A DYNAMICALLY POLARIZED PROTON TARGET FOR MEASUREMENTS OF THE TRANSVERSE SPIN-DEPENDENT TOTAL $\vec{n}-\vec{p}$ CROSS SECTION DIFFERENCE, $\Delta\sigma_T$

by

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ABSTRACT

RAICHLE, BRIAN WILLIAM, A Dynamically Polarized Proton Target for Measurements of the Transverse Spin-Dependent Total $\vec{n}-\vec{p}$ Cross Section Difference, $\Delta\sigma_T$. (Under the direction of Christopher R. Gould and David G. Haase.)

Measurements of the total spin-dependent cross section difference for a polarized-neutron beam scattering from a polarized-proton target, $\Delta\sigma_T$, have been made for incident neutron energies between 10 and 20 MeV. Both beam and target spin axes were oriented transverse to the momentum direction. $\Delta\sigma_T$ is sensitive to the phase-shift parameter ε_1, which characterizes the strength of the tensor component of the nucleon-nucleon interaction. The ε_1 values obtained from the measured values of $\Delta\sigma_T$ are consistent with predictions from potential models and partial-wave analyses, and throw into severe doubt several previously reported experimental values.

These measurements were performed at the Polarized Target Facility located in the Triangle Universities Nuclear Laboratory. The polarized-neutron beam is produced as a secondary beam through polarization-transfer reactions from polarized proton- and deuteron-beams. The beams of polarized charged particles are produced by the TUNL Atomic Beam Polarized Ion Source and accelerated by a tandem Van de Graaff. Charged-particle beam polarization is measured with a scattering chamber located before the neutron-production cell.

A dynamically polarized proton target was constructed for this experiment. A 0.06 b^{-2} thick target of chemically doped propanediol is placed in a 2.5 T magnetic field and cooled to 0.5 K by a ^{3}He evaporation refrigerator. Microwave pumping induces a nuclear polarization of order 70%. Dynamic polarization allows frequent reversal of the target polarization, making the target ideal for experiments to measure small asymmetries. Temperature of the target is determined from ^{3}He vapor-pressure thermometry. Proton polarization is monitored using continuous nuclear magnetic resonance (NMR).

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Chapter 1

Introduction

Evidence for the tensor component of the nucleon-nucleon (NN) force dates back to 1939 with the discovery of the electric quadrupole moment of the deuteron [**?**], and measurements of the anomalous deuteron magnetic dipole moment [**?**]. The tensor force is particularly important in few-nucleon systems because it contributes significantly to the binding energy [**?**]. Nevertheless its strength remains poorly determined.

In low-energy neutron-proton scattering the strength of the tensor interaction is characterized by the phase-shift parameter ε_1, which describes the mixing between the $^3S_1$ and $^3D_1$ states.[1] Since phase shifts are not directly measurably, experimentalists look to observables which are sensitive to ε_1 as a way to study the strength of the tensor interaction. Observables which are sensitive to ε_1 involve measuring at least two of the spins in the *np* system. Examples include spin-correlation coefficients, polarization-transfer coefficients, and the spin-dependent total cross-section differences $\Delta\sigma_T$ and $\Delta\sigma_L$. $\Delta\sigma_T$ is the difference in total cross section between neutron and proton with polarization axes mutually anti-parallel then parallel, while transverse to the incident momentum direction. $\Delta\sigma_L$ is the cross section difference when both neutron and proton polarizations axes are parallel to the incident momentum vector, and mutually parallel then anti-parallel. The cross-section

[1] In spectroscopic notation, $^{2S+1}L_J$ where S is the total spin, L refers to the orbital angular momentum ($S \Leftrightarrow \ell = 0, P \Leftrightarrow \ell = 1, D \Leftrightarrow \ell = 2$, etc), and $\vec{J} = \vec{S} + \vec{\ell}$.

Figure 1.1: Theoretical predictions and experimental measurements of the mixing angle ε_1 below 60 MeV. References are given in Sections 2.4 and 2.5

differences were shown by Tornow [**?**] to be sensitive to ε_1 and insensitive to most other phase shifts. As a result measurements of $\Delta\sigma_T$ and $\Delta\sigma_L$ provide an excellent way of studying ε_1.

Figure 1.1 describes the current experimental and theoretical understanding of the strength of the tensor interaction, as indicated by ε_1, below 60 MeV. References for the data are given in Chapter 2. The curves are from potential-model predictions and partial-wave analyses, also referenced in Chapter 2. It is clear from this figure that there exist several discrepancies between theory and experiment and indeed several discrepancies between measurements. In the region between 15 and 20 MeV some experiments have found a lower than expected ε_1 (weaker tensor force), and between 25 and 40 MeV experiments suggest a larger than expected ε_1 (stronger tensor force). Furthermore, with increasing energy, potential-models and some partial-wave analyses diverge in their prediction of the tensor interaction strength.

In an effort to clear up these discrepancies and to provide greater insight into the strenght of the tensor interation we have attempted to determine the transverse spin-dependent total cross-section difference $\Delta\sigma_T$ by measuring the spin-dependent transmission asymmetry for a polarized-neutron beam through a polarized-proton target. The polarized-neutron beam was produced by charged-particle induced reactions. The proton target was a new dynamically polarized target specifically constructed for these measurements. The experiment was performed at the Triangle Universities Nuclear Laboratory (TUNL) in Durham, NC at three energies below 20 MeV and at 35 MeV.

Compared to the statically polarized hydrogen target previously used at TUNL [?], dynamic polarization offers several advantages for measurements of small transmission asymmetries. Dynamically polarized targets operate at a higher temperature than statically polarized targets, making them less susceptible to beam heating effects. For comparison, the statically polarized proton target employed at TUNL operated at 0.015 K, while the dynamically polarized target used in these measurements operates at 0.5 K. In addition, the spin axis of the target can be rapidly reversed with dynamic polarization (in $\approx$ 30 min). This allows frequent target polarization flips, which are crucial to cancelling instrumental asymmetries. For comparison, reversing target polarization of the TUNL statically polarized proton target took of order one day.

The dynamically polarized proton target consisted of frozen beads of propanediol chemically doped with EHBA Cr^V complex, irradiated with microwaves, and cooled to 0.5 K by a ^3He evaporation refrigerator in a 2.5 T magnetic field. Target polarization was monitored by continuous NMR, and the product of target polarization $\times$ thickness was calibrated by neutron transmission.

In addition to the measurements of $\Delta\sigma_T$, a supplemental measurement was made of the transverse polarization-transfer coefficient $K_y^{y'}(0°)$ for the ^{3}H$(\vec{p},\vec{n})^3$He reaction. This involved a direct measurement of the neutron-beam polarization using a high-pressure ^{4}He gas cell analyzer. Knowledge of $K_y^{y'}(0°)$ is important in the target polarization $\times$ thickness calibration.

The cross-section data and the values of ε_1 extracted from a single-energy, single-parameter phase-shift analysis are compared to theoretical predictions and previous measurements.

Chapter 2

Theoretical Overview

2.1 Partial-Wave Expansion for Spinless Particles

From the optical theorem, the total cross section for spinless particles scattering from a central potential can be written as

$$\sigma_{tot} = \frac{2\pi}{k^2} \sum_{\ell} (2\ell + 1)[1 - \Re\mathfrak{e}(S_\ell)], \tag{2.1}$$

where k is the wave number, ℓ is the relative orbital angular momentum, and $\Re\mathfrak{e}(S_\ell)$ indicates the real part of the scattering factors S_ℓ. The S_ℓ are related to the phase shifts by

$$S_\ell = e^{2i\delta_\ell}. \tag{2.2}$$

Orbital angular momentum ℓ is a good quantum number and the contribution of each ℓ scattering eigenstate to the total cross section is determined by its corresponding phase shift δ_ℓ.

2.2 Partial-Wave Expansion for Particles with Spin

The description of nucleon-nucleon scattering is more complicated than indicated in Equation 2.1 because of the spins of the particles. We consider particles with spin I_a

scattering from a target with spin I_A. The total angular momentum J is a good quantum number, but in general ℓ will not be because the NN force is non-central.

We choose the "channel-spin" angular momentum coupling scheme

$$\vec{J} = \vec{\ell} + (\vec{I}_A + \vec{I}_a) = \vec{\ell} + \vec{s} \tag{2.3}$$

where s is the channel spin. The advantage of the channel-spin representation is the absence of interference between different channels in the total cross-section expression.

The total spin-*dependent* cross section can be calculated from the generalized spin-dependent optical theorem [**?**] as[1]

$$\sigma_{tot} = \sum_{kK} \sigma_{kK} \tilde{t}_{K0}(I_A) \tilde{t}_{k0}(I_a). \tag{2.4}$$

The beam- and target-polarization states are described by the statistical tensors $\tilde{t}_{kq}(I_a)$ and $\tilde{t}_{KQ}(I_A)$. The partial-wave cross sections σ_{kK} are given by

$$\sigma_{kK} = \frac{2\pi}{k^2} \Re\mathfrak{e} \Bigg\{ \sum_J \sum_\ell \sum_{\ell'} \sum_s \sum_q \frac{2J+1}{(2I_a+1)(2I_A+1)} \times \\ F_q(J\ell s\ell' s')[\delta_{\ell\ell'}\delta_{ss'} - S^J_{\ell s\ell' s'}] C^*_{Kq}(\beta_A, \phi_A) C_{kq}(\beta_a, \phi_a) \Bigg\} \tag{2.5}$$

with sums over the initial and final states and the polarization tensor rank of the beam q. The $C(\beta, \phi)$ are geometric terms which describe the orientation of the spin axes. β and ϕ are the polar and azimuthal angles of the spin axis. The scattering amplitudes F_q are

$$F_q(J\ell s\ell' s') = \sum_\Lambda (-1)^K (-1)^{(J-s')} \times \\ \hat{\Lambda}\hat{I}_a\hat{I}_A\hat{\ell}\hat{\ell}'\hat{s}\hat{s}'\hat{k} \langle \Lambda k 0 q | K q \rangle \langle \ell' \ell 0 0 | \Lambda 0 \rangle W(s' s \ell \ell', \Lambda J) \begin{Bmatrix} I_a & s & I_A \\ I_a & s' & I_A \\ k & \Lambda & K \end{Bmatrix}. \tag{2.6}$$

The terms in angular brackets $\langle ab\alpha\beta | c\gamma \rangle$ are Clebsch-Gordon angular momentum coupling coefficients, the $W(s' s \ell \ell', \Lambda J)$ is a Racah angular momentum coupling coefficient, and the expression in curly brackets {} is a 9-j symbol. See Brink and Satchler [**?**] for details

[1] We follow here the derivation of [**?**].

on angular momentum algebra. Λ is the angular momentum transfer $\vec{\Lambda} = \vec{\ell'} - \vec{\ell}$, and $\hat{k} = \sqrt{2k+1}$, etc.

Under the influence of a tensor force angular momentum is not conserved and ℓ does not necessarily equal ℓ', so the S factor defined in Equation 2.2 becomes the $\boldsymbol{S}$ *matrix* whose elements describe a transition from an initial state (J, ℓ, s) to a final state (J, ℓ', s). Terms with $\ell \neq \ell'$ are off-diagonal in the $\boldsymbol{S}$ matrix. $\boldsymbol{S}$ matrix elements are expressed in terms of barred phase shifts according to the Stapp convention [?], so that

$$\boldsymbol{S}_J = \begin{pmatrix} \exp^{i\bar{\delta}_{J-1,J}} & 0 \\ 0 & \exp^{i\bar{\delta}_{J+1,J}} \end{pmatrix} \begin{pmatrix} \cos 2\bar{\varepsilon}_J & i \sin 2\bar{\varepsilon}_J \\ i \sin 2\bar{\varepsilon}_J & \cos 2\bar{\varepsilon}_J \end{pmatrix} \begin{pmatrix} \exp^{i\bar{\delta}_{J-1,J}} & 0 \\ 0 & \exp^{i\bar{\delta}_{J+1,J}} \end{pmatrix} \tag{2.7}$$

where the "nuclear bar" phase shifts $\bar{\delta}$ are related to the δ phase shifts of Blatt and Biedenharn [?], and $\bar{\varepsilon}_J$ are mixing angles which describe the amount of mixing between the angular momentum states $(J, J+1, s)$ and $(J, J-1, s)$. In subsequent notation the bars will be dropped. The reader is reminded that while ℓ is no longer a good quantum number, we continue to label states with their (approximately correct) angular momentum value.

