gamma$ interaction. It is important because this few-body system has exactly calculable wave functions. Other asymmetry-type measurements include decays from polarized $^{19}$F and $^{180}$Hf. There is also a currently ongoing experiment to measure the asymmetry in outgoing protons from the capture of polarized neutrons on $^3$He. This experiment is sensitive to the following linear combination of meson couplings:

$$A_p = -0.18 h_\pi - 0.13 h_\omega^0 + 0.05 h_\omega^1 - 0.14 h_\rho^0 + 0.027 h_\rho^1 + 0.0012 h_\rho^2.$$  \hspace{1cm} (1.2.8)

Neutron spin rotation experiments measure the rotation of neutron spins after traveling through a length of material. This rotation is caused by the parity violating term $\sigma_n \cdot k_n$, which changes the effective index of refraction differently for the two helicities of neutrons \cite{10, 11}. This experiment has been done recently at NIST, using liquid $^4$He as a target, which is sensitive mostly to $h_\pi$, but significant in other parameters as well:

$$\frac{d\phi}{dz} = -0.97 h_\pi - 0.22 h_\omega^0 + 0.22 h_\omega^1 - 0.32 h_\rho^0 + 0.11 h_\rho^1.$$  \hspace{1cm} (1.2.9)

Elastic scattering experiments measure the parity-violating longitudinal analyzing power. Experiments are done with polarized proton beams hitting unpolarized nuclear targets. The beam helicity is rapidly changed, and the asymmetry of the cross sections for the two helicity states is measured.
1.3 Measurements of $h_\pi$

The two most sensitive measurements of $h_\pi$ are from parity violating circular polarization in decays from the excited state of $^{18}\text{F}$, and a parity violating spin asymmetry in the angular distribution of gamma-ray emission from polarized neutron capture on protons, $\bar{n}+p\to d+\gamma$.

The $^{18}\text{F}$ measurement was important as it contradicted theoretical predictions, as well as measurements of $h_\pi$ from anapole moments[12]. $\bar{n}+p\to d+\gamma$ is the simplest process for this measurement, not involving any complex nuclei, and is thus important for resolving these conflicts.

**Parity Violation Measurements in $^{18}\text{F}$**

Measurements of parity violating circular polarization in the 1.081 MeV $\gamma$ transition of $^{18}\text{F}$ are sensitive almost exclusively to $h_\pi$, $|P_\gamma| = (4.2 \pm 1.0) \times 10^3|h_\pi|$[13], making this experiment one of the few comparable to the NPDGamma experiment in sensitivity to $h_\pi$.

$^{18}\text{F}$ has a parity doublet, i.e. two closely spaced energy levels with the same spin but opposite parity, with $J=0^+, I=1$ and $J=0^-, I=0$[5]. The ground state is $1^+, I=0$. The decay from the $0^-$ state is an E1 transition that is isospin forbidden and thus has a very long lifetime. The decay from $0^+$ is an M1 transition with a short lifetime. The closeness of the two states (39 keV) leads to mixing of the states, resulting in parity violation. The PNC observable is also amplified by the ratio of the M1 to E1 transitions, a trait that is common
in complex nuclei parity doublets [5]. This enhancement makes the measurement of PNC in complex nuclei easier, but results are complicated by nuclear structure effects. Since this transition is mainly $\Delta I=1$, measurements of parity violation in $^{18}$F circular polarization allows extraction of the $h_\pi$ parameter.

$$\text{Amplification} = \frac{\langle G.S.|T_{M1}|+\rangle}{\langle G.S.|T_{E1}|-\rangle}$$

(1.3.1)

Several $^{18}$F experiments have been performed [14, 15, 16, 17]. For the experiment the excited flourine target atoms were created using flowing H$_2$O and a $^3$He$^+$ beam for the reaction $^{16}$O($^3$He, p)$^{18}$F*. Four circular polarimeters were placed at right angles around the target, using germanium detectors for gamma ray detection, see Fig. 1.3. The magnetic fields were reversed regularly. The circular polarization is extracted from

$$P_\gamma = A/\eta,$$

(1.3.2)

where $\eta$ is the analyzing power of the polarimeter and

$$A = \frac{R-1}{R+1}$$

(1.3.3)

$$R = \left(\frac{N_L^+ N_R^- N_U^- N_D^-}{N_L^- N_R^+ N_U^+ N_D^+}\right)^{1/4}$$

(1.3.4)

where $N$ is the number of gamma rays (integrated), the superscript is the magnetization state, and subscript is the polarimeter [5].

Adelberger and Haxton [5] calculate the “world average” of $P_\gamma$ in $^{18}$F to be $(8 \pm 39) \times 10^{-5}$, well below the DDH “best” value of $(208 \pm 49) \times 10^{-5}$. This discrepancy puts
into suspect complications that can arise in theoretical calculations of processes in complex nuclei. Theoretical extraction of $h_\pi$ from $^{18}$F is more reliable than for other nuclei. Typically, extraction of the meson coupling constants from nuclear experiments involve *ab initio* calculations of transition matrix elements, however for $^{18}$F these can actually be measured. However, recent model-dependent theoretical calculations of $h_\pi$ contradict each other, as well as the DDH value [12]. The NPDGamma experiment is well poised to resolve this issue, as it involves the simplest nuclear process, instead of requiring complex matrix element calculations in the theory. Extraction of $h_\pi$ from the NPDGamma measurement is model-independent.
LANL NPDGamma Experiment

The $\vec{n}+p\rightarrow d+\gamma$ reaction is the capture of neutron on proton, resulting in a deuteron bound state. The deuteron ground state is of $^3S_1$ configuration with $I=0$, ignoring the $\sim4\%$ $^3D_1$ admixture [9]. The n-p system has possible states $^3S_1$, $I=0$ and $^1S_0$, $I=1$. The transition between $^3S_1$ states is suppressed due to orthogonality of the spatial wavefunctions [9], and $\langle^1S_0|M1|^3S_1\rangle$ is parity conserving and occurs via the strong interaction. Therefore, for parity violation to be included and the weak force to be introduced, admixtures of P-states must arise. The possible P-states are shown in Fig. 1.4, with the main M1 transition and admixed E1 transitions.

![Diagram showing possible transitions for the n-p capture in $\vec{n}+p\rightarrow d+\gamma$ reaction. S-P mixtures ensure parity violation. The blue arrow is the main M1, parity conserving, transition. The red arrows indicate E1, parity violating, admixtures with $\Delta I=1$.](image)

The $\Delta I=1$ transition here, i.e. the transition of $^3S_1$ into $^3P_1$, gives rise to $A_\gamma$ and the pion exchange from the DDH model of N-N interactions. This is what the NPDGamma...
experiment measures. The initial $J=0$ continuum states cannot result in $A_\gamma$ since they are spherical states, and indeed result in parity-violating circular gamma rays see [9, 18].

The $\bar{n}+p\rightarrow d+\gamma$ experiment has been performed previously, the first version at the ILL in Grenoble, France in the 1970’s, with a result of $A_\gamma = (0.6 \pm 2.1) \times 10^{-7}$ [19]. More recently, NPDGamma was performed at the Los Alamos Science Center (LANSCE) at Los Alamos National Laboratory. This experiment measured $A_\gamma = [1.2 \pm 2.1 \text{ (stat.)} \pm 0.2 \text{ (sys.)}] \times 10^{-7}$. Unfortunately, as described in Sec. 1.4 this experiment was statistics limited due to the low flux of the neutron source, and the low polarization of the neutron polarizer.

1.4 Improvements of the NPDGamma Experiment at the Spallation Neutron Source

The SNS version of the NPDGamma experiment is an upgrade to the LANL version of the experiment, which was statistics limited. The setup of the experiment is described in detail in the next chapter. To increase the neutron flux to the target, several important changes were made. The integrated capture flux at Flight Path 12 at LANSCE was reported to be $(2.68 \pm 0.13) \times 10^7 \text{ n/s/cm}^2$ [20]. At the SNS, the integrated capture flux at the end of the beam pipe at 1.4 MW was measured to be roughly $4.45 \times 10^8 \text{ n/s/cm}^2$, over an order of magnitude increase. Whereas the LANL experiment used a $^3\text{He}$ spin filter as a neutron polarizer, the SNS experiment uses a supermirror polarizer, increasing beam polarization from about 55% to about 95%. Additionally, since Al is the top background contributor, the
three Al windows of the cryostat were thinned to 0.063” from 0.125”. These changes combine
to help the SNS NPDGamma to have sufficient statistics for a meaningful measurement of
$A_\gamma$. 
Chapter 2

Experimental Setup

2.1 Introduction

The NPDGamma Experiment was run on beamline 13 of the Spallation Neutron Source at Oak Ridge National Laboratory, in Oak Ridge, Tennessee. The experiment was set up in the beamline 13 experimental cave as in the schematic Fig. 2.1. Protons from the linear accelerator are bunched into 60 Hz pulses in a storage ring, then are released onto a Hg target. Neutrons are released from the target and moderated by cold H$_2$ gas. The cold neutrons travel down a neutron guide, through two neutron choppers. There are two $^3$He beam monitors for monitoring beam changes. Between them is the supermirror beam polarizer, which selects a single neutron spin state.

The polarized neutrons enter a radio frequency spin flipper (RFSF). The spin flipper flips the spins of the neutrons in a pre-programmed sequence. The proton target is liquid H$_2$ contained in an aluminum vessel. Outgoing gamma rays are detected in a segmented CsI detector array. There is also a 10 Gauss magnetic holding field for preserving neutron spin. There is also a removable $^3$He neutron monitor behind the hydrogen target outside the detector array.
Figure 2.1: This shows the relative setup of the NPDGamma experiment as run in hydrogen mode. Neutron beam comes from the left. Schematic adapted from figure by Zhaowen Tang.

### 2.2 Neutron Beam

Neutrons for the NPDGamma experiment are supplied by the Spallation Neutron Source to the Fundamental Neutron Physics Beamline (FnPB), beamline 13b. Beamline 13 is the only beamline at the Spallation Neutron Source that is used for fundamental nuclear physics experiments. A 1000 ft linear accelerator accelerates H ions to 1 GeV. The ions travel around an accumulator ring where they are stripped of their electrons and bunched into 60 Hz pulses [21]. The accumulator ring is about 220 meters in circumference with 0.6 μs pulses [22].

These pulses are released onto a liquid Hg target. The Hg liquid is circulated inside the target chamber to help keep it below 90 degrees C [23]. Hg was chosen as a target in part because of its excellent heat transport properties. The system as a whole has a
“heat transfer capacity of 1.2 MW” [23]. Mercury also has a high atomic number, resulting in the spallation of 20-30 neutrons per proton [23, 21]. The neutrons then interact with a supercritical hydrogen moderator. The moderator temperature is helium-cooled to near 20 K [24]. This reduces the neutron energy to the cold neutron range (∼1-25 meV). The moderator is unpoisoned and coupled, giving the spectrum a tail into the low energies. Using a poison or a decoupler in the moderator would absorb the low energy neutrons [25]. Because of this tail, we must use neutron choppers to avoid overlapping energies, see 2.4. The neutrons then go down a supermirror neutron guide to the beamline 13 experimental cave, approximately 15.15 meters from the moderator to the end of the guide. The neutron energy profile is shown in Fig. 2.2. This measurement was done by Erik Iverson of the SNS Neutronics Group using a $^3$He proportional counter [26].

Figure 2.2: Unchopped flux as a function of wavelength out of the end of the beampipe.
2.3 Neutron Guide

[9, 27, 28] Neutron interactions with materials can be modeled with the time-independent Schrödinger equation:

\[ \nabla^2 \Psi(\vec{r}) + K^2 \Psi(\vec{r}) = 0, \quad (2.3.1) \]

where

\[ K^2 = \frac{2m}{\hbar^2} [E - V(\vec{r})]. \quad (2.3.2) \]

The potential, \( V(\vec{r}) \), is the Fermi pseudopotential, which models s-wave scattering of a free neutron from a nucleus. For low energy neutrons averaged over \( \vec{r} \) this potential is

\[ V = \frac{2\pi \hbar^2 N b}{m}, \quad (2.3.3) \]

where \( N \) is the mean number of scattering nuclei per unit volume and \( b \) is the mean bound scattering length. The quantity \( Nb \) is referred to as the scattering-length density. The neutron energy, \( E \), is given by the de Broglie relation,

\[ E = \frac{\hbar^2 k^2}{2m}, \quad (2.3.4) \]

The index of refraction is defined as

\[ n = \frac{v_1}{v_2}, \quad (2.3.5) \]

where \( v_1 \) is the neutron phase velocity in the initial medium and \( v_2 \) is the phase velocity in the incident medium. Since \( v = \lambda f \) and \( \lambda = \frac{2\pi}{k} \), then

\[ n = \frac{K}{k} = \sqrt{1 - \frac{V}{E}} \quad (2.3.6) \]
Using Eqns. 2.3.3 and 2.3.4, the index of refraction for neutrons incident on a medium, disregarding absorption, becomes

\[ n = \sqrt{1 - \frac{4\pi Nb}{k^2}} \approx 1 - \frac{\lambda^2 Nb}{2\pi} \] (2.3.7)

For many materials Nb is greater than 1, so \( n < 1 \), which makes total external reflection possible. Using Snell’s Law:

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \] (2.3.8)

For total external reflection, \( \theta_2 = \pi/2 \) and the critical angle \( \theta_c \) is

\[ \theta_c = \arcsin \frac{n_2}{n_1} \] (2.3.9)

\[ \sin \theta_c = 1 - \frac{\lambda^2 Nb}{2\pi} \] (2.3.10)

Neutron reflection happens at grazing angles [27], where the transverse velocity is less than the nuclear potential, and the wavelength spans several nuclei.

\[ \theta_c = \frac{\pi}{2} - \theta^*_c \] (2.3.11)

\[ \sin(\frac{\pi}{2} - \theta^*_c) = \cos \theta^*_c = 1 - \frac{\lambda^2 Nb}{2\pi} \] (2.3.12)

At grazing incidence, \( \theta_c \) is large, so \( \theta^*_c \) is small.

\[ 1 - \frac{\theta^*_c}{2} = 1 - \frac{\lambda^2 Nb}{2\pi} \] (2.3.13)

\[ \theta^*_c = \lambda \sqrt{N/n} \] (2.3.14)
Neutron beam guides take advantage of the reflective properties of certain materials to transport neutrons by grazing-incidence interactions from neutron sources to experimental instruments. $^{58}\text{Ni}$ is often used in neutron mirrors due to its high Nb value. Neutron guides are often curved to avoid line-of-sight to the moderator, as is the case at beamline 13. This curvature makes the transmission wavelength dependent, and reduces fast neutron and gamma ray background at the experiment.