For a spin 1/2 beam and target the total cross section (Equation 2.4) simplifies considerably to

$$\sigma_{tot} = \sigma_{00} + \sigma_{01}\tilde{t}_{10}(I_A) + \sigma_{10}\tilde{t}_{10}(I_a) + \sigma_{11}\tilde{t}_{10}(I_A)\,\tilde{t}_{10}(I_a). \tag{2.8}$$

The first term is simply the spin independent (unpolarized) cross section. The middle two terms are parity-violating contributions to the total cross section and for our purposes may be neglected. σ_{11} is the contribution to the total cross section due to *spin-spin* interactions, and the term of interest for these measurements.

2.3 The Spin-Dependent Total Cross-Section Difference

Since phase shifts are not observable, studies of the tensor interaction strength must involve measurements of observables sensitive to ε_1. Ideally these observables will be insensitive to other phase shifts. Wilburn [?] argues that the spin-dependent total $\vec{n} - \vec{p}$

cross-section difference for anti-parallel and parallel spins, defined

$$\Delta\sigma = \sigma(0^\circ, \vec{I}_A, -\vec{I}_a) - \sigma(0^\circ, \vec{I}_A, \vec{I}_a) \tag{2.9}$$

is such an observable. The polarization tensor of the beam or target changes sign when the spin is reversed, so $\Delta\sigma$ depends only on the spin-spin term σ_{11}.

Of particular interest is the case where $\vec{I}_A$ and $\vec{I}_a$ are along the same axis, either longitudinal ($\beta_A = \beta_a = 0^\circ$) or transverse ($\beta_A = \beta_a = 90^\circ$) to the momentum direction of the neutron beam. We define the longitudinal $\Delta\sigma_L$ and transverse $\Delta\sigma_T$ cross-section differences as

$$\Delta\sigma_L = \sigma(\rightleftarrows) - \sigma(\rightrightarrows) \tag{2.10}$$

$$\Delta\sigma_T = \sigma(\uparrow\downarrow) - \sigma(\uparrow\uparrow) \tag{2.11}$$

where the top or first arrow represents the target spin and the second or bottom arrow represents the projectile spin. Explicitly, for $J \leq 2$, $\Delta\sigma_T$ and $\Delta\sigma_L$ become

$$\begin{aligned}\Delta\sigma_T =& \frac{\pi}{k^2}\{\cos 2\delta(^3P_0) - \cos 2\delta(^1S_0) - 3\cos 2\delta(^1P_1) + \cos 2\varepsilon_1[\cos 2\delta(^3S_1) + 2\cos 2\delta(^3D_1)] \\ & - 5\cos 2\delta(^1D_2) + \cos 2\varepsilon_2[2\cos 2\delta(^3P_2) + 3\cos 2\delta(^3F_2)] \\ & - 2\sqrt{2}\sin 2\varepsilon_1[\delta(^3S_1) + \delta(^3D_1)] - 2\sqrt{6}\sin 2\varepsilon_2 \sin[\delta(^3P_2) + \delta(^3F_2)]\} \qquad (2.12) \\ \Delta\sigma_L =& \frac{\pi}{k^2}\{2 - \cos 2\delta(^1S_0) - \cos 2\delta(^3P_1) + 3[\cos 2\delta(^3P_1) - \cos 2\delta(^1P_1)] \\ & + \cos 2\varepsilon_1[\cos 2\delta(^3S_1) - \cos 2\delta(^3D_1)] + 5[\cos 2\delta(^3D_2) - \cos 2\delta(^1D_2)] \\ & + \cos 2\varepsilon_2[\cos 2\delta(^3P_2) - \cos 2\delta(^3F_2)] \\ & + 4\sqrt{2}\sin 2\varepsilon_1 \sin[\delta(^3S_1) + \delta(^3D_1)] + 4\sqrt{6}\sin 2\varepsilon_2[\delta(^3P_2) + \delta(^3F_2)]\} \qquad (2.13)\end{aligned}$$

where the phase shifts δ are labeled in spectroscopic notation $\delta(^{2S+1}L_J)$. An example of the sensitivity of $\Delta\sigma_T$ to phase shifts is given here: at 11 MeV a 1° change in ε_1 causes a 20% change in $\Delta\sigma_T$; a 1° change in $\delta(^1P_1)$ causes a 1% change in $\Delta\sigma_T$.

An observable independent of all singlet phase shifts and with suppressed sensitivity to the $^3S_1$ phase shift (which contributes significantly to low energy *np* scattering) is the difference between $\Delta\sigma_L$ and $\Delta\sigma_T$, which for $J \leq 2$ is

$$\begin{aligned}\Delta =& \Delta\sigma_L - \Delta\sigma_T \\ =& \frac{\pi}{k^2}\{2 - 2\cos 2\delta(^3P_0) + 3\cos 2\delta(^3P_1) + 5\cos 2\delta(^3D_2) \\ &- 3\cos 2\varepsilon_1 \cos 2\delta(^3D_1) - \cos 2\varepsilon_2[\cos 2\delta(^3P_2) + 4\cos 2\delta(^3F_2)] \\ &+ 6\sqrt{2}\sin 2\varepsilon_1 \sin[\delta(^3S_1) + \delta(^3D_1)] + 6\sqrt{6}\sin 2\varepsilon_2[\delta(^3P_2) + \delta(^3F_2)]\}. \end{aligned} \tag{2.14}$$

Tornow [?] points out that Δ is even more sensitive to ε_1 than either $\Delta\sigma_T$ or $\Delta\sigma_L$ separately, and is less sensitive to other phase shifts. For example, at 11 MeV a 1° change in ε_1 causes a 100% change in Δ, while a 1° change in $\delta(^1P_1)$ causes no change in ε_1.

For completeness, the total cross section for unpolarized beam σ_{00} is given in terms of phase shifts:

$$\begin{aligned}\sigma_{00} = \frac{\pi}{2k^2}[&\sin^2\delta(^1S_0) + \sin^2\delta(^3P_0) + 3\sin^2\delta(^3S_1) + 3\sin^2\delta(^1P_1) + 3\sin^2\delta(^3P_1) + \\ &3\sin^2\delta(^3D_1) + 5\sin^2\delta(^3P_2) + 5\sin^2\delta(^1D_2) + 5\sin^2\delta(^3D_2) + 5\sin^2\delta(^3F_2)]. \end{aligned} \tag{2.15}$$

2.4 Summary of NN Interaction Models

Over the past few decades, understanding of the nucleon-nucleon interaction has been advanced by the success of realistic NN potential models. These meson-theory based models, several of which are briefly described in this section, aim to both explain NN data and to provide insight into the underlying physics of the NN interaction.[2]

The Nijmegen potential [?] is a descendent of the earliest meson-theory models, and is based on a one-boson-exchange potential. The NN potential is modeled using nine non-strange bosons. The Nijmegen group employs a local, non-relativistic, r-space potential. The model is restricted for simplicity to single-boson exchanges, and therefore must introduce the fictitious σ-boson to successfully fit data.

The Paris potential [?] employs π- and ω- as well as 2π-exchanges to replace the problematic σ-boson. The 2π-exchange contribution is obtained from dispersion theory.

[2] This review is based on Machleidt's Report [?].

Lower partial waves (shorter range interactions), which are not well predicted by exchange of these particles, are fitted by phenomenology. The Paris potential contains 168 parameters although only around 60 are free. This large number of phenomenological parameters typically provides good fits to the data but makes extracting information about the underlying physics very difficult.

The Bonn group [?] also considers 2π-, π-, and ω-exchanges but, in contrast to the Paris potential, uses field theory to calculate the 2π-exchange contribution. As a result of this physical rather than phenomenological approach only 12 parameters are needed for a complete description of NN observables. An energy-independent Bonn potential (Bonn B) has also been developed [?].

In contrast to the potential-model approach, other groups attempt to describe NN data by fitting partial waves to the scattering data set. Partial-wave fits are more phenomenological than model-based predictions. Groups at VPI and Nijmegen (among others) have enjoyed considerable success in fitting experimental data. Arndt *et al.* at VPI (most recently [?]) performs a multi-energy partial-wave analysis to all *np* and *pp* data to 1.6 GeV. The database, phase-shift solutions, and calculated observables are available through SAID[3] and on-line at `http://clsaid.phys.vt.edu/~CAPS/said_branch.html`. de Swart *et al.* at Nijmegen performs (most recently [?]) a multi-energy partial-wave analyses on all NN scattering data below 350 MeV. Their solutions are available online at `http://nn_online.sci.kun.nl/`.

2.5 Summary of Previous Measurements

In this section a brief summary is given of previous experiments from which ε_1 has been extracted. These ε_1 values are shown in Figure 1.1. In some cases the determination of ε_1 was not performed by the original experimenters.

The four ε_1 values below 12 MeV are determined from measurements of $\Delta\sigma_T$ made

[3] Scattering Analysis Interactive Dial-in.

by Wilburn at TUNL [**?**, **?**]. These measurements involved a beam of polarized neutrons from the ^{3}H($\vec{p}, \vec{n}$)^{3}He or ^{2}H($\vec{d}, \vec{n}$)^{3}He reactions and a brute force polarized TiH_2 proton target. A single-energy single-parameter partial-wave analysis ($\ell \leq 6$) was performed to extract ε_1, with all other phase shifts taken from the Nijmegen PWA93 partial-wave analysis.

The value of ε_1 at 13.7 MeV was reported by Schöberl *et al.* at Erlangen [**?**]. They measured the transverse neutron-proton spin-correlation coefficient A_{yy} at $\theta_{cm} = 90°$. The experiment involved polarized neutrons from the ^{2}H($\vec{d}, \vec{n}$)^{3}He reaction incident on a dynamically oriented LMN target. A single-energy partial-wave analysis ($\ell \leq 5$) was performed in which both ε_1 and $\delta(^1D_1)$ were varied to best fit the data. The fixed phase shifts were taken from SAID.

ε_1 at 17.4 and 25.8 MeV are from Ockenfels *et al.* at Bonn [**?**, **?**]. Both of these values were obtained from measurements of the polarization-transfer coefficient K_y^y for $\vec{n}+p \rightarrow n+\vec{p}$ scattering at $\theta_{cm} = 130°$. The value of ε_1 at 25 MeV is from a single-energy partial-wave analysis in which ε_1 and $\delta(^1D_1)$ were varied. Fixed phase shifts were taken from SAID [$\delta(^1D_2)$, $\delta(S)$ and ε_2], Bonn [$\delta(^1P_1)$ and $\delta(^3D)$], and Paris [$\delta(^3P)$]. The partial-wave analysis to determine ε_1 at 17 MeV was performed at TUNL by Wilburn [**?**].

The value of ε_1 at 16.2 MeV is from a measurement of $\Delta\sigma_T$ performed by Brož *et al.* at Prague [**?**] This experiment involved a polarized-neutron beam from the ^{3}H($d, \vec{n}$)^{4}He reaction and a dynamically polarized propanediol target held in frozen spin mode. ε_1 was extracted by a single-parameter phase-shift analysis, with other phase shifts taken from the full Bonn potential set. We await their measurement of $\Delta\sigma_L$.

The Karlsruhe points [**?**] are from measurements of A_{yy}, and are unpublished. However, a single-parameter phase-shift analysis to extract ε_1 was performed by Wilburn [**?**], with other phase shifts taken from the Nijmegen PWA93 solution.

The ε_1 value at 50 MeV was supplied by Henneck [**?**]. He performed a multiple-energy partial-wave analysis using measurements of the longitudinal spin-correlation coefficient A_{zz} made by Hammans *et al.* at PSI [**?**], $\Delta\sigma_L$ measurements made by Haffter *et* *al.* at PSI [?], and including the Karlsruhe data mentioned above[4]. A_{zz} was measured at 68 MeV with polarized neutrons from the ^{7}Li($\vec{p}, n$) reaction scattered from a dynamically polarized butanol target over a range of angles from $\theta_{cm} = 105°$ through $\theta_{cm} = 170°$. $\Delta\sigma_L$ was measured at 66 MeV using a dynamically polarized proton target.

[4]Excluding the Karlsruhe data yields an ε_1 that is 9% larger in magnitude.