![Figure 2.3: Specular reflection of neutrons from a neutron mirror. The critical angle for total external reflection, $\theta_c$, and corresponding grazing angle of incidence, $\theta^*_c$.](image)

Supermirrors are multilayer neutron mirrors. Supermirrors are used to increase the range of angles with total external reflection [27]. This allows higher reflection of multiple neutron energies. Similar to classic optical multilayer mirrors, multilayer neutron mirrors with alternating high-low index of refraction materials of equal spacing will enhance reflectivity via Bragg’s Law. However, by having variably spaced layers, high reflection for a range of wavelengths can be achieved for increased $\theta^*_c$. The higher critical angle of a supermirror is...
characterized by $m$, which is inversely proportional to the value for $^{58}\text{Ni}$ [28].

$$m = \frac{\theta}{\theta_{58\text{Ni}}} \tag{2.3.15}$$

The beamline 13B beam guide is built from supermirrors and has both straight and curved sections. The beamline starts about 1 meter from the moderator face. The first section is straight, 1.275 m long with a 10 cm x 12 cm rectangular cross section and an $m$ value of 3.6 [26]. The next section is a bent guide approximately 4.5 m long, bending beam-left. The bender has five channels to increase surface interactions, and the top, bottom, and beam-right sides have a $m=3.8$ coating, while the beam-left side has a $m=2.3$ coating. The radius of curvature of the bender is 117 m [26]. The bender reduces backgrounds from fast neutrons and gamma rays by eliminating line-of-sight to the moderator. The final section of the beam guide ends 15 m from the face of the moderator and is a $m=3.6$ supermirror [26].

### 2.4 Choppers

Since the Spallation Neutron Source supplies a 60 Hz pulsed cold neutron spectrum, there is a natural overlap of different neutron energies between pulses. We used neutrons in the 2.5 Å to 6 Å wavelength range (2.3 meV-13 meV) for the NPDGamma experiment. There are a variety of reasons to choose this range. In particular, it is vital to use neutrons with energies less than 15 meV, the energy gap between para- and ortho-hydrogen, as discussed
in Sec. 2.9. Lower energy neutrons also have higher cross sections, and are easier to polarize and spin flip. Additionally, this range is on the peak of the FnPB spectrum, giving the maximum flux for the experiment.

As discussed in Sec 2.7, the spin flipper is tuned to flip only neutrons in a particular wavelength range. Any neutrons outside this range will be only partially polarized, leading to depolarization of the beam. The asymmetry can only be found by correlation of the neutron spin to the gamma direction, so any depolarization will dilute the signal. Overlap neutrons occur when different energy neutrons, from different pulses, arrive at the experiment at the same time.

Figure 2.4: The experiment is at a certain distance down the beamline. By placing choppers between the moderator and the experiment most unwanted neutrons are blocked.

To reduce these wraparound neutrons as much as possible, neutron choppers are used.
Neutron choppers are gadolinium coated rotating disks with partial openings that allow the beam through for a certain amount of time. The choppers rotate at 60 Hz along with the beam pulses, but are phased in a way to block unwanted neutrons. As shown in Fig. 2.4, the pulses come every 16.67 ms. By placing the choppers at certain distances and phasing them correctly, most wraparound neutrons can be blocked. However, it is impossible to block all wraparound neutrons, as very slow ones will leak through several pulses later. These leakage neutrons are seen in Fig. 2.5, shown on log scale to emphasize the amount of wraparounds compared to the real signal. A small amount of wraparounds occur three pulses later, and more six pulses later, however, the flux of these are two orders of magnitude smaller than the flux of the normal pulse.

Figure 2.5: While most unwanted neutrons are blocked by the choppers, some wraparound neutrons still leak through in other pulse windows.
Chopper Phasing Optimization

To optimize the beam for desired neutrons, chopper 1 was placed 5.5 m from the moderator with an opening angle of 132 deg and chopper 2 was placed 7.5 m from the moderator with an opening angle of 167 deg [29]. The phase of a chopper is the angle between the chopper position $t_0$ and the chopper opening. The chopper phases can be optimized to maximize the figure of merit, $\text{Flux} \times \text{Polarization}^2$. I did the following investigation into the best chopper phasing, using results of the McStas model written by Paul Huffman of North Carolina State University, and Christopher Crawford of the University of Kentucky.

First, I compared experimental data taken at 1Hz to the McStas simulation of the same condition. These will not match exactly due to unsimulated conditions that can exist in reality, such as moderator energy and distribution, and uncertainty in detector location. The flat electronic pedestal of the data is removed so that the tails of the data and simulation match, see Fig. 2.6.

Next, the 60 Hz data and 60 Hz McStas are compared, with the pedestal match included. As seen in Fig. 2.7(a), there is still an offset and appears also to be a shape difference. The McStas and experiment data are plotted versus each other, and fitted for the offset and scaling difference. When this second normalization is applied, the results match very well, as seen in Fig. 2.7(b).

Now that the normalized McStas now matches the data well, I used it to model chop-
Figure 2.6: Comparing 1Hz data and 1Hz McStas simulation. The pedestals are matched.

per phases. The chopper phases are varied while trying to maximize the figure of merit, $\text{Flux} \times \text{Polarization}^2$. The simulation includes the beam flux, counter-rotating choppers, wavelength dependent capture on $^2\text{H}$, and the polarization from the supermirror polarizer. It does not include the wraparound neutrons, which are depolarized by the spin flipper.

The results are seen in Fig. 2.8. At this resolution, it is seen that there is a wide range of phase combinations that will maximize the figure of merit.

### 2.5 Beam Monitors

Three beam monitors were used to measure relative neutron flux. Two monitors were fixed, ‘m1’ at the end of the beam pipe and before the supermirror polarizer, and ‘m2’ after the polarizer. The ‘triple monitor’ is a small portable monitor that was typically used in various
Figure 2.7: 60 Hz data and 60 Hz McStas simulation after the scaling factor and offset have been applied to the simulation to match it more exactly to real data. Differences still exist for the gamma flash at the beginning of the pulse. This gamma flash is not modeled.

locations behind the detector array.

All three monitors are $^3$He proportional chambers. They are filled with a partial pressure of $^3$He, about 2% for m1 and 1.3% for m2, and the triple monitor is black to neutrons. $^3$He captures neutrons in the following interaction:

$$ n + ^3He \rightarrow p + t + 760 \text{ keV} \quad (2.5.1) $$

The products ionize the gas, resulting in $e^-$ and $^3$He$^+$ ions, which are then collected by high
Figure 2.8: Both chopper phases were varied and the resulting figure of merit is seen.

voltage wires, resulting in a signal that is converted to voltage and read into a channel of the data acquisition system. These monitors are what are called “1/v” monitors. This means that the capture efficiency of the detectors depends inversely on the velocity of the incoming neutrons. This is because the cross sections go up for slower neutrons, due to increased time inside the interaction area. As can be seen in reference [4], the cross section is given by the transition rate per unit volume times the number of final states over the initial flux.

The transition rate times the number of final states is just the rate of interacting particles (e.g. scattered or absorbed, or both, depending on the desired interaction), $r_i$. The initial flux is given by density of beam particles, times the velocity of the beam through a cross
section, \( \rho_b v_b \). The interaction cross section then becomes:

\[
\sigma = \frac{r_i}{(\rho_b v_b)n_t}
\]  

where the cross section is scaled by the number of particles in the target, \( n_t \), to remove total target dependence. The cross section is now seen to be inversely proportional to the neutron velocity (or relative velocities of target and neutron).

The signals from the first monitor, ‘m1’, are especially used to calculate cuts on unwanted data, as this monitor is located inside the concrete shielding block, lowering backgrounds, and is not correlated with asymmetry measurements made by the detectors. A typical signal is shown in Fig 2.9.

![Monitor 1 Signal](image)

Figure 2.9: **Monitor 1 Signal.** A signal in monitor 1 as a function of time bin, with dropped pulses seen near zero.
the beam after the target, for transmission measurements, and in neutron polarimetry studies.

2.6 Neutron Polarizer

The NPDGamma experiment requires neutrons to be polarized in order to extract $A_\gamma$. They are transversely polarized for convenience of detection. The type of polarizer used is a supermirror polarizer, based on the supermirror technology described in Sec. 2.3. While normal supermirrors reflect all neutrons below the critical angle, magnetized supermirrors reflect only one spin state, creating a polarized neutron beam. This is done by changing the potential to include both the Fermi potential and a magnetic field. The potential becomes:

$$V = \frac{2\pi\hbar^2Nb}{m} - \vec{\mu}_n \cdot \vec{B}$$

(2.6.1)

This changes the index of refraction to

$$n_\pm = 1 - \frac{\lambda^2Nb}{2\pi} \pm \frac{\lambda^2m\mu B}{4\pi^2\hbar^2}$$

(2.6.2)

this can be rewritten in terms of a magnetic scattering length, $b_m$ [27]:

$$b_m = \frac{2\pi\mu mB}{\hbar^2N}$$

(2.6.3)

The index of refraction can now be written [27]:

$$n_\pm = 1 - \frac{\lambda^2N}{2\pi} (b \pm b_m)$$

(2.6.4)
where “−” is for neutron spin parallel to the $\vec{B}$ field and “+” is antiparallel. Therefore, the index of refraction is spin dependent. When $b - b_m$ is near zero then the index of refraction in the mirror is the same as in the incident material and that spin state is transmitted into the glass and absorbed by boron. The other spin state, however, satisfies $b + b_m$ and is reflected if less than the critical angle. This creates a polarized neutron beam with half the flux.

The polarizing supermirror used for the NPDGamma experiment is also a bender, similar to a section of the beam guide described above. It has 45 channels and a radius of curvature of 9.6 m. The polarizer is 40 cm long [30]. The supermirror used is made from alternating layers of Si and ferromagnetic Fe. The substrate is made of boroflex glass, which absorbs the transmitted neutrons to eliminate them from the experimental area [30]. The bend in the polarizer eliminates line of sight to gamma rays produced in the boron. Having many channels allows for a more gradual bend, which gives a transmission of about 26%.

It is necessary to magnetize the Fe layers to take advantage of the spin selecting properties of a magnetic supermirror. The magnetizing field must be at least 300 G and is produced by NdFeB bar magnets placed on either side of the polarizer in pairs [30]. However, due to strict requirements on the magnetic field and magnetic field gradients in the rest of the experimental area, compensating magnets were used to cancel the field outside the polarizer. Four rows containing a total of 44 smaller NdFeB arranged with opposite
polarity to the magnetizing magnets were used to achieve this cancellation [30]. Measurements done by Balascuta, et al. [30] show that the vertical B-field gradients are less than what is required by the NPDGamma experiment, 3 mG/cm.

Since the figure of merit for the NPDGamma experiment is $P^2 F$, where $P$ is the polarization of the beam and $F$ is the flux, it is important to have a high transverse polarization, even more important than a high flux. The polarizing ability of the supermirror polarizer is given by:

$$P = \frac{R_+ - R_-}{R_+ + R_-}$$  \hspace{1cm} (2.6.5)

where $R_+$ and $R_-$ are the two neutron spin states [27].

The polarization, $P$, was measured to better than 1%, using $^3$He neutron polarimetry. The polarimetry measurements were done in 9 locations of the beam cross section and the resulting polarization is averaged over these beam locations and across wavelengths 3.7-5.8 Å. For the supermirror polarizer the polarization is [31]

$$P = 0.943 \pm 0.004.$$ \hspace{1cm} (2.6.6)

### 2.7 Spin Flipper

A neutron spin rotator changes the spin state of the neutrons from spin up to spin down. The spin rotator used is the same as the one used for the LANL NPDGamma experiment. Polarized neutrons travel down the beamline in an approximately 10 G holding field. Using
nuclear magnetic resonance (NMR) techniques, similar to a Rabi flipper, a radio frequency magnetic field is applied perpendicular to the neutron spin direction which matches the precession frequency. This causes the neutron to precess around the resultant field. If the neutron exits the field at the right time, its spin will be in the opposite direction of when it entered the spin flipper. This type of spin flipper, a resonant spin flipper, has several advantages in this experiment over an adiabatic spin flipper. An adiabatic spin flipper uses a static magnetic field gradient. This leads to Stern-Gerlach steering, which would separate the trajectories of the two spin states and lead to false asymmetries if not corrected. Additionally, any magnetic field gradient will cause changes in the neutron kinetic energy, and thus its velocity, for each spin state, again causing false asymmetries [32]. Thus the resonant spin flipper, though efficient only for a range of velocities, is instead used for this experiment.

2.7.1 Neutron Spin Rotation

For the resonant spin rotator used for the NPDGamma experiment, the polarized neutrons leave the supermirror polarizer and retain their polarization by traveling in a constant magnetic holding field, $\vec{B}_0$ in the $\hat{y}$ direction (See Fig. 4.25). Inside the spin rotator, an oscillating RF field is applied:

$$\tilde{B}(t) = B_1 \cos \Omega t \hat{z}$$ (2.7.1)
The RF frequency is matched to the Larmor frequency of the neutron. Since the energy for each spin state is $\pm \frac{1}{2} \hbar \omega$, for a spin flip:

$$\Delta E = \hbar \omega = \Delta \mu \cdot B = 2 \mu B$$

(2.7.2)

where $\mu$ is the magnetic moment of the neutron. It is defined as:

$$\mu = \frac{g \mu_N}{\hbar} I$$

(2.7.3)

$\mu_N$ is the nuclear magneton, $g$ is called the g-factor, which is a scaling factor that is different depending on the particle, and $I$ is the neutron spin, $I = \pm \frac{1}{2} \hbar$. This can be simplified by defining the gyromagnetic ratio of a particle, $\gamma_g$, as the ratio of the magnetic dipole moment to the angular momentum,

$$\gamma_g = \frac{g \mu_N}{\hbar}$$

(2.7.4)

Thus,

$$\Delta E = \hbar \omega = 2 B \frac{g \mu_N}{\hbar} I = 2 \gamma_g \frac{1}{2} \hbar B = \gamma_g \hbar B$$

(2.7.5)

Then the Larmor frequency of the particle about field $B$ is

$$\omega = \gamma_g B$$

(2.7.6)

Magnetic field gradients must be avoided, as they change the kinetic energy of the neutrons, and since the spin flipper only has a magnetic field while flipping, this energy change would be spin dependent. The advantage of an RF spin flipper is that there are no
field gradients in the frame of the neutron along the beam axis on resonance, and therefore no spin-dependent effects [32].

2.7.2 The NPDGamma Spin Flipper

The NPDGamma spin flipper consists of a solenoid coil in an aluminum casing, which acts as a flux return for the applied magnetic field. The solenoid is a single 273 turn layer of 18 gauge copper wire, with a radius of 15 cm and a length of 30 cm [32]. The external dimensions of the aluminum cylinder are radius 20 cm, length 40 cm [32]. The RF spin flipper is attached to the front of the CsI detector array frame. The aluminum windows are 0.5 mm thick, while the rest of the Al case is 5 mm thick [32]. This shields the field so that the field does not leak into the asymmetry signal.

The magnetic holding field for the experiment is kept near \( B_0 = 9.4 \) G [33]. Since \( \gamma_g \) for the neutron is measured to be \( 1.832 \times 10^8 / \text{s/T} \) then according to Eq. 2.7.6 the Larmor frequency is

\[
\omega_L = 27.4 \ \text{kHz}
\] (2.7.7)

This is the frequency that the applied RF field must have in order to be at resonance. As neutrons come down the beamline, they rotate around the holding field, \( B_0 \). When a perpendicular RF field is introduced at the Larmor frequency, the neutron sees the resultant field in its own rotating frame and begins to precess around it. If the neutron spends the right amount of time in this field then it will be flipped by \( \pi \) into the opposite spin state.
Since the neutron beam has a time-of-flight spectrum a range of velocities must be flipped. For a fixed length of coil (L) and a fixed RF field, only one velocity of neutron can be flipped with high efficiency, all others will be partially flipped, leading to a depolarized beam. To account for this the amplitude of the RF field is ramped in relation to the neutron energy. Using Eqn. 2.7.6, we see that the velocity is

\[ v = \frac{L}{\pi \gamma g} B_{RF}. \]

(2.7.8)

Then the B-field is ramped according to the neutron velocity:

\[ B_{RF}(v) = \frac{v \pi}{L \gamma g}. \]

(2.7.9)

The voltage applied to create the current needed to ramp the spin flipper coil is shown in Fig. 2.10. The amplitude decreases with time since the slower, lower energy neutrons will be over-flipped with too high of a B-field. The figure also shows that it takes finite time to achieve the peak amplitude. The spin flipper is an LRC circuit, and as such has a time constant that characterizes the response to the driving current. Since it takes a few bins, each 0.4 \( \mu s \) long, for the spin flipper to get to the right amplitude, the first time bins are not used during analysis.

**Neutron Polarimetry**

We used a polarized \(^3\text{He}\) cell as an analyzer downstream to measure polarization of the RFSF on/off pulses. The analyzer used is a cell of polarized \(^3\text{He}\), which captures neutrons
where $N$ is the neutron number and $N_0$ is the initial neutron number. $n$ is the density, $\sigma$ is the (possibly) spin-dependent cross section and $l$ is the detector length.

Transmission through a polarized cell depends on the polarization of the gas in the analyzer, $P_a$, and the polarization of the incoming neutrons:

- $n_0^\pm = \text{number of incoming neutrons}$ \hspace{1cm} (2.7.11)

- $n_1^\pm = \text{number of outgoing neutrons}$ \hspace{1cm} (2.7.12)

- $n_1^\pm = n_0^\pm e^{-n\sigma l(1\mp P_a)}$ \hspace{1cm} (2.7.13)
Figure 2.11: Spin Flipper Electronics. The electronics that generate the current that drives the spin flipper. When the signal from the proton pulse (t0) is received, the wave generator creates the decaying ramp current, as shown in Fig. 2.10. This is one input into a difference amplifier. The modulator creates the $\sim$30 kHz wavefunction, and the total signal is amplified by an audio amplifier. The pickup coil returns the current through a rectifier to the other input of the difference amplifier. Since the RFSF is a LRC circuit, it will have a certain resistance to the quick rise in current. The feedback loop regulates this rise for the smoothest possible signal, however it was bypassed at the SNS.

The analyzer cell has an average maximum polarization of $P_a = 0.493 \pm 0.012$ for wavelengths 3.2-5.8 Å [31]. Neutron polarization of the initially unpolarized beam, after passing through
the polarizer, is given then by:

$$P_n = \frac{n_1^+ - n_1^-}{n_1^+ + n_1^-} = \tanh(nl\sigma P_a)$$ (2.7.14)

With a spin flipper before the analyzer the polarization includes the flipping efficiency $\epsilon_{SF}$. Additionally, $^3$He has a $1/v$ neutron capture dependence, so transmission is wavelength dependent [31]. A polarized $^3$He cell of 7.5 cm diameter with a proportional $^3$He neutron detector behind it is used to conduct neutron polarimetry [31]. Transmission measurements through this analyzer cell are conducted for the beam passing through the polarized cell, then through the cell with the $^3$He polarization flipped via adiabatic fast passage. A separate measurement is done with the cell unpolarized. Transmission of the polarized beam through the polarized cell when the SF is on is given by [31]:

$$T_{sf}(\lambda) = T_0(\lambda)e^{-\chi\lambda} \cosh(\chi P_a \lambda)[1 + (1 - 2\epsilon_{sf})P_n \tanh(\chi P_a \lambda)]$$ (2.7.15)

where $\chi$ is the $^3$He thickness, $\chi = \frac{n_1\sigma_0}{\lambda_0}$. If the SF is off, then the SF efficiency goes to zero, giving

$$T_{sfoff}(\lambda) = T_0(\lambda)e^{-\chi\lambda} \cosh(\chi P_a \lambda)[1 + P_n \tanh(\chi P_a \lambda)].$$ (2.7.16)

By calculating $T_{sf}(\lambda)$ for both polarization states of the cell (before and after polarization reversal by adiabatic fast passage), and both neutron spin states (SF on and off), ratios are constructed that allow for extraction of $\epsilon_{sf}$.

$$R_{sf} = \frac{T_{sfoff} - T_{sf}}{T_{sfoff} + T_{sf}}$$ (2.7.17)
\[ R_{sfoff} = \frac{T_{sfoff}^{AFP} - T_{sf}}{T_{sfoff}^{AFP} + T_{sfoff}} \]  

(2.7.18)

Therefore,

\[ \epsilon_{sf} = \frac{1}{2} \left( 1 - \frac{R_{sf}}{R_{sfoff}} \right) \]  

(2.7.19)

and \( \epsilon_{sf} \) can be calculated from transmission measurements. The spin flipper efficiency was optimized by varying the magnetic holding field and the RF field of the spin flipper until the ratio of transmission through the \(^3\)He for the two spin states is maximized.

Similarly, by constructing ratios of the transmissions of the two neutron spin states to the transmission through the unpolarized cell, the neutron polarization \( P_n \) is found. If the unflipped spin state transmission is given by \( T \), and the flipped state transmission is \( T_{sf} \), and \( T_0 \) is the transmission through the unpolarized cell, then the ratios are

\[ R_1 = \frac{T_{sfoff}}{T_0} \]  

(2.7.20)

\[ R_2 = \frac{T_{sf}}{T_0} \]  

(2.7.21)

The neutron polarization \( P_n \) is

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

(2.7.22)

and is found via the transmission measurements [31]. More information on the NPDGamma neutron polarimetry and results can be found in the PhD thesis of Matthew Musgrave [31].

The results for neutron beam polarization and spin flipper efficiency are:

\[ P_n = 0.943 \pm 0.004 \]  

(2.7.23)
\[ \epsilon_{af} = 0.975 \pm 0.002 \]  

These results are used in the final hydrogen asymmetry analysis. Polarimetry measurements were done approximately every month to check that no changes had occurred.

### 2.8 CsI Detector Array

The gamma rays produced in the \( \vec{n} + p \to d + \gamma \) reaction are detected by 48 CsI crystal detectors. These detectors are each approximately 15 cm square and arranged in 4 rings of 12 around the hydrogen target, with the beam along the longitudinal axis. These detectors are scintillation detectors, made of CsI doped with Tl. The initial process of the gamma detection is the conversion of the gamma rays to fast electrons. This occurs primarily via three processes: Compton scattering, pair production, and photoelectric absorption [34].

Compton scattering occurs when the incoming gamma ray scatters from an electron, transferring part of its energy to the electron. Pair production occurs when the gamma ray produces a positron and an electron. This can only occur at gamma energies of 1.02 MeV or greater due to mass of \( 2m_0c^2 \) required to create the pair [34]. Photoelectric absorption is when the gamma ray is absorbed by an atomic electron shell, and an electron is emitted from the shell.

Inorganic scintillators, such as CsI have a valence band of bound electrons, and a conduction band of free electrons, separated by a band gap of a certain energy (6.2 eV in the case of thallium doped CsI [35]). Absorbed fast electrons can move a bound electron to
the conduction band, which then emits a photon upon decay back to the valence band. This is both inefficient, and results in a photon with energy too high to be detected with visible light detectors [34]. However, by doping the crystal with an activator, in this case thallium, intermediate excited states become available. This allows quick transitions with lower energy photons produced, which can then be detected [34]. CsI(Tl) crystals yield about 65000 photons per MeV at room temperature with wavelength emission around 540 nm, in the visible range, and short decay times of 0.68 \( \mu s \) 64% of the time, and 3.34 \( \mu s \) 36% of the time. The rise time is 20 ns [34].

To detect this light, vacuum photodiodes are coupled behind the crystals. CsI(Tl) has an index of refraction of 1.8 [34], close to that of glass at 1.5, which makes transition to the photodiode more efficient. The photons enter the photodiode, where they create electron-hole pairs in a thin semiconductor photocathode. A voltage is applied, which collects the charges. Photodiodes have the advantage over photomultiplier tubes for use with the CsI(Tl) detectors because CsI(Tl) detectors emit photons at longer wavelengths, and photodiodes have higher efficiency at longer wavelengths [34]. Most importantly, the photodiodes are insensitive to B-fields. Because of the high event rate in each detector, the detectors are run in current mode. The current is converted to a voltage, multiplied by a gain in a preamplifier, then read out via the DAQ system.

Each of the 48 detectors was calibrated prior to being assembled into the array chassis.
The gains of the individual detectors divide out when constructing the asymmetry, however, the detector gains must be within 25% of their average to avoid signal saturation and second order effects. The gains were found by using a 4.11 μCi Cesium-137 gamma source, mounted on a rotating motor. The motor rotated the source in 10 degree increments around 6π. A MCNP simulation of this, created by S. Balascuta [36], was fitted to a Fourier expansion [37]:

\[
MCNP(\theta) = \frac{a_0}{2} + a_1 \cos \theta + b_1 \sin \theta + a_2 \cos 2\theta + b_2 \sin 2\theta + a_3 \cos 3\theta + b_3 \sin 3\theta + a_4 \cos 4\theta
\]

(2.8.1)

After the data was taken with the rotating arm it was fit to:

\[
signal(\theta) = d_1 \times MCNP(\theta) + \text{offset} + \text{drift}(\theta)
\]

(2.8.2)

where \(d_1\) is 1/gain. If the gains were not within the limits then the feedback resistor in the preamplifier was adjusted until the appropriate value was found.

The center of the detector array is located approximately 17.73 m from the moderator, as measured in straight lines. This large distance causes pulse frame overlap due to differing travel times for different energies. As the neutrons travel down the beamline, the time-of-flight spectrum becomes wider as faster and slower neutrons become further apart. Fig. 2.12 shows the difference in the frame between monitor 1, and the hydrogen target in the detector. The signal in the 4th ring from neutron capture is stretched relative to the signal in m1 since it is further down the beamline. Neither the aluminum Bragg edges nor the chopper
dips align. Too much frame overlap at the spin flipper will mix oppositely polarized pulses.

\[ \text{Monitor 1 and 4th ring signals} \]

\[ \text{4th ring-det 47} \]

\[ \text{Monitor 1} \]

Figure 2.12: Monitor 1 signal and a signal from ring 4. Frame changes are seen by comparing the locations of the chopper phasing and the Bragg edges.

### 2.9 Hydrogen Target

Desired characteristics for the proton target include a high capture cross section, a low scattering cross section, a high density of protons, low background rates, and minimal depolarization of neutrons inside the target. Liquid hydrogen is used as the source of protons for the \( n + p \rightarrow d + \gamma \) reaction.

Molecular hydrogen has both a nuclear singlet and a triplet state. The ground state, parahydrogen, has nuclear spin \( I=0 \). As a singlet state the molecule has spin \( S=0 \), with \( m=0 \). The triplet state, orthohydrogen, has spin \( S=1 \), with \( m=-1,0,1 \).
Figure 2.13: Molecular hydrogen cross sections. Scattering cross sections are shown for parahydrogen and orthohydrogen as a function of incoming neutron energy [38]. Total absorption cross section [39].