Chapter 3

Theory of the Measurement Method

In this chapter it is shown that the transverse spin-dependent cross-section difference $\Delta\sigma_T$ can be experimentally determined by measuring the change in transmitted flux of polarized neutrons through a polarized target when the neutron-beam polarization is reversed. In Section 3.1 expressions are derived from which the neutron-transmission asymmetry ε is determined. As will be shown, the calculation of $\Delta\sigma_T$ from the ε depends also on the neutron-beam polarization P_n and the product of target (proton) polarization P_T and thickness x. In Section 3.2 we derive expressions from which the neutron-beam polarization is calculated, and in Section 3.2 the expressions for calculating $P_T x$ will be determined.

3.1 Neutron-Transmission Asymmetry Expressions

We begin this section by deriving an expression for a spin-dependent transmission asymmetry measured under ideal conditions. Experimentally, however, the measurement of an asymmetry is susceptible to systematic effects, including count rate dependent detector efficiencies. These "non-ideal" effects are also discussed in this section.

3.1.1 Derivation of an Ideal Asymmetry

The general experimental situation for measuring a neutron-transmission asymmetry is illustrated schematically in Figure 3.1. The target has polarization $+P_T$ pointing in the $+\hat{y}$ direction (up) as defined by the Madison Convention [**?**]. Target polarization is given by

$$P_T = \frac{N_p^+ - N_p^-}{N_p^+ + N_p^-} \tag{3.1}$$

where $N_p^\pm$ is the fraction of protons with spins along the $\pm\hat{y}$ direction, and

$$N_p^\pm = \frac{1}{2}(1 \pm P_T). \tag{3.2}$$

Neutrons which pass through the target are detected by the main detector which samples a finite solid angle and is located at $0°$.

Consider a neutron beam produced in a neutron-production cell and with polarization $+P_n$ also pointing in the $+\hat{y}$ direction (up). The polarization of the neutron beam P_n is given by

$$P_n = \frac{N_0^+ - N_0^-}{N_0^+ + N_0^-} \tag{3.3}$$

where $N_0^\pm$ is the number of neutrons in the beam with spins along the $\pm\hat{y}$ direction. The total number of neutrons in the beam is given by

$$N_0^{(0)} = N_0^+ + N_0^- \tag{3.4}$$

from which we obtain

$$N_0^\pm = \frac{N_0^{(0)}}{2}(1 \pm P_n). \tag{3.5}$$

A beam of neutrons is attenuated as it passes through matter, and the attenuation is described by

$$N = N_0 e^{-x\sigma_{p,a}} \tag{3.6}$$

Figure 3.1: Schematic of the experiment to measure neutron-transmission asymmetries

where N_0 is the incident neutron flux, x the thickness of material in units of cm^{-2}, and $\sigma_{p,a}$ is the cross section which depends on the relative beam and target polarizations. The cross section for a proton and neutron with spins parallel (σ_p) or anti-parallel (σ_a) is

$$\sigma_p = \sigma_0 + \frac{1}{2}\Delta\sigma_T \tag{3.7}$$

$$\sigma_a = \sigma_0 - \frac{1}{2}\Delta\sigma_T \tag{3.8}$$

where σ_0 is the cross section for an unpolarized beam and unpolarized target. The attenuation of a beam of polarized neutrons incident on a polarized target is the weighted sum of the attenuations of a beam of spin-up neutrons ($P_n = 1$) passing through a target with both spin up and spin down protons plus the attentation of a beam of spin-down neutrons ($P_n = -1$) passing through a target with both spin up and spin down protons (see Figure 3.2):

$$N_n = N_0^+[e^{-N_p^+ x\sigma_p} e^{-N_p^- x\sigma_a}] + N_0^-[e^{-N_p^+ x\sigma_a} e^{-N_p^- x\sigma_p}]. \tag{3.9}$$

Substituting for $N_0^\pm$, $N_p^\pm$, and $\sigma_{p,a}$ we find

$$\begin{aligned} N_n(P_n) =& \frac{N_0^{(0)}}{2}(1+P_n)\{e^{-x[(\sigma_0+\frac{1}{2}\Delta\sigma_T)\frac{1}{2}(1+P_T)-(\sigma_0-\frac{1}{2}\Delta\sigma_T)\frac{1}{2}(1-P_T)]}\} \\ &+ \frac{N_0^{(0)}}{2}(1-P_n)\{e^{-x[(\sigma_0-\frac{1}{2}\Delta\sigma_T)\frac{1}{2}(1+P_T)-(\sigma_0+\frac{1}{2}\Delta\sigma_T)\frac{1}{2}(1-P_T)]}\} \\ =& N_0^{(0)} e^{-x\sigma_0}\{e^{-\frac{1}{2}xP_T\Delta\sigma_T} + e^{+\frac{1}{2}xP_T\Delta\sigma_T} + P_n[e^{-\frac{1}{2}xP_T\Delta\sigma_T} - e^{+\frac{1}{2}xP_T\Delta\sigma_T}]\} \\ =& N_0^{(0)} e^{-x\sigma_0}\left[\cosh(\frac{1}{2}P_T x\Delta\sigma_T) - P_n \sinh(\frac{1}{2}P_T x\Delta\sigma_T)\right]. \end{aligned} \tag{3.10}$$

We are interested in the neutron-transmission difference when the beam polarization is reversed. For beam polarization $+P_n'$ the transmission is

$$N_n(P_n') = N_0^{(0)} e^{-x\sigma_0}\left[\cosh(\frac{1}{2}P_T x\Delta\sigma_T) - P_n' \sinh(\frac{1}{2}P_T x\Delta\sigma_T)\right] \tag{3.11}$$

and for beam polarization $-P_n''$ the transmission is given by

$$N_n(-P_n'') = N_0^{(0)} e^{-x\sigma_0}\left[\cosh(\frac{1}{2}P_T x\Delta\sigma_T) + P_n'' \sinh(\frac{1}{2}P_T x\Delta\sigma_T)\right]. \tag{3.12}$$

Figure 3.2: Interpreting the spin-dependent cross sections $\sigma^{\pm}$ as refering to individual proton and neutron spins

The transmission asymmetry ε_n due to reversing the beam polarization from $-P_n''$ to $+P_n'$ is defined as

$$\begin{aligned}\varepsilon_n &= \frac{N_n(+P_n') - N_n(-P_n'')}{N_n(+P_n') + N_n(-P_n'')} \\ &= \frac{-(P_n' + P_n'')\sinh(\frac{1}{2}P_T x\Delta\sigma_T)}{2\cosh(\frac{1}{2}P_T x\Delta\sigma_T) - 2(P_n' - P_n'')\sinh(\frac{1}{2}P_T x\Delta\sigma_T)}\end{aligned} \tag{3.13}$$

and in this experiment we always satisfy the conditions

$$\frac{1}{2}P_T x\Delta\sigma_T < 0.02 \ll 1 \tag{3.14}$$

$$P_n' \approx P_n'' \tag{3.15}$$

so that the approximation

$$(P_n' - P_n'')\sinh(\frac{1}{2}P_T x\Delta\sigma_T) \ll \cosh(\frac{1}{2}P_T x\Delta\sigma_T) \tag{3.16}$$

can be used to simplify Equation 3.13. We then have

$$\begin{aligned}\varepsilon_n &\approx \frac{-(P_n' + P_n'')}{2}\tanh(\frac{1}{2}P_T x\Delta\sigma_T) \\ &= -\frac{1}{2}P_n P_T x\Delta\sigma_T.\end{aligned} \tag{3.17}$$

which shows the asymmetry ε_n is sensitive only to the average neutron polarization

$$P_n = \frac{P_n' + P_n''}{2} \tag{3.18}$$

and is independent of incident neutron flux and of the unpolarized cross section. Rearranging, we can write

$$\Delta\sigma_T = \frac{-2\varepsilon_n}{P_n P_T x} \tag{3.19}$$

which relates $\Delta\sigma_T$ to directly measurable experimental quantities.

While this derivation is strictly correct, a simpler alternative derivation has often been used to derive Equation 3.17 [?, ?], and will be presented here for comparison. As a starting point we write, in place of Equation 3.7, the spin-dependent cross section as

$$\sigma_{p,a} \approx \sigma_0 \pm \frac{1}{2}P_n P_T\Delta\sigma_T \tag{3.20}$$

where the target and neutron-beam polarizations are included as weighting factors in the spin-dependent cross section term. In this derivation, σ_p (σ_a) is interpreted as the cross section for a neutron beam with *polarization* parallel (anti-parallel) to the target *polarization*. If the spin-dependent term is small the transmissions $N_n^{\pm}$ can be written

$$N_n^+ = N_0 e^{-x\sigma_p} \tag{3.21a}$$

$$N_n^- = N_0 e^{-x\sigma_a} \tag{3.21b}$$

where the polarizations are now in the exponential.

We now calculate the asymmetry equivalent to Equation 3.13, that is, the transmission asymmetry of an polarized-neutron beam incident on a proton target with polarization $+P_T$, due to flipping the neutron-beam polarization from $-P_n''$ to $+P_n'$

$$\begin{aligned}
\varepsilon_n &= \frac{N_n(P_n') - N_n(P_n'')}{N_n(P_n') + N_n(P_n'')} \\
&= \frac{N_0^{(0)} e^{-x\sigma_p} - N_0^{(0)} e^{-x\sigma_a}}{N_0^{(0)} e^{-x\sigma_p} + N_0^{(0)} e^{-x\sigma_a}} = \frac{e^{-\frac{1}{2}xP_nP_Tx\Delta\sigma_T} - e^{\frac{1}{2}P_nP_Tx\Delta\sigma_T}}{e^{\frac{1}{2}P_nP_Tx\Delta\sigma_T} + e^{-\frac{1}{2}P_nP_Tx\Delta\sigma_T}} \\
&= -\tanh(\frac{1}{2}P_nP_Tx\Delta\sigma_T) \\
&\approx -\frac{1}{2}P_nP_Tx\Delta\sigma_T
\end{aligned} \tag{3.22}$$

which is equivalent to Equation 3.17. Consequently, if the argument of the tanh is small (as is the case here) then these two derivations are equivalent. For the rest of this section we will use the later interpretation, and consider the transmission of a neutron beam with polarization P_n through a target with polarization P_T.

3.1.2 Derivation of the Measured Asymmetry

In practice, the measurement of a transmission asymmetry is susceptible to many systematic effects, and a derivation which isolates the various systematic asymmetries is required. We consider effects stemming from the following: tensor polarization dependence of neutron-production reactions, beam current asymmetries, count-rate dependent detector efficiencies, and dead-time correction asymmetries. In this section we pursue a derivation

Figure 3.3: Definition of the main detector solid angle $\Delta\theta$ and misalignment θ

of the measured neutron-asymmetry expression in terms of logarithmic derivatives, which accommodates treatment of these systematic asymmetries.

We begin by considering asymmetries which result from the production of polarized neutrons. In this experiment, charged-particle induced reactions (^{3}H$(\vec{p},\vec{n})^3$He, ^{2}H$(\vec{d},\vec{n})^3$He, and ^{3}H$(\vec{d},\vec{n})^4$He) are used to produce a polarized-neutron beam. The proton beam has vector polarization P_z, and the deuteron beam has vector polarization P_z and tensor polarization P_{zz}, although no particular spin-axis orientation is implied. The main neutron detector is positioned directly in the beam and views a solid angle $\Delta\theta$ so we are interested in neutrons produced about 0°. The number of neutrons produced at 0° by an incident beam current I is

$$N_0 = kI(1 + \rho P_z + \gamma P_{zz}) \tag{3.23}$$

where k is a proportionality constant. The neutron-production cross section contains a term proportional to the tensor polarization of the deuteron beam, indicated by P_{zz}, where the proportionality constant is $\gamma = \gamma(0°)$. The neutron-production reactions used in this experiment have an analyzing power, so that an incident charged-particle beam will produce neutrons with a left/right asymmetry proportional to the beam's vector polarization indicated by P_z. This analyzing power varies with angle but is symmetric about 0°. However, a misalignment of the main detector will cause the detector to view a solid angle not symmetric about 0°, and therefore will see a neutron flux asymmetry. The $\rho = \rho(\theta)$ term accounts for a misalignment of the 0° detector by an angle θ. Figure 3.3 shows these angles.

To be detected by the main detector a neutron must pass through the polarized target. The number of polarized neutrons N_n which are transmitted through the target and hit the 0° detector is as before

$$N_n = N_0 e^{-x\sigma} \tag{3.24}$$

where σ is the spin-dependent cross section given in Equation 3.20 and x is the target thickness.