Since orthohydrogen is a triplet state, when incoming neutrons with spin $\pm1/2$ scatter from orthohydrogen, it is possible for the neutrons’ spins to be flipped. A flip from $1/2$ to $-1/2$, for example, is $\Delta m = -1$, which is allowed in the triplet state. This is very undesirable for NPDGamma since the measurement of the gamma asymmetry is dependent on knowledge of the spin state of the captured neutron. Parahydrogen does not allow spin flip scattering since the $m$ values are not available. The fraction of parahydrogen must be high to limit depolarization and scattering. At 15.4 K $\pm$ 0.5 K the concentration of parahydrogen is 0.99985 [40]. The absorption length for hydrogen is about 24 cm at 5 Å, and the diameter of the target is 30 cm, and the length is 30 cm, causing most scattered neutrons to be reabsorbed.

Ortho- and parahydrogen states are separated by 14.5 meV [40]. If an incoming neutron
has 14.5 meV of energy or greater, it can excite the hydrogen from the para state to the
ortho state and become depolarized. Fig. 2.13 shows the scattering and absorption cross
sections for molecular hydrogen as a function of neutron energy. As seen here, the absorption
cross section follows the $1/v$ law, with greater absorption at lower energies. It also shows
that orthohydrogen has a high scattering cross section, and the scattering cross section of
parahydrogen has a sharp increase at about 14.5 meV. These combined properties indicate
that molecular parahydrogen is a good target for npd$\gamma$ for low neutron energies in the
$\sim$2.4-14 meV range.

The fraction of parahydrogen in the target is a function of temperature. The partition
function is given by:

$$ Z = \sum_s g_s e^{-E_s/k_B T} $$

summed over states ‘s’. $g_s$ is $2L+1$ for parahydrogen and $3(2L+1)$ for orthohydrogen [38].

At low temperatures this gives an orthohydrogen fraction of

$$ f_{ortho} = \frac{9 e^{-E/k_B T}}{1 + 9 e^{-E/k_B T}}. $$

Using $E=14.5$ meV for the excited state (orthohydrogen), the ortho fraction is plotted as a
function of target temperature in Fig. 2.15. The NPDGamma target is kept below 16 K so
that the fraction of orthohydrogen is $<0.024\%$.

The 16 L liquid parahydrogen target is contained in an aluminum vessel, Fig. 2.14. This
target vessel is 30 cm long, with a front window only 0.063” thick, and side walls 0.12”
thick [41]. The front window is as thin as possible to minimize scattering of neutrons in the aluminum material. The liquid hydrogen is continuously circulated through a gas handling system, including three cryo-refrigerators and an ortho-to-para converter. The target is wrapped on the non-beam sides and back with $^6$Li loaded plastic to shield the CsI detectors from out-scattering of neutrons from the target.

Figure 2.14: This photo shows the hydrogen vessel. The hydrogen target is inside the cylindrical container.

Molecular hydrogen occurs at room temperature at approximately a 3:1 ortho-to-para ratio [38]. As it is cooled to the low temperatures where the para state will dominate, it slowly comes to equilibrium. Conversion to parahydrogen just through cooling has a time constant on the order of 3.5 days, and so would take weeks to achieve the ortho fraction at 16
Figure 2.15: Fraction of orthohydrogen as a function of temperature, at equilibrium. The lower the temperature, the more parahydrogen in the target.

K of 0.02% [42]. To speed this process, an ortho-to-para converter (OPC) is used. The two nuclei in orthohydrogen have parallel spins, while in parahydrogen they are antiparallel. To flip one, and only one, of the proton spins in orthohydrogen, one of the atoms in the molecule must come into contact with a magnetic field gradient [38]. To create this condition, the OPC is constructed of Fe$_2$O$_3$ (rust) powder. The magnetic domains catalyze the conversion of orthohydrogen to parahydrogen. This catalyst significantly shortens the conversion time, the best time constant we achieved for NPDGamma was about a day [42].

2.10 DAQ System

The data acquisition system includes everything from the output of the detectors, monitors, and spin flipper, to the ROOT ntuple used to organize the data and analyze it. There were three distinct data acquisition configurations used during the NPDGamma runs: 1.) the
original configuration which borrowed heavily from the LANL version of the experiment

2.) a modified version which was temporarily used after problems were encountered to take
the data for this thesis (see Sec. 4.1), and 3.) the final version that was used for most
production data.

![Data trail LANL diagram](image)

Figure 2.16: Data trail LANL.

We read the signals from the 48 gamma ray detectors, up to three $^3$He monitors and
a boron monitor, and the spin flipper voltage and current. To handle these channels two
VME boards are used, called VME2 and VME3. VME1 was used at LANL to record the
proton current, but was only used to relay the t0 at the SNS.

For the original DAQ configuration the analog signal chain included average detector ring signals and the differences of each detector from its ring’s average. This was done to minimize effects from the ADC bit noise by allowing for greater dynamic range [18]. There are four rings of 12 detectors each. The detectors in each ring are averaged in analog, creating four “sum” signals. Each detector signal has the average from that ring subtracted from it, creating 48 “difference” signals. The difference signals go into VME3 channels and receive a gain of 10. The sum signals go into VME2 channels, without any gain. For noise reduction, the sum and difference signals then go through Bessel filters in the sum/difference boards and receive a gain of 3. The difference signals are sampled by a 50 kHz ADC in VME3, while the VME2 channels are sampled by a 62.5 kHz ADC. For each time bin, VME3 channels are a sum of 25 samples, and VME2 channels are a sum of 20 samples [18], see Fig. 2.16. The detectors have a range of 10 V, and the ADCs are 16 bit. By using difference signals instead of the direct signal, there are more bits available per volt, which allows for greater dynamic range.

Due to timing differences between the LANSCE neutron source and the SNS, there were some changes made in the data stream. The SNS operates at a pulse frequency of 60 Hz, versus 20 Hz at LANSCE. All data taking is triggered from this 60 Hz t0 signal, with one data pulse created for each 60 Hz neutron pulse. Each pulse contains 40 time-of-flight bins,
each 0.4 ms long, for a total of 16 ms of data out of a 16.666 ms window. As mentioned, the
data from VME2 channels are a sum of 20 samples per bin, and VME3 data is 25 samples
per bin. Each “sequence” consists of 8 data pulses, for a total of 320 bins of data, followed
by a 9th pulse, where no data is taken, and the data is read out to the computer.

The DAQ configuration was changed temporarily for about 4000 runs, called ‘Three
Ring’ data, which are the data discussed in this thesis, and then was changed again for the
final configuration. The reason changes were made is because of cross talk between channels
in VME3. The spin sequence signal was picked up in the sum channels, which would lead
to a false asymmetry as it caused spin dependent changes in the sum signals. To fix this,
the sum channels were removed from VME3 and put into VME2. To make room for the
sum channels in VME2, the first ring of channels for the difference signals were unplugged.
Therefore, all Three Ring data has only three rings worth of detector signals, 36 detectors,
instead of the full 48 detectors, see Fig. 2.17.

At this time there was also an issue with the timing signal shifting, which was due to
problems with the internal clock in VME3. This was resolved by taking less data each pulse.
Instead of taking 16 ms of data for each t0, only 12.8 ms of data were taken. This was still
spread out over 40 bins, however less samples were taken in each bin, only 20 in VME3 and
16 in VME2.

The final configuration bypassed completely the sum and difference scheme. All detector
signals went directly through a new Bessel filter, again with a gain of 3. The timing was
returned to normal, 40 bins for 16 ms and sampling of 25 and 20 per bin. See Fig. 2.18.

The binary data output by the ADCs were read into data files. These files were read by
analysis classes that used the ROOT analysis framework and libraries [43]. Here the data
is converted into a TTree with branches for each of the signals of interest, including the
file headers, sums and differences, spin flipper voltage and current, final detector voltages,
and monitor voltages. Once a tree exists for each run, ROOT commands can be used
Figure 2.18: Data trail, final configuration.

to do further data analysis, such as constructing histograms, time-of-flight graphs, and asymmetries.

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Chapter 3

Beam Characterization

It is important to characterize the neutron beam. Knowing both the horizontal and vertical profiles provides information about the beam alignment. Knowing the neutron flux allows determination of the beam time needed to successfully run the experiment.

3.1 Beam Profile

To measure the beam profile a new detector was made that was mounted on an x-y scanning table. The detector used boron to convert neutrons to gamma rays, and a CsI crystal to detect the gamma rays. The signal was read out in the NPDGamma DAQ system via a preamplifier circuit. The vertical and horizontal profiles were measured and compared to simulations.

Boron-10 has a very high absorption cross section for thermal neutrons. The absorption cross section, $\sigma_{abs}$, for thermal neutron capture on $^{10}$B is 3835 barns [27]. For this reason it has long been used in various kinds of neutron detectors. A gas of BF$_3$ can be used in proportional counters or ionization chambers [44]. Multiple forms of boron-based semiconductor diodes have been used to create neutron detectors [45]. Boron loaded scintillators are also used for slow neutron detection, where the products of neutron interactions with
3.1.1 Detection Mechanism and Construction

The boron-based neutron detector used for the NPD-γ experiment was different from these examples in a number of ways. The detected signal is from the gamma rays, not the other reaction products, eliminating the need for a thin boron target. Also, the detector is run in current mode, not counting mode, thus there is no requirement for a minimum energy.

Boron-10 reacts with incident neutrons according to the following reactions:

\[ ^{10}B + n \rightarrow ^{7}Li + \alpha \]  \hspace{1cm} (3.1.1)

with a branching ratio of 6.43% [47], and

\[ ^{10}B + n \rightarrow ^{7}Li^* + \alpha \]  \hspace{1cm} (3.1.2)

with a branching ratio of 93.57%. The \(^7\)Li* subsequently decays to its ground state and emits a 0.48 MeV gamma ray [27].

Natural boron is 19.8% \(^{10}\)B [34], with the remainder \(^{11}\)B. The thermal absorption cross section of \(^{11}\)B is only 0.0055 barns [27], therefore it contributes minimally to neutron interactions. A disc of boron carbide, B\(_4\)C, was chosen as the source of \(^{10}\)B, with the natural abundance of each isotope of boron. It was approximately 1 inch in diameter and 0.125 inches thick. This target is black to neutrons, as can be seen by the following calculation of the transmission of thermal neutrons through boron carbide.
The transmission of a neutron through a medium is

\[ T = e^{-nl\sigma} \]  \hspace{1cm} (3.1.3)

where \( n \) is the number density, \( l \) is the length of the target medium, and \( \sigma \) is the absorption cross section in the medium. The number density of \( \text{B}_4\text{C} \) is calculated from the molecular mass of its constituents, and scaled by the percentage of the molecule that is Boron-10 to get the number density of \( ^{10}\text{B} \) in the target, which is \( 2.18 \times 10^{22} \) atoms/cm\(^3\). Then, after 1/8th inch of boron carbide, the transmission of thermal neutrons is

\[ T = 3.152 \times 10^{-12} \]  \hspace{1cm} (3.1.4)

or negligible. The capture of cold neutrons in the sample is effectively 100%.

The neutron interaction with \( ^{10}\text{B} \) produces gamma rays of 0.48 MeV at a 93.57% branching ratio. Here is a rough estimate of the transmission of the produced photons through the \( \text{B}_4\text{C} \) target: Using the mass energy-absorption coefficients at 0.5 MeV found in[48] from the NIST X-Ray Attenuation Databases, we can use the following equation [49]:

\[ \frac{E}{E_0} = e^{-\frac{\mu_{\text{en}}}{\rho} \rho t} \]  \hspace{1cm} (3.1.5)

where \( \frac{\mu_{\text{en}}}{\rho} \) is the mass attenuation coefficient, \( \rho \) is the density, and \( t \) is the thickness. Using the density fractions of B and C in the molecule \( \text{B}_4\text{C} \), and the mass energy-absorption coefficients, the fraction of transmitted energy is found to be 0.5865. This is an estimation as other processes will occur within the target (such as multiple scatterings and lower energy
absorptions), and not all neutrons will interact at the front face of the target. A MCNPX simulation was done by Kyle Grammer to more accurately model this situation.

The boron carbide target is attached at the front of a 3 inch x 3 inch thallium-doped CsI crystal, see Figure 3.1. CsI is a commonly used inorganic scintillator. The scintillation light is then detected in a vacuum photodiode, which is directly behind the CsI crystal. The same type of preamplifier was used for this neutron detector as was used for the CsI gamma ray detectors in the detector array, described earlier. The final signal is processed through the same DAQ system as the rest of the experiment. A discussion of this type of detector is in Sec. 2.8.

![Figure 3.1: Side View of Beam Profile Monitor.](image)

Figure 3.1: Side View of Beam Profile Monitor. An illustration of the beam profile monitor from the side. Neutrons are incident from the right on the boron carbide target, gamma rays are produced which are wavelength converted in the CsI crystal. Those photons enter the vacuum photodiode (VPD) where they are converted to a charge that is read out by the preamplifier to the DAQ system. The motor controls the Lithium-6 shutter, which is used to block neutrons for background measurements.

The entire monitor was covered in $^6$Li plastic, which is a neutron absorber, to eliminate
Figure 3.2: Front View of Beam Profile Monitor. An illustration of the beam profile monitor from the front. This shows the $^6$Li neutron shielding shutter that rotates to block the boron carbide target.

backgrounds and interactions of neutrons with anything other than the boron carbide target.

A double layer lithium-6 covered aluminum shutter was attached to a motor so that it could be rotated to cover or uncover the B$_4$C target for background measurements in situ.

3.1.2 Measurements

The Beam Profile Monitor (BPM) was mounted on a X-Y table. This table allowed the BPM to be scanned across the neutron beam both horizontally and vertically. The table was measured to be reproducible to 0.007 inch or better. The scanning arm was mounted behind the NPDGamma CsI detector array. All measurements made with the BPM were done before the installation of the hydrogen target into the center of the CsI detector array. Thus the BPM had a clear line of sight through the array. The BPM was free to scan across the back opening of the CsI array, which is about 18 inches in diameter, see Fig. 3.3. The
BPM was used to measure the beam profile in X and Y. Background measurements were done by closing the $^{6}\text{Li}$ shutter in situ, then the shutter was opened and neutron data was taken. Then the scanner moved the detector 1/2 inch for the next measurement.

Figure 3.3: **BPM Scanner Assembly** The BPM was mounted on a X-Y table. This table was mounted behind the back detector array frame, and was used to move the BPM across the beam.

The boron monitor was calibrated using a sealed radioactive source. The Cs-137 source was about 4.2 mCi and was placed directly on top of the CsI crystal housing. Source and pedestal data was taken, and the gain calculated:

$$G = \frac{E_{\gamma,\text{Cs}} B_{\text{Cs}} C_{\text{Cs}} \Omega_{\text{Cs}}}{V_{\text{Cs}}} S_s \quad (3.1.6)$$

where $E_{\gamma,\text{Cs}}=0.662$ MeV is the energy of the Cs-137 gamma ray, $B_{\text{Cs}}=0.946\times0.85$ is the branching ratio for decays via $\beta$ emission and then gamma emission. $C_{\text{Cs}}$ is the conversion factor from decays/s to Ci. The energy deposition solid angle $\Omega$ was calculated using MCNPX by Kyle Grammer and is 0.2479. $S_s$ is the source strength and $V_{\text{Cs}}$ is the voltage measured in the VPD of the Cs source.
Using the calibrated gain, the BPM signals can be converted into neutron flux

\[ F = \frac{V_B G}{E_{\gamma,B} B_B \Omega_{Cs}}. \]  

(3.1.7)

\( V_B \) is the voltage signal from the neutron interactions with the boron of the BPM, \( G \) is the gain, \( E_{\gamma} = 0.488 \) MeV is the energy of the boron gamma ray, \( B_B = 0.94 \) is the boron branching ratio, and \( \Omega_{Cs} = 0.2387 \) is the energy deposition solid angle of the boron from MCNPX.

### 3.1.3 Results

Horizontal scan results and backgrounds are shown in Fig. 3.4(a). The signal minus background shows the shape and location of the beam. The background at beam-right is due to the bends in the beam guide moving the neutrons to the left, while the fast neutrons and gamma rays continue in a more direct path. Thus the background is offset from the beam signal. The vertical background is seen to be in line with the signal shape in Fig. 3.4(b).

The horizontal and vertical profiles are fitted to find the beam center. Fits were done to Gaussian curves, though the beam profiles are not exact Gaussians at this location. The horizontal fit puts the center at:

\[ x_0 = 0.002 \pm 0.05 cm \]  

(3.1.8)

and vertical fit is

\[ y_0 = 0.024 \pm 0.024 cm \]  

(3.1.9)
3.2 Neutron Flux

Knowledge of the neutron flux at the FnPB is important for calculations of statistics and beam time needed for the experiment. Since the goal was to measure $A_\gamma$ to the $10^{-8}$ level, $10^{16}$ neutrons were needed. Knowing the flux of neutrons allows calculation of data-taking time needed.

To measure the neutron flux, a boron carbide plate was placed in the center of the detector, at a 45 degree angle to the beam. The plate was 12 inches wide by 7.25 inches
Figure 3.5: Horizontal and vertical beam profiles fitted to Gaussian curves to extract the distance from the neutron beam center.

high by 0.07 inches thick, making it black to neutrons [50]. The resulting gamma rays are detected in the nearby CsI detectors, and then the neutron flux is calculated.

The number of neutrons, \( N_n \), is related to the number of gammas seen in the signal, \( N_\gamma \), thus:

\[
\frac{\Delta N_\gamma}{\Delta t_{bin}} = \frac{\Delta N_n}{\Delta t_{bin}} B_B \Omega_B
\]  

(3.2.1)

where \( \Delta t_{bin} \) is the bin width used, \( B_B \) is the branching ratio in boron, and \( \Omega_B \) is the solid
angle of the boron gammas into the detector. The voltage from the boron signal is given by:

\[ V_B = B_B R_n \Omega_B E_{\gamma,B} G \]  

(3.2.2)

where \( R_n \) is the rate of neutrons/second, \( E_{\gamma,B} \) is the energy of the gamma ray from boron, and \( G \) is the detector gain. Since the detector gain is unknown, a measurement with a known source is required to cancel out the gain. This is done with a known Cs source:

\[ V_{Cs} = S_{Cs} B_{Cs} \Omega_{Cs} E_{\gamma,Cs} G \]  

(3.2.3)

where \( S_{Cs} \) is the strength of the Cs source. Then the final equation allows us to solve for the neutron flux per second per angstrom, \( N_n = R_n / \lambda \):

\[ N_n = \frac{V_B S_{Cs} B_{Cs} \Omega_{Cs} E_{\gamma,Cs}}{V_{Cs} B_B \Omega_B E_{\gamma,B}} \frac{\Delta t}{60 \text{Hz} \Delta \lambda}. \]  

(3.2.4)

The results of this analysis are shown in Fig. 3.6. My flux calculation is compared in this graph with a measurement done by Erik Iverson in 2009 at the end of the beampipe, before the experiment was installed. To compare them at the same location, I scaled Iverson’s flux by transmission through 1.88m of air, m1 and m2, relevant aluminum windows, and the polarizer.

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Figure 3.6: **Neutron Beam Flux.** Beam flux in the center of the detector for the boron plate measurement compared with the measurement done before installation of the experiment.
Chapter 4

Analysis

4.1 Data Set and Characteristics

The goal is to calculate the parity violating gamma ray asymmetry of neutron capture on hydrogen. The data set analyzed in this work was acquired in May and June, 2012. This data set has some unique characteristics that differentiate it from other hydrogen data sets in the NPDGamma experiment. As explained in Chapter 2, the signals were initially summed into an average signal for each ring, and then analog differences are determined for each of the 48 detectors. These sums and differences were used to calculate the voltage seen in each detector for analysis with higher bit resolution. In the preliminary configuration, the modules that process the sums were setup in a different rack than the electronics for the differences.

The “Three-Ring” experimental setup used for this analysis is somewhat different from this. Spin-dependent cross-talk was seen in the sum signals due to proximity to spin flipper electronics in the rack, see Fig. 4.1. To work around this problem while a permanent solution was constructed, one ring of the difference signals were conscripted for use for the sum signals. This reduced the data output to only 3 rings, with the first ring missing (the
first ring has the largest backgrounds).

Figure 4.1: **Crosstalk in VME3.** This histogram shows the signal in each VME3 channel as a function of spin state. To the left of the black line are the sum channels. It is clear that there is spin dependence in the signal, which occurs because of crosstalk from the spin flipper channels nearby.

Another unique feature of this data set is a change in timing. As discussed in Sec. 2.10, a problem occurred where the DAQ became unable to acquire data for the full 16 ms, causing the signal to travel. The way this was fixed until a permanent solution could be found was by taking less data during each sequence. There is still the same number of bins and sample frequency, so that the data structure is the same, but less samples are taken per bin, so that there is only 12.8 ms of data taken instead of 16 ms. This means there is less data at the end of each pulse and less data in each bin. The data processing code was adjusted to take these changes into account.
After the problems with timing and signal cross-over were fixed, data was taken for all four rings. However, this three-ring data cannot be analyzed together with the four-ring data. This analysis was done separately as shown in this thesis. The successful analysis of the three-ring data means that it can be combined with the results from the four-ring data to improve the error bar on the final gamma ray asymmetry value.

As discussed earlier, the spin flipper runs in a 16-step sequence, \( \uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\downarrow\uparrow \), spanning two readout pulses. For purposes of data analysis, this has been split into two 8-step sequences, \( a = \uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\downarrow \) and \( b = \downarrow\uparrow\uparrow\downarrow\uparrow\downarrow\uparrow \).

As covered in the Sec. 2.10, 40 time bins of data were acquired every 12.8 ms. This was done 8 times, for either ‘a’ or ‘b’ spin sequences, and then the collected data were read out during a 9th “read-out pulse”. Each ADC sample was converted into voltages for analysis. A “sequence” is one ‘a’ or ‘b’ sequence and its companion read-out pulse. Typically, 2500 of these sequences (1250 ‘a’ and 1250 ‘b’) were taken in a ‘run’, however, occasionally less were taken, which poses no problem. For this analysis, about 3947 runs were used, some of which were cut, or parts cut, due to various reasons described below.

### 4.2 Explanation of Asymmetry: Theory

To calculate the experimental asymmetry, \( A_{\text{exp}} \), first start with two pulses, \( a \) and \( b \). We will assume here that neutron intensity is constant in each of three regions: the n1 region between the SM polarizer and the spin flipper, the n2 region after the spin flipper, and n3,
the gamma yield after capture in hydrogen. This is shown in Fig. 4.2.

Figure 4.2: NPDGamm Schematic with Regions Regions n1, n2, and n3 shown in the schematic of the experiment.

For each region, 1, 2 and 3, we define \( n_i \) as the total number of neutrons from two pulses, one of which will remain spin-up after the SF and one of which will become spin-down after the SF. Therefore \( n_i \) for the two pulses, \( a \) and \( b \), is:

\[
n_i = (n_{ia} + n_{ib})
\]  

(4.2.1)

We can also define \( n_i^\pm \) in terms of the total number of neutrons \( (n_i) \) and the polarization, \( P \), produced by the polarizer.

\[
n_i^\pm = \frac{1}{2} n_i (1 \pm P)
\]

(4.2.2)

We introduce the beam asymmetry, \( A_b \), the asymmetry that can occur between pulses of different spin states after the SF:

\[
A_b = \frac{n_{1a} - n_{1b}}{n_{1a} + n_{1b}}
\]

(4.2.3)
After the SF, the two pulses $n_{2a}$ (SF OFF) and $n_{2b}$ (SF ON) are in their different spin states. However, the SF has a certain efficiency with which it can flip, therefore, each pulse is a combination of two spin states, weighted by the efficiency of the spin flipper, $\epsilon_a, \epsilon_b$:

$$n_{2a}^± = \epsilon_a n_{1a}^± + (1 - \epsilon_a)n_{1a}^\mp$$ (4.2.4)

$$n_{2b}^± = \epsilon_b n_{1b}^± + (1 - \epsilon_b)n_{1b}^\mp$$ (4.2.5)

In hydrogen the two spin states capture with cross sections $\sigma_±$:

$$n_3^± = \sigma_± n_2^±$$ (4.2.6)

Each pulse after a spin flip contains a mixture of both neutron spins, based on the efficiency of flipping each state that comes out of the polarizer. Therefore, for SF OFF:

$$n_{3a} = \sigma_+(\epsilon_a n_{1a}^- + (1 - \epsilon_a)n_{1a}^+) + \sigma_-(\epsilon_a n_{1a}^+ + (1 - \epsilon_a)n_{1a}^-)$$ (4.2.7)

And for SF ON:

$$n_{3b} = \sigma_+(\epsilon_b n_{1b}^- + (1 - \epsilon_b)n_{1b}^+) + \sigma_-(\epsilon_b n_{1b}^+ + (1 - \epsilon_b)n_{1b}^-)$$ (4.2.8)

The capture cross section in hydrogen is defined in terms of the physics asymmetry, A.

$$\sigma^± = \sigma_0(1 \pm A)$$ (4.2.9)

These definitions can be used to redefine $n_{3a}$ and $n_{3b}$ in terms of the polarization, P, and
the physics asymmetry, $A$.

$$n_{3a} = \sigma_0(1+A)(\epsilon_a \frac{1}{2}n_{1a}(1-P)+(1-\epsilon_a)\frac{1}{2}n_{1a}(1+P)) + \sigma_0(1-A)(\epsilon_a \frac{1}{2}n_{1a}(1+P)+(1-\epsilon_a)\frac{1}{2}n_{1a}(1-P))$$  \hfill (4.2.10)

which reduces to

$$n_{3a} = n_{1a}\sigma_0(1+PA_f a) \quad \quad \quad (4.2.11)$$

$$n_{3b} = n_{1b}\sigma_0(1+PA_f b) \quad \quad \quad (4.2.12)$$

where $f_{ab} = 1 - 2\epsilon_{ab}$ Now that we have the equations for the number of neutrons in each pulse out of the hydrogen, we can calculate the measured asymmetry, $A_{exp}$.

$$A_{exp} = \frac{n_{3a} - n_{3b}}{n_{3a} + n_{3b}} \quad \quad \quad (4.2.13)$$

$$A_{exp} = \frac{n_{1a}\sigma_0(1+PA_f a) - n_{1b}\sigma_0(1+PA_f b)}{n_{1a}\sigma_0(1+PA_f a) + n_{1b}\sigma_0(1+PA_f b)} \quad \quad \quad (4.2.14)$$

Using the substitutions

$$n_{1ab} = n_{1}(1 \pm A_b) \quad \quad \quad (4.2.15)$$

$$n_{1} = \frac{1}{2}(n_{1a} + n_{1b}) \quad \quad \quad (4.2.16)$$

where $A_b$ is defined in 4.3.12.

This then reduces to

$$A_{exp} = \frac{A_b + A_b PA(1 - \epsilon_a - \epsilon_b) + PA(\epsilon_b - \epsilon_a)}{1 + PA(1 - \epsilon_a - \epsilon_b) + A_b PA(\epsilon_b - \epsilon_a)} \quad \quad \quad (4.2.17)$$
In the ideal case, the SF is completely off during the $a$ pulse. Then, as $\epsilon_a \to 0$

$$A_{exp} = \frac{A_b + A_bPA(1 - \epsilon_b) + \epsilon_bPA}{1 + PA(1 - \epsilon_b) + \epsilon_bA_bPA}$$  \hspace{0.5cm} (4.2.18)

![Spin flipper 'b']

Figure 4.3: Spin Flipper Sequence.