The number of neutrons $\hat{N}_n$ which are *counted* by the detector depends on the detector efficiency g which is related to the energy threshold and the probability that a neutron scatters in the detector. Ideally this efficiency is independent of count rate, however, our data suggest that the efficiency is count rate dependent. We expand the efficiency $g = g(N_n)$ in a Taylor series around the flux $N_n^{(0)}$

$$g(N_n) = g(N_n^{(0)}) + (N_n - N_n^{(0)}) \left.\frac{\partial g(N_n)}{\partial N_n}\right|_{N_n^{(0)}} + \cdots \tag{3.25}$$

where we keep terms to first order. The number of neutrons *counted* by the detector is the product of the number of incident neutrons multiplied by the efficiency

$$\begin{aligned}
\hat{N}_n &= g(N_n)N_n \\
&= g(N_n^{(0)})N_n + (N_n - N_n^{(0)}) \left.\frac{\partial g(N_n)}{\partial N_n}\right|_{N_n^{(0)}} N_n \\
&= \left[g(N_n^{(0)}) - N_n^{(0)} \left.\frac{\partial g(N_n)}{\partial N_n}\right|_{N_n^{(0)}} \right] N_n + \left[\left.\frac{\partial g(N_n)}{\partial N_n}\right|_{N_n^{(0)}} \right] N_n^2 .
\end{aligned} \tag{3.26}$$

If we define

$$\alpha \equiv g(N_n^{(0)}) - N_n^{(0)} \left.\frac{\partial g(N_n)}{\partial N_n}\right|_{N_n^{(0)}} \tag{3.27}$$

and

$$\beta \equiv \left.\frac{\partial g(N_n)}{\partial N_n}\right|_{N_n^{(0)}} \tag{3.28}$$

then we can write Equation 3.26 as

$$\begin{aligned}
\hat{N}_n &= \alpha N_n + \beta N_n^2 \\
&= \alpha N_n \left(1 + \frac{\beta}{\alpha} N_n \right)
\end{aligned} \tag{3.29}$$

which explicitly shows a count-rate dependent deviation from linearity which is parameterized by the term β/α.

Before being stored by the data-acquisition computer, signals from the 0° detector are pulse-shape discriminated to filter out gamma events. Because this discrimination takes time, PSD introduces a dead-time correction δ (see Section 5.5.2) to the number of *counted* neutrons

$$\tilde{N}_n = \delta(\hat{N}_n)\hat{N}_n \tag{3.30}$$

where typically $\delta > 0.99$. The dead-time correction is determined by comparing a pulser gated with the live-time signal from the PSD module to the ungated pulser. Equation 3.29 is then written

$$\tilde{N}_n = \alpha\delta N_n\left(1 + \frac{\beta}{\alpha}N_n\right). \tag{3.31}$$

Substituting from Equations 3.24 and 3.23, we can rewrite Equation 3.31 as

$$\tilde{N}_n = kI\alpha\delta(1 + \rho P_z + \gamma P_{zz})e^{-x\sigma}\left[1 + kI\frac{\beta}{\alpha}(1 + \rho P_z + \gamma P_{zz})e^{-x\sigma}\right]. \tag{3.32}$$

We are interested in the spin dependence of $\tilde{N}_n$. It is illuminating to examine the logarithmic derivative of Equation 3.32. Taking the natural logarithm of both sides of this equation gives

$$\ln\tilde{N}_n = \ln k + \ln I + \ln\alpha + \ln\delta + \ln(1 + \rho P_z + \gamma P_{zz}) - x\sigma + \ln(1 + \xi_n) \tag{3.33}$$

where we have defined

$$\xi_n \equiv kI\frac{\beta}{\alpha}(1 + \rho P_z + \gamma P_{zz})e^{-x\sigma}. \tag{3.34}$$

After differentiating we have

$$\begin{aligned}\frac{d\tilde{N}_n}{\tilde{N}_n} &= \frac{dI}{I} + \frac{d\delta}{\delta} + \left(\frac{\rho P_z}{1 + \rho P_z + \gamma P_{zz}}\right)\frac{dP_z}{P_z} + \left(\frac{\gamma P_{zz}}{1 + \rho P_z + \gamma P_{zz}}\right)\frac{dP_{zz}}{P_z} - x\,d\sigma \\ &+ \frac{\xi_n}{1 + \xi_n}\left[\frac{dI}{I} + \left(\frac{\rho P_z}{1 + \rho P_z + \gamma P_{zz}}\right)\frac{dP_z}{P_z} + \left(\frac{\gamma P_{zz}}{1 + \rho P_z + \gamma P_{zz}}\right)\frac{dP_{zz}}{P_{zz}} - e^{x\sigma}x\,d\sigma\right]\end{aligned} \tag{3.35}$$

since α, β, k, $\rho(\theta)$, $\gamma(0°)$, and x are constants, and after rearranging

$$\frac{d\tilde{N}_n}{\tilde{N}_n} = \frac{d\delta}{\delta} + \frac{1+2\xi_n}{1+\xi_n}\left[\frac{dI}{I} + \left(\frac{\rho P_z}{1+\rho P_z+\gamma P_{zz}}\right)\frac{dP_z}{P_z} + \left(\frac{\gamma P_{zz}}{1+\rho P_z+\gamma P_{zz}}\right)\frac{dP_{zz}}{P_{zz}}\right] - \left[\frac{1+\xi_n\left(1+e^{x\sigma}\right)}{1+\xi_n}\right]x\,d\sigma. \quad (3.36)$$

To convert the differentials in Equation 3.36 to (measurable) spin-dependent asymmetries, we consider the small changes in $\tilde{N}_n$, I, δ, P_{zz}, and σ associated with flipping the neutron-beam polarization from $-P_n$ to $+P_n$. The measured neutron asymmetry $\varepsilon_{\tilde{N}_n}$ is

$$\varepsilon_{\tilde{N}_n} = \frac{\tilde{N}_n^+ - \tilde{N}_n^-}{\tilde{N}_n^+ + \tilde{N}_n^-} = \frac{d\tilde{N}_n}{2\tilde{N}_n^{(0)}} \quad (3.37)$$

where the $+$ $(-)$ refers to $+P_n$ $(-P_n)$ beam polarization and $\tilde{N}_n^{(0)}$ refers to the average neutron count rate. Similarly,

$$\varepsilon_I = \frac{I^+ - I^-}{I^+ + I^-} = \frac{dI}{2I^{(0)}} \quad (3.38a)$$

$$\varepsilon_{P_{zz}} = \frac{P_{zz}^+ - P_{zz}^-}{P_{zz}^+ + P_{zz}^-} = \frac{dP_{zz}}{2P_{zz}^{(0)}} \quad (3.38b)$$

$$\varepsilon_\delta = \frac{\delta^+ - \delta^-}{\delta^+ + \delta^-} = \frac{d\delta}{2\delta^{(0)}}. \quad (3.38c)$$

If the changes are small so that ($d\tilde{N}_n \ll \tilde{N}_n^{(0)}$), then

$$\frac{d\tilde{N}_n}{2\tilde{N}_n} \approx \frac{d\tilde{N}_n}{2\tilde{N}_n^{(0)}} = \varepsilon_{\tilde{N}_n}\ , \text{ etc.} \quad (3.39)$$

To express the $d\sigma$ term in Equation 3.36 in terms of measurable quantities, we invoke Equation 3.20 and write

$$\begin{aligned} d\sigma &= \sigma^+ - \sigma^- \\ &= \sigma^{(0)} + \frac{1}{2}P_nP_T\Delta\sigma_T - \left(\sigma^{(0)} - \frac{1}{2}P_nP_T\Delta\sigma_T\right) \\ &= P_nP_T\Delta\sigma_T \end{aligned} \quad (3.40)$$

and using Equation 3.22 we have

$$x\,d\sigma = P_nP_Tx\Delta\sigma_T = -2\varepsilon_n. \quad (3.41)$$

The term in Equation 3.36 containing the change in vector polarization dP_z can be rewritten by noting that since $+P_z \approx -P_z$, then

$$dP_z = +P_z - (-P_z) = 2\bar{P}_z \approx 2P_z \tag{3.42}$$

where $\bar{P}_z$ is the average of $\pm$ vector polarization magnitudes.

After making the following convenient definitions,

$$\xi'_n = \frac{1+2\xi_n}{1+\xi_n} \tag{3.43a}$$

$$\rho' = \frac{\rho P_z}{1+\rho P_z + \gamma P_{zz}} \tag{3.43b}$$

$$\gamma' = \frac{\gamma P_{zz}}{1+\rho P_z + \gamma P_{zz}}, \tag{3.43c}$$

and substituting for the differentials, Equation 3.36 can then be written

$$\varepsilon_{\tilde{N}_n} = \varepsilon_I + \varepsilon_\delta + \xi'_n \rho' + \xi'_n \gamma' \varepsilon_{Pzz} + \left[\frac{1+\xi_n \left(1+e^{x\sigma^{(0)}}\right)}{1+\xi_n} \right] \varepsilon_n. \tag{3.44}$$

Examining the coefficient of ε_n we see that to first order

$$\frac{1+\xi_n(1+e^{x\sigma^{(0)}})}{1+\xi_n} = \frac{1+\xi_n+\xi_n(1+x\sigma^{(0)})}{1+\xi_n} = \xi'_n + \frac{\xi_n x \sigma^{(0)}}{1+\xi_n} \approx \xi'_n \tag{3.45}$$

where this approximation introduces an error of less that 0.7% in all cases presented here. Equation 3.44 can be written finally

$$\varepsilon_{\tilde{N}_n} = \varepsilon_\delta + \xi'_n(\varepsilon_I + \rho' + \gamma' \varepsilon_{P_{zz}} + \varepsilon_n). \tag{3.46}$$

The measured neutron asymmetry $\varepsilon_{\tilde{N}_n}$ scales linearly with the asymmetry of interest ε_n, but includes false asymmetries related to asymmetries in the beam current, dead-time correction, and from the vector and tensor beam polarizations. The scaling parameter ξ'_n is associated with a count-rate dependent drift in the neutron-detector efficiency. If the efficiency does not vary with count rate ($\beta/\alpha = 0 = \xi$), then ξ'_n is unity and the measured asymmetry is simply the sum of the five asymmetries.

Figure 3.4: Graphical method to determine $\varepsilon_{\tilde{N}_n}(\varepsilon_I = 0)$ and ξ'_n

3.1.3 Extraction of the "True" Asymmetry ε_n

Solving Equation 3.46 for the "true" asymmetry ε_n, that is, the asymmetry due to the spin-dependent cross section, gives

$$\varepsilon_n = \frac{\varepsilon_{\tilde{N}_n} - \varepsilon_\delta}{\xi'_n} - \varepsilon_I - \rho' - \gamma' \varepsilon_{Pzz}. \tag{3.47}$$

which is the asymmetry of interest. An analysis is needed that extracts ε_n from measurable asymmetries.

Data were collected and analyzed in 800 ms units, during which time the beam polarization was reversed in an 8 step sequence $(+--+-++-)$. A neutron asymmetry $\varepsilon_{\tilde{N}_n}$ and a beam current asymmetry ε_I are measured for each beam spin-flip sequence. The $\varepsilon_{\tilde{N}_n}$ are then plotted vs. the ε_I measured during the same spin-flip sequence. This plot shows the dependence of $\varepsilon_{\tilde{N}_n}$ on ε_I and if one were to write Equation 3.46 in the form

$$\varepsilon_{\tilde{N}_n} = C + \xi'_n \varepsilon_I$$

where C is a constant, then the slope gives ξ'_n and the intercept is the measured asymmetry $\varepsilon_{\tilde{N}_n}$ for ε_I =0, as shown in Figure 3.4. A weighted least-squares linear fit [?] is used to determined the slope ξ'_n and intercept $\varepsilon_{\tilde{N}_n}(\varepsilon_I = 0)$.