In the case that the SF ON efficiency is close to 1, $\epsilon_b \approx 1$, then $A_{exp}$ reduces to

$$A_{exp} = \frac{A_b + PA}{1 + A_bPA}$$  \hspace{0.5cm} (4.2.19)

If $A_b$ is small, then

$$A_{exp} = PA$$  \hspace{0.5cm} (4.2.20)

This calculation can also be done for a two-detector asymmetry, where the gains of the detectors are $G_A$ and $G_B$. Then $n_3$ becomes

$$n_{3abA,B} = n_{1ab}\sigma_0G_{A,B}(1 + PAf_{ab})$$  \hspace{0.5cm} (4.2.21)
4.3 Beam and Detector Asymmetries

When measuring the physics asymmetry, $A_p$, it is important to consider all processes that might create a false asymmetry, i.e. a spin-dependent asymmetry. Any false asymmetry will mimic the true physics asymmetry. Two false asymmetries are asymmetries from the beam, via spin-dependent beam changes, and from conjugate detectors via their mismatched gains and other factors.

We can write out the flux for each case of spin state and detector number, $B_+$ for signal from ‘+’ state, $B_-$ for signal from ‘-’ state, $D_1$ for signal in one detector, and $D_2$ for signal in the conjugate detector. $A_b$ is the beam asymmetry, and $A_d$ is the detector asymmetry.

$$B_+ = (1 + A_b)B_0 \quad (4.3.1)$$

$$B_- = (1 - A_b)B_0 \quad (4.3.2)$$

$$D_1 = (1 - A_d)D_0 \quad (4.3.3)$$

$$D_2 = (1 + A_d)D_0 \quad (4.3.4)$$

The equations for yield in each detector for each spin state can then be written, with a factor from $A_\gamma$ to account for the parity violating asymmetry.

$$Y^1_+ = B_+ D_1 (1 + A_\gamma) = Y_0 (1 + A_b)(1 + A_d)(1 + A_\gamma) \quad (4.3.5)$$
\[ Y_1 = B_+ D_1 (1 - A_\gamma) = Y_0 (1 - A_b)(1 + A_d)(1 - A_\gamma) \] (4.3.6)

\[ Y_2^+ = B_+ D_2 (1 - A_\gamma) = Y_0 (1 + A_b)(1 - A_d)(1 - A_\gamma) \] (4.3.7)

\[ Y_2^- = B_- D_2 (1 + A_\gamma) = Y_0 (1 - A_b)(1 - A_d)(1 + A_\gamma) \] (4.3.8)

where \( B_0 D_0 = Y_0 \). We can then use these yields to isolate \( A_{\text{exp}} \). Let us define the experimental asymmetry:

\[ A_{\text{exp}} = \frac{(Y_1^+ - Y_2^-) - (Y_1^+ - Y_2^-)}{(Y_1^+ + Y_2^- + Y_1^- + Y_2^+)} \] (4.3.9)

By plugging in Eqs. 4.3.5-4.3.8, \( A_{\text{exp}} \) reduces to

\[ A_{\text{exp}} = \frac{A_\gamma + A_b A_d}{1 + A_b A_d A_\gamma} \] (4.3.10)

Since \( A_b A_d A_\gamma \) is small, this will reduce to

\[ A_{\text{exp}} = A_\gamma + A_b A_d \] (4.3.11)

If \( A_b \) and/or \( A_d \) are sufficiently small, the second term can be neglected. Else, it must be determined and subtracted.

The beam asymmetry, \( A_b \), is the asymmetry between spin states, averaged over conjugate detectors, as shown in 4.3.12. This can be produced by fluctuations in the beam, due, for example, to changes in beam power. The number of neutrons produced changes when the power of the proton beam hitting the tungsten spallation target changes.
\[ A_b = \frac{(Y_1^1 + Y_2^1) - (Y_1^1 + Y_2^2)}{(Y_1^1 + Y_2^2 + Y_1^1 + Y_2^2)} \]  
\[ A_d = \frac{(Y_2^1 + Y_1^2) - (Y_2^1 + Y_2^2)}{(Y_2^1 + Y_2^2 + Y_1^1 + Y_2^2)} \]  

(4.3.12)  

(4.3.13)  

In the analysis, cuts are made on the beam fluctuations using m1, so that there is no bias. Since the beam fluctuations are minimized via cuts, \( A_b \) is small.  

The detector asymmetry, \( A_d \), is the asymmetry between detector yields, averaged over spin state, as shown in 4.3.13. This can be produced by differences in detector gains and responses. This should be small enough that the product of \( A_d \) with \( A_b \) is below the desired error in the \( A_\gamma \) measurement, \( 1 \times 10^{-9} \), see Fig. 4.4.  

Figure 4.4: \( A_b A_d \) Histogram. This histogram shows the product of detector asymmetry, \( A_d \), with beam asymmetry, \( A_b \).  

Since the quantity \( A_b A_d \) is consistent with zero, as shown in Fig. 4.4, it is neglected in
the result.

4.4 Explanation of Cuts

Not all data that is acquired can be used in the calculation of the gamma asymmetry, due to abnormalities or experimental problems. Some data must be removed so that it does not contribute a false asymmetry, or add needlessly to the variation in the data. There are several issues to address, which include the header integrity, the spin flipper state, extremely low or no beam, and dropped pulses.

4.4.1 Header Integrity

Each data run has two associated data files, one corresponding to VME2 and the other corresponding to VME3. Each of these files has a header, which contains flags, a UNIX time stamp, the time since last write, last write time, and a few other things [51]. The header integrity branch checks that the pulse numbers match and checks that the beginning and ending flags are correct. It checks this for the current pulse, the next pulse, and the 3rd pulse (i.e. ‘a’, ‘b’, and ‘c’). Since ‘a’ and ‘b’ are a pair that are evaluated and cut together, each must be checked for header integrity. The third pulse, ‘c’, is also checked because it is possible for the header of a pulse file to be wrong because of something that went wrong in the pulse before it. Thus it is only by checking 3 sequences that it is possible to cut all problems in a 16-step pulse pair.
4.4.2 Checking SF state

The spin rotator flips the spins of the neutrons in a 16-step sequence, but this sequence in the data stream is actually two separate 8-step sequences, ‘a’ and ‘b’, with sequences inverted with respect to each other. The 8 signals of each spin-state are summed together before the asymmetry is calculated. A run can start with either the ‘a’ or ‘b’ sequence. We must check the type of each sequence so that its pulses will be assigned the correct spin type. Thus all ‘up’ pulses are summed and all ‘down’ pulses are summed to make the asymmetry. The spin sequence check is done by summing the 40 bins of the first pulse, and summing the 40 bins of the second pulse, then taking the ratio of these two sums. Then, as seen in Fig. 4.5, the states can be distinguished. This is done for both of ‘a’ and ‘b’ sequences. Once the sequence type is identified, like spin states are combined to calculate the asymmetry.

4.4.3 Beam cuts, dropped pulses

The power of the neutron beam delivered by the SNS was not constant. There were hundreds of beam trips each day, each in length from a few seconds to several hours [52]. As the beam recovers from a beam-off period it takes time to return to higher power, sometimes strung out over minutes. During beam ramp up, there are a high proportion of dropped pulses, which is bad for data quality. These beam drops can occur at anytime during a run. It is also possible for the beam to be run at a higher or lower power at any time. All these
Figure 4.5: **Spin State Ratio.** This representative plot shows the ratio of the sums of pulse 0 over pulse 1. If pulse 0 is on and pulse 1 is off then the value is in the high band, if pulse 1 is on and pulse 0 off then the value is in the low band, near zero. By calculating which band the signal is in, then the spin sequence is known. As can be seen in this graph, the sequence can change between runs, so checking the spin sequence is essential.

Possibilities show up in the data as changes in the magnitude of the signal. Fig. 4.6 shows dropped pulses as well as beam power changes in pulse 6. Changes in beam power will not produce a false asymmetry, unless the change affects the signal in a spin-dependent manner, but introduces noise and reduces statistics. The spin sequence suppresses linear and quadratic drifts in the beam power [32]. This can be seen by labeling each of the pulses first as linear in time $t$, $1t$, $2t$, $3t...8t$. By adding these according to the spin sequence, we see that the result is zero: $1t - 2t - 3t + 4t - 5t + 6t + 7t - 8t = 0$. Thus linear drifts are cancelled. Similarly for quadratic drifts: $1t - 4t - 9t + 16t - 25t + 36t + 49t - 64t = 0$. 


Even higher orders are somewhat suppressed with the 16-step sequence, although there is a readout pulse in the middle that limits this suppression. However, any spin-dependent changes will appear as a false asymmetry, and must be cut out, such as the single-pulse beam changes seen in Fig. 4.6.

Figure 4.6: **Uncut Detector Signal.** This graph of a detector signal for 8 steps shows that the signal can vary substantially due to beam power, as seen in pulse 6. Note also the many dropped pulses near zero.

Dropped pulses are pulses where the proton beam is not delivered to the mercury target, so no neutrons are produced, see Fig. 4.8. The resulting signal is a combination of wrap-around neutrons, decaying backgrounds and electronic pedestal, see Fig. 4.8. Dropped pulses are not predictable, as the facility may drop them with a particular frequency, 0.1 Hz, or they may happen arbitrarily. When a pulse is dropped, not only will the neutrons
be missing for that pulse, but the wrap-around neutrons that would have appeared in later pulses will also be missing. The spectrum is shown at 1 Hz in Fig. 4.7 and with the extended range the wraparound neutrons are visible. A small amount of wraparounds are seen at the end of the second window following the pulse. A greater amount of wraparounds appear in the 6th following window. These wraparounds are on the order of 0.8% of the maximum signal. We cut sequences with dropped pulses to avoid possible spin-dependent issues with missing pulses or missing wraparounds.

**Monitor signal with choppers**

![Monitor signal with choppers](image)

Figure 4.7: **Wraparound Neutrons.** Chopper windows at 1 Hz. Wraparound neutrons can be seen at the end of the second window following the pulse, and in the 6th. There is also a small amount of wraparounds in the 8th window (not shown).

Both ‘a’ and ‘b’ sequences are cut when a pulse is dropped in either sequence, and when a pulse is dropped in the ‘b’ sequence, then the next ‘a’ and ‘b’ sequences are also cut so
that no pulses will have less signal due to missing wraparound neutrons. In this case a total of four 8-step sequences (two 16-step sequences) are cut.

To tell if a pulse is dropped or of too low power, a comparison is made with the average of the sequence, as in Eq. 4.4.1, where \( x \) is the percent deviation from the average of the 8 pulses that will be allowed, \( \sum P \) is the pulse signal summed over 40 bins, and \( \sum S \) is the entire sequence signal summed over 320 bins.

\[
\frac{|\sum P - \frac{1}{8} \sum S|}{\frac{1}{8} \sum S} < x\% \tag{4.4.1}
\]

Figure 4.8: The signal in m1 with a dropped pulse.

Figure 4.9 shows the sum of all 320 time-of-flight bins in the m1 ‘b’ sequence signal as a function of pulse sequence. This shows the discrepancy in signal when \( n \) pulses are dropped. The top band level corresponds to no dropped pulses, all 8 pulses present. The
second lower level is when one pulse is dropped, third lower level for two dropped pulses, etc., until the lowest level, which is all pulses missing, i.e. pedestal signal. Figure 4.10 shows that the entries with dropped pulses are eliminated when a 10% cut is applied via Eq. 4.4.1.

![Figure 4.9: The sum of the 320 bins, in volts, of monitor 1 'b' signal vs sequence number with no cuts. The highest magnitude signals are for normal 8-pulse beam. Each lower band corresponds to dropping 1, 2, 3...8 pulses, with low beam inbetween.](image)

4.4.4 9th Pulse

While the cuts above take care of dropped and low power pulses in the 8-step sequences, if a dropped pulse occurs in the 9th, or read-out, pulse, there will be missing wraparound neutrons later in the data. Data is not taken during the 9th pulse, and therefore the method of cutting dropped pulses used for the sequences will not work for this purpose. However,
Figure 4.10: This shows the bins, in volts, for each sequence in the m1 ‘b’ signal with a cut on 1% of the sequence average. All cuts are applied.

Further down the beamline there is enough frame overlap that the end of the 9th pulse can be seen in the beginning of the first data pulse. The difference between a normal and dropped 9th pulse can be seen in Fig. 4.11.

When there is a dropped signal in the 9th pulse, it can be identified by histogramming the sum of the first few time bins of the sequence. A normal pulse will have a larger sum than a dropped pulse. The 9th pulse cut is done after the cut on the 16-step sequence and the header integrity cut. The sums are normalized by the average signal strength of the 320 bins in the entire sequence, so as to limit the effect of beam flux changes. The 9th pulse cut is made by cutting around the peak of the sum of bins for normal pulses.

To match the cuts done for the dropped pulses in the 8-step sequences, the same RMS
Figure 4.11: 9th Pulse. The first few bins in detector 31 shows the separation between the signal in a normal pulse versus a dropped pulse.

width is used to cut on the ninth pulse sums as is used in the percentage cuts for the 8-steps.

For example, a 1% cut is found around the peak of wanted 8-step sequence pulses, which equates to 13.91 standard deviations (Fig. 4.12). Then the 9th pulse peak is fit, its RMS is found and multiplied by 13.91 to match the cut made for on the 8-step data. Cuts are then made 13.91 standard deviations around the 9th pulse peak mean (Fig. 4.13). This matches the cuts for both the regular 8-step sequence data and the 9th pulse data.
(a) Sum of pulse 0, normalized. The other large peaks are from the other 7 pulses. The peak at zero is from beam off data. The low in-between data are from beam changes or other outlying signals.

(b) Fit of peak. Fit of the pulse 0 peak for finding its RMS. The underlying background is from outlying data, such as changing beam.

Figure 4.12: Plot (a) shows the sum of signals for the bins of pulse 0. This quantity is compared to the average value for the entire 8-step sequence, and then a cut is made based on how far it is from the average. The fit of the main peak of the normalized pulse sum in (b) gives the RMS value. Then the number of sigma is calculated for a 1% (1.01) cut. This same number of sigma is used to make cuts around the 9th pulse sum peak so that the same RMS is used for both cuts.
(a) Normalized sum of first 5 bins, where 9th pulse is visible.

(b) Fit of 9th pulse sum.

Figure 4.13: RMS is found and multiplied by number of RMS from the pulse sum to match the percentage cut.