At this point we reverse the target polarization from $P_T = +\hat{y}$ to $P_T = -\hat{y}$. In effect, this interchanges the definitions of parallel and anti-parallel spins and so interchanges σ^+ and σ^-. As a result ε_n changes sign. The charged-particle beam polarization is unchanged, so P_z and P_{zz}, and therefore ρ' and $\gamma' \varepsilon_{P_{zz}}$, are unaffected. If we assume that P_z and P_{zz} are stable over the time of the target spin-flip sequence (around 8 hr), then taking the difference of the spin-dependent asymmetries with target polarization in the $+\hat{z}-(-\hat{z})$ direction gives

$$(\varepsilon_n)_{+P_T} - (\varepsilon_n)_{-P_T} = \left(\frac{\varepsilon_{\tilde{N}_n} - \varepsilon_\delta}{\xi'_n} - \rho' - \gamma'\varepsilon_{Pzz}\right)_{+P_T} - \left(\frac{\varepsilon_{\tilde{N}_n} - \varepsilon_\delta}{\xi'_n} - \rho' - \gamma'\varepsilon_{Pzz}\right)_{-P_T}$$
$$= \left(\frac{\varepsilon_{\tilde{N}_n} - \varepsilon_\delta}{\xi'_n}\right)_{+P_T} - \left(\frac{\varepsilon_{\tilde{N}_n} - \varepsilon_\delta}{\xi'_n}\right)_{-P_T}. \quad (3.48)$$

ξ'_n and ε_δ are not spin dependent, but depend on count rate and will in general be different for any given measurement. We define the average of the asymmetry magnitudes

$$\bar{\varepsilon}_n = \frac{(\varepsilon_n)_{+P_T} - (\varepsilon_n)_{-P_T}}{2} \quad (3.49)$$

and finally have

$$\bar{\varepsilon}_n = \frac{1}{2}\left[\left(\frac{\varepsilon_{\tilde{N}_n} - \varepsilon_\delta}{\xi'_n}\right)_{+P_T} - \left(\frac{\varepsilon_{\tilde{N}_n} - \varepsilon_\delta}{\xi'_n}\right)_{-P_T}\right]. \quad (3.50)$$

Equation 3.50 can be used to extract the average "true" asymmetry $\bar{\varepsilon}_n$ from a pair of measured neutron-transmission asymmetries $\varepsilon_{\tilde{N}_n}$ with target polarizations $+P_T$ and $-P_T$. In this way, systematic asymmetries related to the beam current and beam polarizations have been cancelled.

The sum of the neutron asymmetries with target polarizations $+P_T$ and $-P_T$ gives

$$\left(\frac{\varepsilon_{\tilde{N}_n} - \varepsilon_\delta}{\xi'_n}\right)_{+P_T} + \left(\frac{\varepsilon_{\tilde{N}_n} - \varepsilon_\delta}{\xi'_n}\right)_{-P_T} = 2(\rho' + \gamma'\varepsilon_{P_{zz}}) \quad (3.51)$$

since now the ε_n cancel. Summing the measured asymmetries in this way estimates the magnitude of the asymmetries due to beam polarizations.

3.1.4 Monitor Normalization

For the $\gamma'\varepsilon_{P_{zz}}$ terms to completely cancel upon target polarization reversal, P_{zz} must be the same in both spin states.[1] This requirement can be avoided by directly measuring and normalizing to the neutron flux incident on the target.[2] To model this monitor detector we

[1] The $+(-)$ spin state has $+P_z$ $(-P_z)$, $+P_{zz}$.

[2] This was done for the $\Delta\sigma_T$ measurements at $E_n = 11$,15, and 17 MeV by use of a small detector located directly after the neutron production cell.

can immediately write down the neutron flux N_m incident on the detector as (see Figure 3.5)

$$N_m = N_0. \tag{3.52}$$

In analogy with the 0° detector, the number of neutrons *counted* by the monitor detector is a function of the count-rate dependent efficiency of the detector $g_m(N_0)$ and paralleling the derivation found in Equations 3.25 through 3.29 we have

$$\begin{aligned}\tilde{N}_m &= g_m(N_0)N_0 \\ &= \alpha_m N_0 \left(1 + \frac{\beta_m}{\alpha_m} N_0\right)\end{aligned} \tag{3.53}$$

where we have defined

$$\alpha_m \equiv g_m(N_0^{(0)}) - N_0^{(0)} \left.\frac{\partial g_m(N_0)}{\partial N_0}\right|_{N_0^{(0)}} \tag{3.54}$$

and

$$\beta_m \equiv \left.\frac{\partial g_m(N_0)}{\partial N_0}\right|_{N_0^{(0)}} \tag{3.55}$$

where α_m parameterizes the linear response of the monitor detector and β_m the quadratic response.

The asymmetry in the number of neutrons *counted* by the monitor detector due to flipping the neutron-beam polarization is found by paralleling the derivation in Equations 3.33 through 3.44 and is given by

$$\varepsilon_{\tilde{N}_m} = \xi'_m \varepsilon_I + \xi'_m \rho'_m + \xi'_m \gamma'_m \varepsilon_{Pzz} \tag{3.56}$$

where we define

$$\xi'_m = \frac{1 + 2\left[kI\frac{\beta_m}{\alpha_m}(1 + \rho P_z + \gamma P_{zz})\right]}{1 + \left[kI\frac{\beta_m}{\alpha_m}(1 + \rho P_z + \gamma P_{zz})\right]} \tag{3.57a}$$

$$\rho'_m = \frac{\rho P_z}{1 + \rho P_z + \gamma P_{zz}} \tag{3.57b}$$

$$\gamma'_m = \frac{\gamma P_{zz}}{1 + \rho P_z + \gamma P_{zz}} \tag{3.57c}$$

Figure 3.5: Schematic of experimental setup for monitor normalization

in analogy with Equations 3.43.

If we plot the $\varepsilon_{\tilde{N}_m}$ vs. ε_I (as described in the Section 3.1.3) the slope gives ξ'_m and the intercept gives $\varepsilon_{\tilde{N}_m}(\varepsilon_I = 0)$. The measured monitor asymmetry is

$$\varepsilon_{\tilde{N}_m}(\varepsilon_I = 0) = \xi'_m \rho'_m + \xi'_m \gamma'_m \varepsilon_{P_{zz}}. \tag{3.58}$$

Substituting for the monitor asymmetry into Equation 3.47, we can write

$$\varepsilon_n = \frac{\varepsilon_{\tilde{N}_n} - \varepsilon_\delta}{\xi'_n} - \frac{\varepsilon_{\tilde{N}_m}}{\xi'_m} + (\rho'_m - \rho') + (\gamma'_m - \gamma')\varepsilon_{Pzz}. \tag{3.59}$$

If the 0° and monitor detectors sample the same solid angle of neutron flux, then $\rho'_m = \rho'$ and $\gamma'_m = \gamma'$ and this equation simplifies to

$$\varepsilon_n = \frac{\varepsilon_{\tilde{N}_n} - \varepsilon_\delta}{\xi'_n} - \frac{\varepsilon_{\tilde{N}_m}}{\xi'_m} \tag{3.60}$$

where all beam related asymmetries have been eliminated. It is likely that the two detector's solid angles are not identical, so these asymmetries will not vanish, but are suppressed by the difference terms $(\rho'_m - \rho')$ and $(\gamma'_m - \gamma')$. Upon reversing the target polarization and forming the average asymmetry $\bar{\varepsilon}_n$ (as in Equation 3.48), any surviving terms proportional to P_z or P_{zz} will cancel.

3.1.5 Uncertainty in the Neutron Asymmetry

Counts from the neutron detector obey a Poisson distribution so the uncertainty in the number of counts N is given simply by

$$\Delta N = \sqrt{N} \tag{3.61}$$

and the statistical uncertainty of an asymmetry is

$$\Delta\varepsilon = \frac{2\sqrt{N^+ N^-}}{(N^+ + N^-)^{\frac{3}{2}}}. \tag{3.62}$$

Uncertainty in the dead-time asymmetry, calculated by use of a gated pulser, results from the finite resolution of the digitization process. The dead-time correction is typically less than 1%. Since the dead-time pulser operates at 100 kHz, uncertainty in the dead-time correction and the dead-time asymmetry, is negligible.

Asymmetries and their associated statistical uncertainties are calculated for the 0° and monitor detector on a beam spin-flip (800 ms of data) basis for a given target polarization. Uncertainty in the mean and standard deviation about the least-squares fit line are calculated according to the standard formulas [?]

$$\overline{\Delta\varepsilon} = \sqrt{\frac{1}{\sum_{i=1}^{n} \frac{1}{\Delta\varepsilon_i^2}}} \tag{3.63}$$

$$\overline{\sigma}_\varepsilon = \sqrt{\frac{\frac{\sum_{i=1}^{n}(\varepsilon_i - \overline{\varepsilon})^2}{\Delta\overline{\varepsilon}^2}}{n(n-1)}} \tag{3.64}$$

where the sum is over n bins of ε_I. A mean asymmetry and standard deviation is calculated separately for $+P_T$ and $-P_T$ target polarizations.

In addition to statistical uncertainty there are systematic uncertainties in calculating the mean asymmetry. Determination of the scaling factors ξ_n' and ξ_m' are subject to a systematic uncertainty due to the least-squares fit. Uncertainty in the least-squares fit parameters determine the uncertainties $\Delta\xi_n'$, $\Delta\varepsilon_{\tilde{N}_n}(\varepsilon_I = 0)$, $\Delta\xi_m'$ and $\Delta\varepsilon_{\tilde{N}_m}(\varepsilon_I = 0)$.

3.2 Beam-Polarization Expressions

Since the neutron beam is produced as a secondary beam via reactions with known polarization-transfer coefficients, it is sufficient to measure charged-particle beam polarization to learn the neutron-beam polarization. Charged-particle beam polarization is determined from measurements of a left/right scattering asymmetry from the ^{4}He$(\vec{p},p)^4$He and ^{3}He$(\vec{d},p)^4$He reactions[3], where the scattering asymmetry is related to the beam polarization and the analyzing powers of the reaction. Expressions to calculate proton-beam polarization from a measured scattering asymmetry are derived in Section 3.2.1, and expressions to calculate the deuteron-beam polarizations from measured scattering asymmetries

[3]Some deuteron-beam polarization measurements were made with the TUNL spin-filter polarimeter [?].

are derived in Section 3.2.2. Neutron-beam polarization can then be calculated from the charged-particle beam polarization by equations found in Section 3.2.3.

3.2.1 Proton-Beam Polarization

Proton-beam vector polarization P_p can be calculated from counts recorded in detectors located at left and right angles. From Ohlsen [?] we can write, for a beam of spin 1/2 particles with polarization P_p^+ (P_p^-) incident on a spin 0 target,

$$N_L^\pm = N^\pm \epsilon_L (1 + P_p^\pm A_y) \tag{3.65a}$$

$$N_R^\pm = N^\pm \epsilon_R (1 - P_p^\pm A_y) \tag{3.65b}$$

where N_L^+ (N_L^-) is the number of protons which elastically scatter into the left detector, and N_R^+ (N_R^-) is the number of protons which scatter into the right detector. These expressions are in terms of detector efficiencies $\epsilon_{L,R}$, incident fluxes N^+ (N^-), and the vector analyzing power of the reaction $A_y = A_y(E, \theta)$. We define the ratio γ as

$$\begin{aligned}\gamma \equiv & \frac{N_L^+}{N_L^-}\frac{N_R^-}{N_R^+} = \frac{N^+\epsilon_L(1+P_p^+A_y)}{N^-\epsilon_L(1+P_p^-A_y)}\frac{N^-\epsilon_R(1-P_p^-A_y)}{N^+\epsilon_R(1-P_p^+A_y)} \\ = & \frac{(1+P_p^+A_y)(1-P_p^-A_y)}{(1+P_p^-A_y)(1-P_p^+A_y)}\end{aligned} \tag{3.66}$$

which is independent of detector efficiencies and incident fluxes. The sum $\bar{P}_p$ and difference P_p of positive and negative polarization magnitudes are

$$\bar{P}_p = \frac{P_p^+ + P_p^-}{2} \tag{3.67}$$

$$P_p = \frac{P_p^+ - P_p^-}{2} \tag{3.68}$$

and with some rearranging, Equation 3.66 becomes

$$\gamma = \frac{(1+P_pA_y)^2 - \bar{P}_p^2A_y^2}{(1-P_pA_y)^2 - \bar{P}_p^2A_y^2}. \tag{3.69}$$

Since for our polarized ion source $|P_p^+| \approx |P_p^-|$, then $\bar{P}_p^2A_y^2 \ll P_p^2A_y^2$ and

$$\gamma \approx \frac{(1+P_pA_y)^2}{(1-P_pA_y)^2}. \tag{3.70}$$

We then have

$$P_p = \frac{1}{A_y}\frac{\sqrt{\gamma}-1}{\sqrt{\gamma}+1} \tag{3.71}$$

which gives the average proton-beam polarization in terms of the measured quantity γ and the analyzing power of the reaction A_y.