### 4.5 Backgrounds

Background signals in the CsI detectors must be accounted for in the calculation of the asymmetry, not because they create false asymmetries, but because they dilute the signal and change the width of the asymmetry peak. Only spin-dependent backgrounds can create a false asymmetry.

The background consists of signals from a number of sources. Backgrounds dilute the
value of $A_\gamma$ by increasing the denominator. There is a largely flat electronic pedestal plus underlying electronic noise from various hardware components. There are gamma rays from the interactions of neutrons with the various elements in the experimental area. There are several aluminum windows in the beam path, the SM polarizer, and many other elements present. From these interactions arise both prompt and beta-delayed gammas, which have a known lifetime of 194 seconds.

In order to subtract the backgrounds they should be measured. Unfortunately, we cannot measure the pedestal while taking beam because the chopper is open nearly the full pulse. This is a change from the LANL version of the experiment, where the chopper was closed for 10 ms so pedestals could be measured after each pulse. For the SNS experiment there is no time in a pulse where the choppers sit closed or when the beam is off. However, the dropped pulses, which had to be cut from the analysis of the asymmetry, can be used in the extraction of the backgrounds. The dropped pulses can occur randomly, or they can occur periodically under the control of the facility, every 600 pulses or 0.1 Hz. If we do not have a dropped pulse near all data, we assume that the background is constant between dropped pulses. This is not an absurd assumption as the elements present in the beam will remain constant. However, the beam power may shift between dropped pulses, giving a slight uncertainty to the pedestal.

The necessary condition for the analysis of the backgrounds is that $A_b A_d < 1 \times 10^{-9}$
since

\[ A_{\text{raw}} = A_{\text{phys}} + A_b A_d \]  \hspace{1cm} (4.5.1)

and the requirement for the experiment is a measurement to \(10^{-9}\).

Inside the total signal of each pulse is both the data from the current neutrons, as well as a decaying tail from backgrounds and an electronic pedestal. This tail causes a dilution of the signal and must be accounted for in the calculation of the asymmetry. By simulating a 1 Hz pulse, i.e. without the overlapping windows that 60 Hz signals have, the underlying tail can be found and removed from the data.

The total signal, \(S_T\), is the sum of the signal and tail, \(S_T = S + T\). A ratio, \(R\), is constructed

\[ R = \frac{T}{S_T} \]  \hspace{1cm} (4.5.2)

Since the tail comes from the previous pulse, in half of the cases it has the opposite spin state of the signal. In that case the value of the tail must be subtracted twice to cancel the spin effects from having two different spin states (i.e. make the contribution unpolarized).

The dilution factor, \(D\)

\[ D = \frac{\text{Real Signal}}{\text{Total Signal}} = \frac{S_T - 2T}{S_T} = 1 - 2R \]  \hspace{1cm} (4.5.3)

where \(T\) is the tail value.

However, when the tail is of the same spin state, it is not a dilution at all. Thus there are two cases, in half of cases the previous pulse is of the same spin state, and in the other
half the previous pulse is of opposite spin state. Averaging the dilution factors from the two cases gives the equation that is used uniformly over all the data, disregarding spin state. When the previous pulse is the same spin state, then there is no dilution and

\[ D = 1 \]  \hspace{1cm} (4.5.4)

When the previous pulse is a different spin state then the dilution is Eq. 4.5.3. When averaged together the total dilution factor is

\[ D = 1 - R \]  \hspace{1cm} (4.5.5)

The change in beam power must be taken into account. First, a ‘pseudo-1 Hz’ pulse is constructed. A real 1 Hz signal would be a single beam pulse that occurs at sufficiently low frequency (1 Hz) that many 60 Hz pulse lengths can be seen. This allows all characteristics obscured by the overlap of 60 Hz pulses to be uncovered. A false 1 Hz pulse is constructed by subtracting dropped pulses from clean pulses, since the dropped pulses contain the backgrounds that are hidden. From the pseudo-1 Hz we construct two ratios:

\[ R_1 = \frac{T_1}{S_1} \]  \hspace{1cm} (4.5.6)

\[ R_2 = \frac{T_2}{S_2} \]  \hspace{1cm} (4.5.7)

Where \( T_{1,2} \) is the tail value in a range of bins and \( S_{1,2} \) is the signal value in the corresponding bin range. The two ranges are required so that both the tail and the background can be solved for. These ratios will be the same for all pulses, but the 60 Hz signal values must
be scaled by beam power and pedestal. The 60 Hz signal is the sum of the pseudo-1 Hz signal and the pseudo-1 Hz tail from the previous pulse, scaled by the beam power and other changes, with the pedestal added. For an arbitrary pulse sums are created over the two ranges, yielding:

\[ a_1 = (S_1 + T_1)B + P \]

\[ = S_1(1 + R_1)B + P \]  

(4.5.8)

and

\[ a_2 = S_2(1 + R_2)B + P \]  

(4.5.9)

where \( B \) is the scaling for beam power (or other) and \( P \) is the pedestal. Then solving for \( B \) and \( P \):

\[ B = \frac{a_1 - a_2}{S_1(1 + R_1) - S_2(1 + R_2)} \]  

(4.5.10)

\[ P = a_1 - S_1(1 + R_1)B \]  

(4.5.11)

The data analysis procedure is as follows. First, all dropped pulses in the run are identified. This is done by checking if the 20th bin in each pulse is above 0.025 Volts for M1. Readout pulses are checked by summing the first five bins in detector 36 and evaluating if the value is outside a range. The dropped pulses that are at least 30 16-step sequences (entries) away from the previous dropped (or otherwise bad) pulse and at least 4 entries away from the next dropped (or otherwise bad) pulse are then individually shifted so that the dropped pulses from each sequence are aligned. This is done to increase statistics for this dropped pulse histogram as much as possible for the run.
Figure 4.14: Dropped pulses as a function of 16-pulse sequence number. Dropped or missing pulses are in white, normal pulses are in red. The vertical axis is the pulse number in a sequence: 8 pulses, 9th readout, 8 more pulses, another readout pulse. You can see that the dropped pulses happen periodically, and a beam off period can also be seen, with increasing frequency of pulses as the beam power increases to normal.

Figure 4.15: The clean signal, data without dropped pulses, is shown in blue. The corresponding dropped pulse data is shown in red. Note the lower signal in the third pulse, due to missing wraparound neutrons.
Figure 4.16: Pseudo-1Hz pulse from detector 12. Shown are the bin ranges used for calculations of \( s_1, s_2, t_1, t_2 \). Ranges are 13 bins each, chosen to include the pulse peak and to avoid the chopper moving portions of the pulse.

A similar procedure is used to create a ‘clean’ spectrum, see Fig. 4.15. The clean histogram is composed of 12 sequences before a dropped pulse, histogrammed together and shifted the same way as the dropped pulses to get the same statistical variations at the beginning and end of the histogram. The dropped pulse spectrum is then subtracted from the clean pulse spectrum to produce a ‘pseudo-1 Hz’ spectrum, i.e. a spectrum that simulates a 1 Hz beam, with a single pulse instead of overlapping pulses. This allows the full background tail to be seen, which would ordinarily overlap with the next pulse (see Fig. 4.16). Ratios \( R_1 \) and \( R_2 \) are constructed to compare the signal, \( S_1 \) and \( S_2 \), in corresponding bin ranges with the tail, \( T_1 \) and \( T_2 \). These are then used to solve for the backgrounds and pedestals, \( B \) and \( P \), as in the equations above. The corresponding bin
ranges in each individual pulse are used to find $a_1$ and $a_2$ as in Eqns. 4.5.8 and 4.5.9.

Histograms showing the spread of the background scaling factor (B) and the pedestal (P) are shown in Figs. 4.17 and 4.18 below, and the dilution factor (D) is shown in Fig. 4.19.

Figure 4.17: The background factor as a function of run number. B can be very broad if the beam power changes significantly during the run. There is no need to cut such runs as their data is still usable.
Figure 4.18: The pedestal as a function of run number. This is very constant, as it is mainly an electronic pedestal.

Figure 4.19: The dilution factor as a function of run number. It is interesting to see how the dilution increases as the beam is on longer after there has been no beam on the target.

The ratio in Eq. 4.5.2 is constructed using the tail value for each bin, $T$, along with the signal plus tail for each bin, $S_T = S + T$ from the pseudo-1 Hz data. Since the pseudo-1 Hz
The curve is created once per run, $R$ will be the same for a particular detector and time bin for the run. This $R$ is then used to find the dilution factor, $D$, in Eq. 4.5.5. The dilution factor and the average pedestal for the sequence are used to find the experimental asymmetry:

$$A_{exp} = \frac{(\sum S_{i,\uparrow} - \sum S_{j,\uparrow}) - (\sum S_{i,\downarrow} - \sum S_{j,\downarrow})}{D_{conj}((\sum S_{i,\uparrow} + \sum S_{j,\uparrow}) + (\sum S_{i,\downarrow} + \sum S_{j,\downarrow}) - 16P_i - 16P_j)}$$ (4.5.12)

where $D_{conj}$ is the average dilution factor over the two conjugate detectors, $P$ is the pedestal, $S_{i,j,\uparrow,\downarrow}$ is the signal for the $i$ or $j$ detector for the two spin states, and $A_{exp}$ is a function of detector and time bin.

The detector asymmetry as a function of detector pair $i,j$ and time bin is:

$$A_{det} = \frac{(\sum S_{i,\uparrow} + \sum S_{i,\downarrow}) - (\sum S_{j,\uparrow} + \sum S_{j,\downarrow}) - 16P_i + 16P_j}{D_{conj}((\sum S_{i,\uparrow} + \sum S_{j,\uparrow}) + (\sum S_{i,\downarrow} + \sum S_{j,\downarrow}) - 16P_i - 16P_j)}$$ (4.5.13)

The total asymmetry including all relevant time bins was weighted as follows.

$$A_{exp, tot} = \frac{\sum A_{exp, t} F_{exp, t}}{\sum F_{exp, t}}$$ (4.5.14)

$F$ is the flux in the detector pair for that time bin.

$$F_{det, t} = (\sum S_{i,\uparrow} + \sum S_{j,\uparrow}) + (\sum S_{i,\downarrow} + \sum S_{j,\downarrow}) - 16P_i - 16P_j$$ (4.5.15)

If a run has no dropped pulses that satisfy these parameters, it was not used. It also occasionally occurred that there were not enough dropped pulses to fill the blank 9th pulse spaces, or all the dropped pulses were in the same spot. The pseudo-1 Hz then is not smooth, but has pulses where there was nothing subtracted in the sequence, creating a hole.
at the 9th readout pulse, see Fig. 4.20. If this stray pulse occurs in the bin ranges used for the calculations, it was also cut. This ensures that only good data was used to calculate the asymmetries.

![dropped pulse](image1)

(a) A histogram showing all the dropped pulses shifted to be in the same position. There is not enough variation in the pulse position to fill the blank readout pulse.

![pseudo pulse](image2)

(b) Pseudo-1Hz of clean spectrum minus (a). Blank readout pulses are immediately following the pseudo-1Hz pulse, and 9 after.

Figure 4.20: Since the pseudo 1Hz pulse is directly followed by an unwanted pulse there is no tail. Therefore any run with this characteristic is cut and unused in the asymmetries.
Aluminum

The major background contribution of the asymmetry measurement is due to neutron capture on aluminum. The capture cross section of thermal neutrons on Al-27 is $\sigma_{\text{cap}} = 0.231$ barns. After capture, there is a cascade of prompt 7.725 MeV gamma rays from the decay of excited Al-28 to its ground state [39]. This is followed 194 seconds later by 1.779 MeV gamma rays that are beta-delayed, i.e. emitted after the beta decay of Al-28 to Si-28 excited state to Si-28 ground state [53], (see Fig. 4.21).

![Aluminum Decay Scheme](image)

Figure 4.21: Aluminum Decay Scheme. This diagram shows how neutron interactions with aluminum in the experimental area causes background signals for the asymmetry measurement.

The beta-delayed backgrounds are removed from the data as part of the pedestal. To extract the effects of the prompt aluminum signal, the asymmetry for aluminum is measured
and subtracted, as in Eq. 4.6.9. To measure the aluminum fraction, the shutter was closed and the decay of the signal was measured and fitted to the aluminum and iodine decays [54]. By comparing the fitted decay amplitude to the signal before the shutter was closed, the fraction of prompt aluminum was found. Fig. 4.23 shows the results for each detector.

The weighted average for the three rings is 17.02%.

**Fitting Function:** $F(t) = [0] + [1] \exp(-t/198) + [2] \exp(-t/2160)$

Figure 4.22: **Background Decay Fit.** Fit of decay data to pedestal, aluminum, and iodine. From [54], used by permission.
Figure 4.23: Aluminum Background Fraction.

Figure 4.24: Aluminum Decay. Decay of Aluminum-28, half life 2.2406 minutes. Vertical lines indicate 100 sequences.
4.6 Asymmetry Calculations

4.6.1 Geometry Factors

There are both parity conserving (PC) and parity violating (PV) asymmetries in the n+p → d+γ reaction. The PC spin asymmetry comes from interactions proportional to

\[ \hat{k}_\gamma \cdot (\hat{\sigma}_n \times \hat{k}_n) \propto \sin \theta \]  

(4.6.1)

where \( \theta \) is the angle between the gamma momentum and the vertical. Parity is conserved in this process because both neutron and gamma momenta are inverted under the parity operator while the neutron spin remains the same. This PC asymmetry is seen only in the left-right direction (\( \hat{x} \)). This is because the neutron spin, \( \hat{\sigma}_n \), is in the up-down direction, \( \hat{y} \), and the neutron momentum is downstream in the \( \hat{z} \) direction. The PV process results in a spatially non-uniform gamma ray distribution, due to interactions proportional to

\[ \hat{k}_\gamma \cdot \hat{\sigma}_n \propto \cos \theta \]  

(4.6.2)

Since only the gamma momentum changes sign under the parity operator, this process is parity violating. Both the PV and PC components are present in the measured data. The coordinate system used is shown in Fig. 4.25. If the detector array is rotated by an angle \( \phi \), then the PC asymmetry will leak into the up-down calculation as \( \sin \phi \), creating a false asymmetry measurement.