Statistical uncertainty in proton polarization is explicitly given by

$$\Delta P_p = \frac{\sqrt{\gamma}}{(\sqrt{\gamma}+1)^2}\sqrt{\frac{1}{N_L^+}+\frac{1}{N_L^-}+\frac{1}{N_R^+}+\frac{1}{N_R^-}}. \tag{3.72}$$

Due to systematic effects, however, the scatter between individual measurements is larger than expected from counting statistics, and so the uncertainty in the average P_p is obtained from the standard deviation σ of the distribution of measurements

$$\Delta P_p = \frac{\sigma}{\sqrt{N}} \tag{3.73}$$

where N is the number of measurements. Uncertainty in analyzing power ΔA_y is treated as a systematic uncertainty.

3.2.2 Deuteron-Beam Polarization

Deuteron-beam vector P_d and tensor P_{dd} polarizations can be determined from counts recorded in detectors at left and right angles, and at 0°. Again from [?], and switching to a spherical representation[4], we can write for a beam of spin 1 particles with transverse vector $\hat{t}_{10}^{+}$ ($\hat{t}_{10}^{-}$) and tensor $\hat{t}_{20}^{+}$ polarizations incident on a spin 1/2 target, that

$$N_L^{\pm} = \epsilon_L N^{\pm}\left(1+\sqrt{2}\,\hat{t}_{10}^{\pm}\,iT_{11}-\frac{1}{2}\,\hat{t}_{20}^{\pm}\,T_{20}-\sqrt{\frac{3}{2}}\,\hat{t}_{20}^{\pm}\,T_{22}\right) \tag{3.74a}$$

$$N_R^{\pm} = \epsilon_R N^{\pm}\left(1-\sqrt{2}\,\hat{t}_{10}^{\pm}\,iT_{11}-\frac{1}{2}\,\hat{t}_{20}^{\pm}\,T_{20}-\sqrt{\frac{3}{2}}\,\hat{t}_{20}^{\pm}\,T_{22}\right) \tag{3.74b}$$

$$N_C^{\pm} = \epsilon_C N^{\pm}\left(1-\frac{1}{2}\,\hat{t}_{20}^{\pm}\,T_{20}^{C}-\sqrt{\frac{3}{2}}\,\hat{t}_{20}^{\pm}\,T_{22}^{C}\right) \tag{3.74c}$$

where N_L^+ (N_L^-) is the number of protons produced by the $^3\text{He}(\vec{d},p)^4\text{He}$ reaction which scatter into the left detector, N_R^+ (N_R^-) is the number of protons which scatter into the

[4] See [?] for a comparison of the Cartesian and spherical representations.

right detector, and N_C^+ (N_C^-) is the number of protons which scatter into the 0° detector. These expressions are in terms of the detector efficiencies $\epsilon_{L,R,C}$ and the incident fluxes N^+ (N^-).

The T's in Equation 3.74 are the $^3\text{He}(\vec{d},p)^4\text{He}$ analyzing powers: the vector analyzing power $iT_{11} = iT_{11}(E,\theta)$ and the tensor analyzing powers $T_{20} = T_{20}(E,\theta)$ and $T_{22} = T_{22}(E,\theta)$. $T_{20}^C = T_{20}^C(E,\Delta\theta)$ and $T_{22}^C = T_{22}^C(E,\Delta\theta)$ are the tensor analyzing powers at 0° for a detector with solid angle $\Delta\theta$.[5] After some algebra we have

$$\frac{N_L^\pm}{\epsilon_L N^\pm} = 1 + \sqrt{2}\,\hat{t}_{10}^\pm\, iT_{11} - \frac{1}{2}\,\hat{t}_{20}^\pm(\,T_{20} + \sqrt{6}\,T_{22}\,) \tag{3.75a}$$

$$\frac{N_R^\pm}{\epsilon_R N^\pm} = 1 - \sqrt{2}\,\hat{t}_{10}^\pm\, iT_{11} - \frac{1}{2}\,\hat{t}_{20}^\pm(\,T_{20} + \sqrt{6}\,T_{22}\,) \tag{3.75b}$$

$$\frac{N_C^\pm}{\epsilon_C N^\pm} = 1 - \frac{1}{2}\,\hat{t}_{20}^\pm(\,T_{20}^C + \sqrt{6}\,T_{22}^C\,). \tag{3.75c}$$

To unambiguously know the deuteron-beam polarizations, we must determine nine unknowns (four deuteron polarizations, three detector efficiencies, and two incident fluxes) from these six equations.

Since this task is algebraically impossible, we must employ some trick: we measure a scattering asymmetry using unpolarized beam. The number of protons which scatter from an unpolarized beam into the three detectors is given by

$$N_L^{(0)} = \epsilon_L N^{(0)} \tag{3.76a}$$

$$N_R^{(0)} = \epsilon_R N^{(0)} \tag{3.76b}$$

$$N_C^{(0)} = \epsilon_C N^{(0)} \tag{3.76c}$$

where $N^{(0)}$ is the incident unpolarized beam flux. This is an additional three equations. We define

$$\tilde{\epsilon}_L^{(0)} \equiv \frac{\epsilon_L}{\epsilon_C} = \frac{N_L^{(0)}}{N_C^{(0)}} \tag{3.77a}$$

$$\tilde{\epsilon}_R^{(0)} \equiv \frac{\epsilon_R}{\epsilon_C} = \frac{N_R^{(0)}}{N_C^{(0)}} \tag{3.77b}$$

---

[5] T_{22}^C is identically zero at 0° but this term contributes due the finite solid angle seen by the 0° detector. iT_{11} is also identically zero at 0°, but is antisymmetric about 0°, and so averages to zero over a finite solid angle.

which are center-detector normalized, left/right detector efficiencies for unpolarized beam. Similarly, for polarized beam we define the normalized efficiencies

$$\tilde{\epsilon}_L^{\pm} \equiv \frac{\epsilon_L^{\pm}}{\epsilon_C^{\pm}} = \frac{N_L^{\pm}}{N_C^{\pm}} \tag{3.78a}$$

$$\tilde{\epsilon}_R^{\pm} \equiv \frac{\epsilon_R^{\pm}}{\epsilon_C^{\pm}} = \frac{N_R^{\pm}}{N_C^{\pm}}. \tag{3.78b}$$

Substituting Equations 3.77 and 3.78 into Equations 3.75a and 3.75b gives

$$\frac{N_L^{\pm}}{\epsilon_L N^{\pm}} = \frac{(\tilde{\epsilon}_L^{\pm} N_C^{\pm})}{(\tilde{\epsilon}_L^{(0)} \epsilon_C) N^{\pm}} = 1 + \sqrt{2}\, \hat{t}_{10}^{\pm}\, iT_{11} - \frac{1}{2}\, \hat{t}_{20}^{\pm} (\, T_{20} + \sqrt{6}\, T_{22}\,) \tag{3.79a}$$

$$\frac{N_R^{\pm}}{\epsilon_R N^{\pm}} = \frac{(\tilde{\epsilon}_R^{\pm} N_C^{\pm})}{(\tilde{\epsilon}_R^{(0)} \epsilon_C) N^{\pm}} = 1 - \sqrt{2}\, \hat{t}_{10}^{\pm}\, iT_{11} - \frac{1}{2}\, \hat{t}_{20}^{\pm} (\, T_{20} + \sqrt{6}\, T_{22}\,) \tag{3.79b}$$

while Equation 3.75c can be rewritten

$$\epsilon_C N^{\pm} = \frac{N_C^{\pm}}{1 - \frac{1}{2}\, \hat{t}_{20}^{\pm} (\, T_{20}^C + \sqrt{6}\, T_{22}^C\,)}. \tag{3.80}$$

After substituting Equation 3.80 into Equations 3.79a and 3.79b, we have

$$\frac{\tilde{\epsilon}_L^{\pm}}{\tilde{\epsilon}_L^{(0)}} \left[1 - \frac{1}{2}\, \hat{t}_{20}^{\pm} (\, T_{20}^C + \sqrt{6}\, T_{22}^C\,)\right] = 1 + \sqrt{2}\, \hat{t}_{10}^{\pm}\, iT_{11} - \frac{1}{2}\, \hat{t}_{20}^{\pm} (\, T_{20} + \sqrt{6}\, T_{22}\,) \tag{3.81a}$$

$$\frac{\tilde{\epsilon}_R^{\pm}}{\tilde{\epsilon}_R^{(0)}} \left[1 - \frac{1}{2}\, \hat{t}_{20}^{\pm} (\, T_{20}^C + \sqrt{6}\, T_{22}^C\,)\right] = 1 - \sqrt{2}\, \hat{t}_{10}^{\pm}\, iT_{11} - \frac{1}{2}\, \hat{t}_{20}^{\pm} (\, T_{20} + \sqrt{6}\, T_{22}\,) \tag{3.81b}$$

which gives us four equations and four unknowns.

Taking the sum and difference of these equations gives expressions for the deuteron-beam vector and tensor polarizations:

$$\hat{t}_{10}^{\pm} = \frac{\left(\frac{\tilde{\epsilon}_L^{\pm}}{\tilde{\epsilon}_L^{(0)}} - \frac{\tilde{\epsilon}_R^{\pm}}{\tilde{\epsilon}_R^{(0)}}\right) [1 - \frac{1}{2}\, \hat{t}_{20}^{\pm} (\, T_{20}^C + \sqrt{6}\, T_{22}^C\,)]}{2\sqrt{2}\, iT_{11}} \tag{3.82}$$

$$\hat{t}_{20}^{\pm} = \frac{2 - \left(\frac{\tilde{\epsilon}_L^{\pm}}{\tilde{\epsilon}_L^{(0)}} + \frac{\tilde{\epsilon}_R^{\pm}}{\tilde{\epsilon}_R^{(0)}}\right)}{(\, T_{20} + \sqrt{6}\, T_{22}\,) - \frac{1}{2} \left(\frac{\tilde{\epsilon}_L^{\pm}}{\tilde{\epsilon}_L^{(0)}} + \frac{\tilde{\epsilon}_R^{\pm}}{\tilde{\epsilon}_R^{(0)}}\right) (\, T_{20}^C + \sqrt{6}\, T_{22}^C\,)}. \tag{3.83}$$

The spherical-representation expressions are related to the Cartesian representation simply by

$$P_d = \sqrt{\frac{2}{3}}\,\hat{t}_{10}^{\pm} \tag{3.84}$$

$$P_{dd} = \sqrt{2}\,\hat{t}_{20}^{\pm}. \tag{3.85}$$

where P_d is the vector polarization and P_{dd} is the tensor polarization.

Statistical uncertainty in deuteron-beam polarization is explicitly given by

$$\Delta_{\hat{t}_{20}^{\pm}} = \frac{(T_{20}^{C} - T_{20}) + \sqrt{6}(T_{22}^{C} - T_{22})}{\left[T_{20} + \sqrt{6}\,T_{22} - \frac{1}{2}(T_{20}^{C} + \sqrt{6}\,T_{22}^{C})(\frac{\tilde{\epsilon}_L^{\pm}}{\tilde{\epsilon}_L^{(0)}} + \frac{\tilde{\epsilon}_R^{\pm}}{\tilde{\epsilon}_R^{(0)}})\right]^2} \times$$
$$\left\{\frac{1}{(\tilde{\epsilon}_L^{(0)})^2}\left[\Delta^2_{\tilde{\epsilon}_L^{\pm}} + (\tilde{\epsilon}_L^{\pm}\Delta^2_{\tilde{\epsilon}_L^{(0)}})\right] + \frac{1}{(\tilde{\epsilon}_R^{(0)})^2}\left[\Delta^2_{\tilde{\epsilon}_R^{\pm}} + (\tilde{\epsilon}_R^{\pm}\Delta^2_{\tilde{\epsilon}_R^{(0)}})\right]\right\}^{\frac{1}{2}} \tag{3.86}$$

and

$$\Delta_{\hat{t}_{10}^{\pm}} = \left\{\left[\frac{\frac{1}{2}(T_{20}^{C} + \sqrt{6}\,T_{22}^{C})(\frac{\tilde{\epsilon}_L^{\pm}}{\tilde{\epsilon}_L^{(0)}} - \frac{\tilde{\epsilon}_R^{\pm}}{\tilde{\epsilon}_R^{(0)}})\Delta_{\hat{t}_{20}^{\pm}}}{2\sqrt{2}\,iT_{11}}\right]^2 + \left[\frac{1 - \frac{1}{2}(T_{20}^{C} + \sqrt{6}\,T_{22}^{C})\,\hat{t}_{10}^{\pm}}{2\sqrt{2}\,iT_{11}}\right]^2\right.$$
$$\left.\times\left[\frac{1}{(\tilde{\epsilon}_L^{(0)})^2}(\Delta^2_{\tilde{\epsilon}_L^{\pm}} + (\tilde{\epsilon}_L^{\pm}\Delta_{\tilde{\epsilon}_L^{(0)}})^2) + \frac{1}{(\tilde{\epsilon}_R^{(0)})^2}(\Delta^2_{\tilde{\epsilon}_R^{\pm}} + (\tilde{\epsilon}_R^{\pm}\Delta_{\tilde{\epsilon}_R^{(0)}})^2)\right]\right\}^{\frac{1}{2}} \tag{3.87}$$

where

$$\Delta\tilde{\epsilon}^{\pm} = \tilde{\epsilon}^{\pm}\sqrt{\frac{1}{N^{\pm}} + \frac{1}{N_C^{\pm}}}. \tag{3.88}$$

is the uncertainty in $\tilde{\epsilon}^{\pm}$ due to counting statistics. However, more scatter is seen between individual deuteron-beam polarization measurements than is predicted by counting statistics, so uncertainty in the average deuteron-beam polarization is obtained from the standard deviation σ of the measurements according to

$$\Delta P_d = \frac{\sigma}{\sqrt{N}}, \quad \Delta P_{dd} = \frac{\sigma}{\sqrt{N}} \tag{3.89}$$

where N is the number of measurements. Uncertainty in the analyzing powers $\Delta\, iT_{11}$, $\Delta\, T_{20}$, $\Delta\, T_{22}$, $\Delta\, T_{20}^{C}$, and $\Delta\, T_{22}^{C}$ are treated as a systematic uncertainties.

3.2.3 Neutron-Beam Polarization

Polarized neutrons are produced as a secondary beam from charged-particle induced reactions. This reactions are characterized by polarization-transfer coefficients. Therefore, to determine neutron-beam polarization, we measure the charged-particle beam polarization and calculate the neutron-beam polarization from these transfer coefficients.

We first consider the polarization-transfer reaction which has the spin structure of $\vec{\frac{1}{2}} + A \rightarrow \vec{\frac{1}{2}} + B$, for example the ${}^{3}\mathrm{H}(\vec{p},\vec{n}){}^{3}\mathrm{He}$ reaction. For an incident proton beam with transverse polarization P_p, the outgoing transverse neutron-beam polarization P_n at 0° is given simply by [?]

$$P_n(0^\circ) = P_p K_y^y(0^\circ) \tag{3.90}$$

with uncertainty

$$\Delta P_n(0^\circ) = P_n \sqrt{\left(\frac{\Delta P_p}{P_p}\right)^2 + \left(\frac{\Delta K_y^y(0^\circ)}{K_y^y(0^\circ)}\right)^2} \tag{3.91}$$

where $K_y^y(0^\circ)$ is the 0° vector polarization-transfer coefficient.

Next we consider the polarization-transfer reaction which has the spin structure of $\vec{1} + A \rightarrow \vec{\frac{1}{2}} + B$, for example the ${}^{2}\mathrm{H}(\vec{d},\vec{n}){}^{3}\mathrm{He}$ and ${}^{3}\mathrm{H}(\vec{d},\vec{n}){}^{4}\mathrm{He}$ reactions. For an incident deuteron beam with transverse vector polarization P_d and tensor polarization P_{dd}, the outgoing neutron beam has transverse polarization P_n given by [?]

$$P_n(0^\circ) = \frac{\frac{3}{2} P_d K_y^y(0^\circ)}{1 + \frac{1}{2} P_{dd} A_{yy}(0^\circ)} \tag{3.92}$$

with uncertainty

$$\Delta P_n(0^\circ) = P_n \left[\left(\frac{\Delta P_d}{P_d}\right)^2 + \left(\frac{\Delta K_y^y(0^\circ)}{K_y^y(0^\circ)}\right)^2 + \left(\frac{\Delta P_{dd}}{P_{dd}}\right)^2 \left(\frac{\frac{1}{2} P_{dd} A_{yy}}{1 + \frac{1}{2} P_{dd} A_{yy}}\right)^2 + \left(\frac{\Delta A_{yy}}{A_{yy}}\right)^2 \left(\frac{\frac{1}{2} P_{dd} A_{yy}}{1 + \frac{1}{2} P_{dd} A_{yy}}\right)^2 \right]^{\frac{1}{2}} \tag{3.93}$$

where $A_{yy}(0^\circ)$ is the 0° tensor polarization-transfer coefficient.

3.3 $P_T x$ Expressions

By rearranging Equation 3.19 we can solve for the product of target polarization × thickness

$$P_T x = \frac{2\varepsilon}{P_n \Delta\sigma_T}. \tag{3.94}$$

At low energy (below 5 MeV) $\Delta\sigma_T$ is constrained by kinematics and properties of the deuteron. Theoretical predictions of $\Delta\sigma_T$ from potential model and partial-wave analyses are in good agreement in this energy range so we can say that $\Delta\sigma_T$ is known at low energy. Therefore, if ε_n and P_n are measured then Equation 3.94 can then be used solve for $P_T x$. $P_T x$ of targets used for measurements of $\Delta\sigma_T$ were calibrated at $E_n \approx 2$ MeV in this way.

To account for differences in target polarization between the $P_T x$ calibration measurement and the $\Delta\sigma_T$ measurements, $P_T x$ is scaled by the ratio of P_T as measured by NMR during the $P_T x$ calibration and the $\Delta\sigma_T$ measurements. Equation 3.94 is then written

$$P_T x = \frac{2\varepsilon}{P_n \Delta\sigma_T} \left[\frac{P_T(\Delta\sigma_T)}{P_T(P_T x)} \right] \tag{3.95}$$

with target polarization averaged over the entire measurement. This scaling factor introduces a correction to $P_T x$ of less that 2% for all $\Delta\sigma_T$ measurements.

Chapter 4

The Polarized Proton Target

The proton target is polarized using dynamic nuclear polarization (DNP). Dynamic nuclear polarization is a means of achieving significant nuclear polarization; that is, an unequal population distribution of spin magnetic sub-states is obtained by applying radiation tuned to the frequencies of the spin sub-state splittings to a sample in a magnetic field. Target polarization can rapidly be reversed by retuning the microwave frequency. This feature makes a dynamically polarized target useful for removing systematic effects in experiments designed to measure small asymmetries. In addition, dynamically polarized targets operate at warmer temperatures and lower magnetic fields than statically polarized targets [?], making them less susceptible to the effects of beam heating.

To dynamically polarize a sample it must be cooled and placed in a magnetic field, in this experiment 0.5 K and 2.5 T. This temperature is reached with a ^{3}He evaporation refrigerator which is discussed in Section 4.2. Thermometry is discussed in Section 4.3. The target and target material are described in Section 4.4. Target polarization is measured with nuclear magnetic resonance, as described in Section 4.5. The chapter begins with a tutorial on the dynamic nuclear polarization process.

4.1 Dynamic Nuclear Polarization

4.1.1 Theory

The energy splitting δE of a spin 1/2 particle[1] in a magnetic field is given by

$$\delta E^{\pm} = \mp \frac{g\mu B_z}{2} \tag{4.1}$$

where g is the nuclear g-factor, μ is the magnetic moment, B_z is the external magnetic field which defines the spin quantization axis, and the $+$ $(-)$ corresponds to the spin projection $m = +1/2$ $(-1/2)$.

Interaction of the particle with an external thermal bath induces transitions between levels, and in time each level reaches an equilibrium population described by Boltzmann statistics. At a temperature T, the population n^+ (n^-) of the substate with spin projection $m = +1/2$ $(-1/2)$ measured in the direction of the magnetic field B_z is

$$n^{\pm} = e^{\pm \frac{g\mu B_z}{2kT}} \tag{4.2}$$

where k is Boltzmann's constant. Equilibrium polarization is defined as

$$P = \frac{n^+ - n^-}{n^+ + n^-} = \tanh(\frac{g\mu B_z}{2kT}). \tag{4.3}$$

This behavior is exploited by the brute-force polarization technique where nuclear polarization is achieved with very low temperatures and very high magnetic fields. In DNP, thermal equilibrium polarization is enhanced by dynamically altering these spin-state populations.

We are interested in how dynamic polarization affects the populations of spin energy levels in bulk matter. As an intermediate step we first consider the simpler case of an ensemble of isolated proton-electron pairs. This simplification ignores any perturbation to the external magnetic field caused by the proton and electron magnetic dipole moments, but the model is still a useful pedagogical tool. The proton has nuclear spin $I = 1/2$ and magnetic moment $\mu_I = 2.793\mu_N$, where μ_N is the nuclear magneton. The electron has electronic spin $S = 1/2$ and magnetic moment $\mu_S = 1838\mu_N$. If we examine this sample of

[1] A discussion of systems with higher spin can be found in [?].

Figure 4.1: Energy-level splitting of a proton-electron pair in a magnetic field

proton-electron pairs in a magnetic field, neglecting the dipolar interaction for the moment, the proton and electron energy levels are split, as shown in Figure 4.1. These energy levels are labeled by the quantum numbers $m_I = \langle I_z \rangle$ and $m_S = \langle S_z \rangle$. Energy splitting is given by $\Delta = h\nu_S$ and $\delta = h\nu_I$, and is dominated by the larger electron magnetic moment.

Quantum selection rules forbid transitions where a proton and electron simultaneously flip spin: $\Delta m_S = \pm 1$ and $\Delta m_I = \pm 1$ [?]. The allowed electron spin-flip transitions are then $\Delta m_S = \pm 1$ and $\Delta m_I = 0$ (such as W_{12} and W_{34} in Figure 4.2a), mediated by the coupling of the electron spin to the crystal lattice. In this process spins transfer energy to the lattice in the form of heat. The electron spin-lattice relaxation is characterized by the electron spin-lattice relaxation time T_{1e} and is the dominant electron relaxation mechanism. The allowed nuclear spin-flip transitions $\Delta m_S = 0$ and $\Delta m_I = \pm 1$ are negligible at low temperature since the proton is only weakly coupled to the lattice.

We now turn on the dipolar interaction, which is of the form $\vec{I} \cdot \vec{S}$. As a result these otherwise pure spin states are slightly mixed, and so are only approximately characterized by the quantum numbers m_S and m_I. As a consequence of this mixing, the forbidden transitions are now allowed to second order. Therefore, the mutual electron-proton spin-flip transitions $\Delta m_S = \pm 1$ and $\Delta m_I = \pm 1$ (such as W_{14} and W_{32} in Figure 4.2a) become the primary mechanism for nuclear spin relaxation.

As the sample is cooled in a magnetic field, the lower energy states preferentially

(a) Allowed (dashed) and forbidden (dotted) transitions

(b) Dynamic polarization by driving the transition $W_+ = W_{41}$

Figure 4.2: Transitions between Zeeman levels in a proton-electron pair

populate according to Equation 4.2. At $B = 2.5$ T and $T = 0.5$ K, the electron and nuclear equilibrium polarizations are $P_S = -0.99$ and $P_I = 0.0056$. That is, the electrons are almost completely polarized, and the protons are only slightly polarized.

Dynamic nuclear polarization involves selectively driving one of the so-called forbidden transitions by the application of microwaves. For example, if we "pump" the sample with radiation of frequency $h\nu^- = \Delta - \delta$, and if ν_I is less than the electron transition linewidth (i.e. well resolved), then we induce the transition W_{23} (see Figure 4.2a); that is, an electron flips from $m_S = -1/2$ to $m_S = +1/2$, and a proton simultaneously flips from $m_I = -1/2$ to $m_I = +1/2$. If this transition is driven at a rate greater than all relaxation rates, and since induced emission or absorption transitions are equally likely, the transition will saturate and the population of the two states will equalize. Similarly, if we "pump" the sample with radiation of frequency $h\nu^+ = \Delta + \delta$, then we induce the transition W_{41} (see Figure 4.2a); that is, an electron flips from $m_S = -1/2$ to $m_S = +1/2$, and a proton simultaneously flips from $m_I = +1/2$ to $m_I = -1/2$. Likewise, we can equalize population of these two levels. This is the usual saturation of a forbidden transition.