Each of the 48 CsI detectors is comprised of two crystals. These crystals are not equal in
efficiency. This causes the effective absorption center to change, which results in an angular shift of the detector [55]. This creates an effective angle of the detector. The experiment has both a finite source and finite detectors. Additionally, it is possible for a gamma ray to deposit energy in multiple detectors. All of these things contribute to what are called “geometry factors.” These geometry factors were calculated by Kyle Grammer using a MCNPX simulation [56]. The simulation includes the target and detector geometries, materials encountered, and tracks neutrons, electrons, and photons through their deposition. The alignment of the detector array was measured using a small sealed source and incorporated into the MCNP simulation [56, 57].

![Detector Layout](image)

**Figure 4.25: Detector Layout.** The detector array looking down the beam, $+\hat{z}$ direction, (a), and from the side, (b). Up is $+\hat{y}$ and beam left is $+\hat{x}$. The beam travels in the $+\hat{z}$ direction.

The following equations show how $G_{LR}$ and $G_{UD}$ are calculated for each detector
\[ G_{LR} = \frac{\langle E_i \hat{k}_\gamma \cdot (\sigma^*_n \times \hat{k}_n) \rangle}{\langle E_i \rangle} = \frac{\langle E_i \hat{k}_\gamma \cdot \hat{x} \rangle}{\langle E_i \rangle} \] (4.6.3)

\[ G_{UD} = \frac{\langle E_i \hat{k}_\gamma \cdot \sigma^*_n \rangle}{\langle E_i \rangle} = \frac{\langle E_i \hat{k}_\gamma \cdot \hat{y} \rangle}{\langle E_i \rangle} \] (4.6.4)

4.6.2 Asymmetry

The asymmetry in the data is calculated as in Eq. 4.5.12 and shown in Fig. 4.26. After the geometry factors were calculated, they were fitted to the raw asymmetry to extract \( A_{UD}^f \) and \( A_{LR}^f \) using a least square fit, minimizing

\[ \chi^2 = \sum_{i=1}^{n} \left( \frac{[A_i - (A_{UD}^f G_{UD} + A_{LR}^f G_{LR})]}{\sigma_i} \right)^2 \] (4.6.5)

where the \( \sigma_i \) used is the error in the mean of the asymmetry, \( A_i \) is the mean from the asymmetry histograms, and the sum is over detector pairs.

\[ A_{raw} = G_{UD} A_{UD}^f + G_{LR} A_{LR}^f \] (4.6.6)

This gives values for \( A_{UD}^f \) and \( A_{LR}^f \) for a 1\% cut on dropped pulses:

\[ A_{UD}^f = 3.2258 \pm 0.30995 \times 10^{-8} \] (4.6.7)

\[ A_{LR}^f = 4.4555 \pm 30.9434 \times 10^{-9} \] (4.6.8)

To calculate the actual left-right and up-down asymmetry, the fitted asymmetry values must be modified for the backgrounds. This equation must also include corrections for
actual neutron beam polarization, $P_n$, spin flipper efficiency, $\epsilon_{SF}$, depolarization in the hydrogen target, $C_h$, and depolarization due to aluminum in the beam, $C_{Al}$.

$$A_{LR,UD} = \frac{A_{LR,UD}^f - F_{bg}A_{LR,UD}^Al}{P_n\epsilon_{SF}C_h}$$  \hspace{1cm} (4.6.9)

Both $P_n$, the neutron polarization, and $\epsilon_{SF}$, the spin flipper efficiency, were found using neutron polarimetry, the values for the approximate wavelength range used in this analysis are [58]:

$$P_n = 0.943 \pm 0.004 \hspace{1cm} (4.6.10)$$

$$\epsilon_{SF} = 0.975 \pm 0.003 \hspace{1cm} (4.6.11)$$

The depolarization in the target, for both hydrogen, $C_h$, and for aluminum in the apparatus, $C_{Al}$, are found via MCNP simulation calculations, see [59].

$$C_h = 0.9485 \pm 0.041 \hspace{1cm} (4.6.12)$$

Ring 2 $C_{Al} = 0.963 \pm 0.042$

Ring 3 $C_{Al} = 0.952 \pm 0.042 \hspace{1cm} (4.6.13)$

Ring 4 $C_{Al} = 0.938 \pm 0.041$

Since only one value can be used for the final calculation, the weighted average of the ring values and errors for $C_{Al}$ is calculated.

$$C_{Al} = 0.952 \pm 0.0417 \hspace{1cm} (4.6.14)$$
I calculate the weighted average of the background fraction from each detector for use in the equation for final asymmetry, Eq. 4.6.9:

\[ F_{bg} = 0.170 \pm 0.003 \] (4.6.15)

All these values are then used to find the final asymmetry, Eq. 4.6.9, which for a 1% beam cut is:

\[ A_{UD} = (6.254 \pm 37.694) \times 10^{-9} \] (4.6.16)

\[ A_{LR} = (16.72 \pm 37.62) \times 10^{-9} \] (4.6.17)

These values show that the asymmetry is consistent with zero.

The same procedure is done for a 2% beam cut, resulting in:

\[ A_{UD} = (5.725 \pm 37.696) \times 10^{-9} \] (4.6.18)

\[ A_{LR} = (16.643 \pm 37.622) \times 10^{-9} \] (4.6.19)

The consistency of this solution to the 1% cut shows the insensitivity of the cuts.

4.7 Systematic Errors

Systematic errors can arise both from background physics interactions and experimental asymmetries. Any process that creates a spin-dependent signal that is not from the physics PV \( \bar{n}+p\rightarrow d+\gamma \) observable is a false asymmetry that adds systematic error. Physical processes that can cause false asymmetries include Stern-Gerlach steering, Mott-Schwinger...
scattering, gamma ray circular polarization, $\beta$-decay, and capture on $^{6}$Li. Systematic errors that are measured and extracted include the aluminum asymmetry and the parity conserving left-right asymmetry.

**Stern-Gerlach Steering**

The polarized neutrons are subject to a magnetic holding field to guide the spin. If there is a gradient in this field, then the neutrons will experience a force $F = \mu \cdot \nabla B$. A gradient, for example, in the up direction will force up-spinning neutrons to move upward and down-spinning neutrons to move downward from the initial momentum line, an effect called Stern-Gerlach steering. This gives a spin-dependence in the relative solid angle between the up and down detectors, creating a false asymmetry. For a gradient of 1 mG/cm the false asymmetry is on the order of $10^{-11}$. The field gradient was measured to be less than 3 mG/cm\[30\].

**Mott-Schwinger Scattering**

Mott-Schwinger scattering is a spin-orbit interaction, where the spin of the neutron interacts with the magnetic field created by the nucleus it passes. The nucleus has a Coulomb field $\vec{E}$, so the neutron sees the magnetic field $\vec{B} = \vec{v} \times \vec{E}$, with energy $V = \mu \cdot (\vec{v} \times \vec{E})$. Neutrons with the same spin passing on opposite sides of the nucleus see B-fields in opposite directions. For example, a spin-up neutron passing on the left of a nucleus sees a B-field in the same direction as its spin, and a spin-up neutron passing on the right will see a B-field in the
opposite direction of its spin. The energy thus is greater in one direction than the other, deflecting the beam in a spin-dependent way. This creates a L-R asymmetry. This Mott-Schwinger scattering is extracted as part of the PC left-right asymmetry. However, if there is a misalignment of the detector, this will leak into the U-D asymmetry. This misalignment was measured to be less than 40 mrad [60] and incorporated into the geometry factors as discussed in Sec. 4.6.1.

Circularly Polarized $\gamma$-rays

As discussed in the first chapter, the $\vec{n}+p\rightarrow d+\gamma$ reaction also produces parity violating circularly polarized gamma rays. While NPDGamma is not set up to distinguish the circular polarization, subsequent interactions of escaped circular gamma rays with the lightly magnetized steel plates above and below the experiment can scatter gamma rays back into the detectors in a spin-dependent way. This effect is very small, on the order of $10^{-12}$ [61].

Capture on $^6$Li

$^6$Li is used as a shielding material due to its high neutron capture cross section. Polarized neutron capture on $^6$Li results in an $\alpha$ and a triton, a parity violating process where the alpha particles are emitted asymmetrically. The asymmetry for this $^6$Li interaction is calculated to be small, on the order of $10^{-11}$ [61].
Asymmetry from $\beta$ Decay

Neutron $\beta$ decay is a parity violating process, with electron emission correlated with the neutron spin state. Neutrons can beta decay in-flight, or via interactions with aluminum in the beam. For the case of in-flight decays, the electrons are absorbed before entering the detectors, however, they can emit bremsstrahlung radiation, which is collected in the CsI detectors.

$$\vec{n} \rightarrow p + e^{-} + \nu_e$$ (4.7.1)

An order of magnitude calculation has been done to estimate the asymmetry from this interaction, based on a GEANT4 simulation in [41]. Combining the beta decay correlation coefficient $A = -0.119$ and a capture rate of 60% on hydrogen, the asymmetry is less than $4 \times 10^{-11}$. This does not include the electron-photon direction correlation, which is on the order of 1.

Radiative $\beta$ decay can also occur in-flight:

$$\vec{n} \rightarrow p + e^{-} + \nu_e + \gamma$$ (4.7.2)

depositing energy into the detectors in a spin-dependent way. Using the same fraction of beam decay for the length of the detector, $6.8 \times 10^{-7}$, as was used above for normal beta decay, along with a branching ratio of $3.13 \times 10^{-3}$, the asymmetry is less than $2.3 \times 10^{-10}$. This does not include the correlation coefficient for this process, which should be on the
same order as normal beta decay, thus lowering the affect of this asymmetry another order of magnitude [41].

There is also beta decay from neutron interactions with $^{27}$Al:

$$\bar{n} + ^{27}\text{Al} \rightarrow ^{28}\text{Al}^* \rightarrow ^{28}\text{Si}^* + e^- \quad (4.7.3)$$

For an 8-step spin sequence, each pulse taking $t=16.6$ ms, time-dependent errors are suppressed to second order, so asymmetry is as $(t/\tau)^3$. The lifetime for the beta decay is 194 seconds, resulting in a false asymmetry on the order of $10^{-13}$ [41].

<table>
<thead>
<tr>
<th>Cause</th>
<th>Error Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stern-Gerlach</td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td>Mott-Schwinger</td>
<td>measured</td>
</tr>
<tr>
<td>Circular Radiation</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>Capture on $^6\text{Li}$</td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td>In-flight $\beta$ Decay</td>
<td>$&lt;4\times10^{-11}$</td>
</tr>
<tr>
<td>Radiative $\beta$ Decay</td>
<td>$&lt;2.3\times10^{-10}$</td>
</tr>
<tr>
<td>$^{28}\text{Al} \beta$ Decay</td>
<td>$&lt;6.3\times10^{-13}$</td>
</tr>
<tr>
<td>PC Left-Right Asymmetry</td>
<td>measured</td>
</tr>
<tr>
<td>Al Asymmetry</td>
<td>measured</td>
</tr>
</tbody>
</table>

The systematic errors from false asymmetries are listed in Table 4.1. All of the calculated false asymmetries are well below the statistical precision of the NPDGamma experiment and are therefore immaterial to the result. Measured asymmetries are extracted via analysis so that they do not affect the final result. Multiplicative instrumental asymmetry was
measured to be \((-0.23 \pm 9) \times 10^{(-10)}\) and the additive instrumental asymmetry was measured to be \((5.7 \pm 7.4) \times 10^{(-10)}\) \cite{[62]}.

4.8 Conclusion

We presented analysis of the “Three-Ring” data, about 3947 runs. This analysis was done separately from the rest of the hydrogen measurements due to complications in this data set from hardware changes and timing changes. The raw asymmetry was extracted from data taken on hydrogen and fitted using calculated geometry factors to find intermediate values for the left-right and up-down asymmetries. The previously calculated asymmetry from aluminum was adjusted for scaling parameters resulting from depolarization, spin flipper efficiency, neutron beam polarization, and the fraction of aluminum signal. This aluminum background was extracted and the final hydrogen asymmetry was found. This then gives the final results for the parity-conserving and parity-violating asymmetries in neutron capture on protons:

\[
A_{UD} = (6.254 \pm 37.694) \times 10^{-9} \quad (4.8.1)
\]

\[
A_{LR} = (16.72 \pm 37.62) \times 10^{-9}. \quad (4.8.2)
\]

Neglecting the small effects from other meson terms, we can calculate \(h_\pi\) from this
result:

\[ h_\pi = (-0.57 \pm 3.4) \times 10^{-7}. \]  

(4.8.3)

These results are statistics limited, however this is only a small part of the overall data taken, less than 4000 runs out of a total of 45126 runs, or less than 9%. Since this data is only three rings instead of the four used in later runs, this result will affect the final error bar by less than 3.3%. If the full data set has a statistical error on the order of 1×10^{-8} then the error on \( h_\pi \) will be about 9×10^{-8}. This is better than the error in \( h_\pi \) from the world average of \(^{18}\text{F}\) measurements of \( \Delta h_\pi = 3.9 \times 10^{-7} \). This makes the NPDGamma measurement the definitive measurement of \( h_\pi \), and one that can be used to assess measurements with complex nuclei.

The hydrogen data analyzed in this work has been fully analyzed and should be incorporated in the final NPDGamma result to maximize statistics and data used.

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Figure 4.26: **Experimental Asymmetry.** Each column shows a ring of pairwise asymmetry histograms. The mean and spread values are used to fit for the $A_{UD}^f$ and $A_{LR}^f$.  

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Figure 4.27: **Raw Asymmetry vs Run.** Raw asymmetry as a function of run.

Figure 4.28: **Pairwise Asymmetry.** Raw asymmetry for each pair. These values are fitted to the geometry factors to extract $A_{LR}^f$ and $A_{UD}^f$. 
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