To calculate the polarization enhancement due to inducing one of these forbidden transitions[2], let's assume we are driving the transition W_{41} at a rate W_+ and the only thermal relaxation process is the electron spin-lattice relaxation, as in Figure 4.2b. The rate equations for the probability p_i of occupying the level i are

$$\frac{dp_1}{dt} = p_2 W_{21} - p_1 W_{12} + (p_4 - p_1) W_+ \tag{4.4a}$$
$$\frac{dp_2}{dt} = p_1 W_{12} - p_2 W_{21} \tag{4.4b}$$
$$\frac{dp_3}{dt} = p_4 W_{43} - p_3 W_{34} \tag{4.4c}$$
$$\frac{dp_4}{dt} = p_3 W_{34} - p_4 W_{43} + (p_1 - p_4) W_+ \tag{4.4d}$$

where W_{ij} is the probability of a transition per unit time between the i and j levels. In addition, the probabilities of occupation must sum to unity

$$p_1 + p_2 + p_3 + p_4 = 1. \tag{4.5}$$

We are interested in the steady-state solution, so the time derivatives in Equations 4.4 are set to zero. Assuming can saturate the transition W_+, we take the limit $p_4 = p_1$. Therefore,

$$p_1 = p_4 \tag{4.6a}$$
$$p_2 = p_1 \frac{W_{12}}{W_{21}} = p_1 B_{12} \tag{4.6b}$$
$$p_3 = p_4 \frac{W_{43}}{W_{34}} = p_4 B_{43} \tag{4.6c}$$

where the Boltzmann ratio B_{ij} is defined

$$B_{ij} = e^{\frac{E_i - E_j}{kT}}. \tag{4.7}$$

[2]We follow here the treatment of Slichter [?].

Solving for the occupational probabilities in terms of the B_{ij} gives

$$p_1 = p_4 = \frac{1}{2 + B_{12} + B_{43}} \tag{4.8a}$$

$$p_2 = \frac{B_{12}}{2 + B_{12} + B_{43}} \tag{4.8b}$$

$$p_3 = \frac{B_{43}}{2 + B_{12} + B_{43}}. \tag{4.8c}$$

The expectation value of the nuclear spin I_z is defined

$$\begin{aligned} \langle I_z \rangle &= \sum_i p_i \langle i | I_z | i \rangle \\ &= \frac{1}{2}(p_1 + p_2 - p_3 - p_4) \end{aligned} \tag{4.9}$$

so that

$$\langle I_z \rangle = \frac{1}{2} \left(\frac{B_{12} - B_{43}}{2 + B_{12} + B_{43}} \right) = P \tag{4.10}$$

where P is the nuclear polarization.

Insight into this equation can be gained by examining the high-temperature limit ($kT \gg E_i - E_j$, above 20 K or so), where Equation 4.7 can be expanded

$$B_{ij} \approx 1 + \frac{E_i - E_j}{kT} \tag{4.11}$$

and after substituting for the B_{ij}, the dynamically induced polarization can be written

$$P = \frac{1}{2} \frac{E_1 + E_3 - E_2 - E_4}{4kT}. \tag{4.12}$$

To see the enhancement due to dynamic polarization we set $W_+ = 0$ and solve for the polarization P_{te} at thermal equilibrium:

$$P_{te} = \frac{1}{2} \frac{E_3 + E_4 - E_1 - E_2}{4kT} \tag{4.13}$$

and after substituting for the relative energies in terms of the energy splitting Δ and δ, the enhancement due to DNP over thermal equilibrium polarization is given by

$$\frac{P}{P_{te}} = \frac{\Delta}{\delta} \tag{4.14}$$

Figure 4.3: Proton polarization growth due to dynamic polarization

which is a theoretical enhancement of around 650. At 0.5 K the theoretical maximum dynamic enhancement is around 350.

For DNP to be optimized, T_{1e}, the rate at which electrons relax independently (electron spin-lattice relaxations W_{12} and W_{34}) must be greater than N_e/N_n times T_{ss}, the rate of mutual electron-proton relaxation (spin-spin relaxations W_{12} and W_{34}), where N_e/N_n is ratio of electron to proton concentrations. Under these conditions electrons will return to their ground state without destroying nuclear polarization and are then available to "service" another proton through another induced mutual spin flip. To meet this condition we utilize a diamagnetic target material (propanediol) to provide free hydrogen (protons), with a small concentration of paramagnetic dopant (EHBA Chromium (V) complex) to provide unpaired electrons. We have $N_e/N_n \approx 10^{-3}$, $T_{1e} \approx 10^{-3}$ s, and $T_{ss} \approx 10^3$ s.

Figure 4.3 shows a measurement of the growth of proton polarization from negative to positive due to dynamic polarization. The vertical axis is area of the NMR signal which is proportional to proton polarization. Polarization is this figure is approximately 60%.

4.1.2 Equipment

The magnetic field is supplied by a 10.16 cm bore split-coil superconducting magnet[3], oriented vertically. Field homogeneity is rated to better than 0.01% over a volume of 1 cm^3. The magnet is wound with Nb-Ti wire and operated in persistent mode during the experiment.

Microwaves of frequencies $\nu^+ = 69.969$ GHz and $\nu^- = 69.991$ GHz are provided by a klystron powered by a solid-state power supply. Microwave frequency is changed by adjusting the klystron resonance cavity and the power-supply reflector voltage to a previously optimized setting. Approximately 6 mW of microwave power[4] is continuously delivered to the target via a 0.635 cm diameter cylindrical waveguide. A microwave horn couples the cylindrical waveguide to the rectangular microwave cavity. Microwave frequency is measured by observing the beat frequency between the microwaves and a reference frequency. Forward and reflected microwave power are monitored with microwave power meters.

4.2 The ^{3}He Evaporation Refrigerator

The target is cooled to 0.5 K by a refrigerator of a PSI[5] design [?]. Modifications made to the original PSI design include enlarging the microwave cavity to accommodate a larger target and enlarging the vacuum can to allow the superconducting magnet to be mounted either vertically or horizontally.

Operation of the refrigerator is divided into two separate systems, each exploiting the latent heat of evaporation and large vapor pressure of a helium isotope at low temperature. The ^{4}He cryostat (described in Section 4.2.1) is cooled to 2 K by pumping on a bath of ^{4}He. The ^{4}He bath is in thermal contact with the ^{3}He condenser, and condenses incoming ^{3}He gas. The ^{3}He refrigerator (described in Section 4.2.2) cools the target to 0.5 K by pumping on ^{3}He.

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[3] American Magnetics Inc., Oak Ridge, TN.

[4] Microwave power was calibrated by comparing the temperature rise due to microwave absorption to resistive heating of an RuO sensor in the target cup.

[5] Paul Scherrer Institute, Switzerland.

4.2.1 ^{4}He Cryostat

The ^{4}He cryostat consists of a stainless-steel dewar surrounded by a vacuum jacket (See Figure 4.4). The dewar is connected to the superconducting magnet via two stainless steel bellows. The magnet is surrounded by several layers of aluminized-mylar super insulation, two 0.102 cm thick copper radiation shields thermally anchored to the ^{4}He dewar, and the vacuum jacket. The two copper shields thermalize at 4 K and 100 K. The inner wall of the dewar is in thermal contact with the outer wall of the ^{3}He condenser through a close-tolerance slip fit with approximately 250 cm^2 of contact area.

Helium level in the dewar is maintained at a height of between 7 and 14 cm. Liquid is transferred into the cryostat from a commercial supply dewar through a flexible transfer tube which is left in place during operation. The relatively small capacity of the dewar requires a liquid helium transfer every 40 min, with approximately 0.6 liquid liters transferred each fill. The transfer process is automated by a superconducting helium level sensor controlling a solenoid-actuated cryogenic foot valve on the transfer line. Liquid helium consumption including liquid helium transfers, dewar boil-off, and coldplate usage averages 1.1 liquid liters per hour.

The ^{4}He bath is cooled to 2.2 K by a λ-fridge [?]. The λ-fridge consists of a coldplate made of 1.91 cm diameter stainless-steel tubing and a coldplate pump. The coldplate is immersed in liquid helium and is filled with ^{4}He through a needle valve[6] at the bottom of the coldplate. The coldplate pump is an Alcatel 2033 mechanical pump with a rated pumping speed of 8.3 l/s at STP. Inlet pressure of the coldplate pump was kept at $\approx$ 7 torr by adjusting the needle valve.

The minimum operating temperature of the cryostat is set at 2.2 K by the specific heat of ^{4}He approaching infinity at 2.2 K. With the coldplate inlet near the bottom of the dewar, the low thermal conductivity of liquid ^{4}He establishes a temperature gradient in the helium bath from 2.2 K near the coldplate inlet to 4 K at the top of the bath. Maintaining the surface of the helium bath above the ^{4}He superfluid transition at 2.2 K is important for

[6] It is unclear whether there was liquid in the coldplate or if the valve was acting as an expansion valve.

Figure 4.4: Schematic of the ^{4}He cryostat

minimizing superfluid creep up the walls of the cryostat and posing an unnecessary heat leak.

4.2.2 ^{3}He Refrigerator

Cooling below 2 K is accomplished by pumping on ^{3}He. While the latent heat of evaporation of ^{3}He is less than ^{4}He, the vapor pressure of ^{3}He remains large at lower temperatures. Since ^{3}He is rather costly, recirculating pumps are used and the entire ^{3}He gas handling system is closed. A schematic of the ^{3}He gas handling system is shown in Figure 4.5 and the ^{3}He pumping system is shown in Figure 4.6.

The ^{3}He refrigerator is modular in construction and independent from the ^{4}He system. The refrigerator is top loading and is normally loaded into the cryostat before a cooldown, but can be inserted and removed with liquid helium in the dewar. Alignment pins fix the orientation of the refrigerator relative to the cryostat. The space in the cryostat into which the refrigerator is inserted is the pumping line, so the entire refrigerator is immersed in the exiting ^{3}He gas. Feedthroughs are available for temperature sensors and the static pressure tube (see Section 4.3).

The refrigerator is supported by three 93.6 cm long, 0.476 cm diameter stainless-steel rods which extend from room temperature to the ^{3}He cup. The rods are connected by two copper heat exchange disks and the condenser, a baffled stainless-steel cylinder 43.8 cm in length (see Figure 4.7) and containing eight additional heat exchangers. At the cold end of the refrigerator is the ^{3}He cup, a $2.0 \times 2.0 \times 8.5$ cm box of 0.025 cm thick copper. The ^{3}He fill tube runs along the length of the refrigerator and is thermally anchored at the heat exchangers.

During operation, ^{3}He gas is delivered from the gas handling system to the refrigerator fill tube via stainless-steel tubing. Gas entering the condenser is cooled to 2.2 K by thermal contact with ^{4}He in the dewar. Condenser pressure is regulated by a needle valve at the exit of the condenser. Typical condenser pressure is 250 torr. The ^{3}He is further cooled to 1.6 K at it expands through the ^{3}He valve. Liquid ^{3}He then flows through additional tubing from the condenser into the ^{3}He cup. During equilibrium operation liquid is maintained in the cup such that the target is fully immersed in ^{3}He.

Figure 4.7: The target insert and ^{3}He refrigerator

Liquid in the ^{3}He cup is pumped by a series combination of Roots blowers (Alcatel RVS 600 and RVS 300) backed by a hermetically sealed mechanical pump (Alcatel 2063). Pumping speeds are rated at 140, 80, and 20 l/s at STP respectively. Cold gas pumped from the cup helps to cool the entering ^{3}He through contact with the heat exchangers located in the condenser and on the refrigerator.

Cooling power $\dot{Q}$ of a ^{3}He evaporation refrigerator is given by

$$\dot{Q} = L\dot{n} \tag{4.15}$$

where L is the ^{3}He latent heat of evaporation and $\dot{n}$ is the ^{3}He molar flow rate. This equation is not strictly true for a continuously recirculating system since enthalpy of the incoming ^{3}He gas must be removed. However, this heat is removed by the ^{4}He bath and does not affect performance of the refrigerator. For a constant volume pump, flow rate and therefore cooling power is determined by vapor pressure. At 0.5 K, ^{3}He vapor pressure is 175 mtorr giving a flow rate of 0.6 mmol/sec, and $\dot{Q}$ = 15 mW. This cooling power is sufficient to overcome heat leaks from room temperature and heating from microwave pumping. Base operating temperature of the refrigerator is controlled by adjusting liquid flow into the ^{3}He cup by use of the ^{3}He needle valve.[7]

[7] For operation at temperatures above 0.6 K the pumping speed must also be reduced.

4.3 Thermometry

Knowledge of temperatures within the refrigerator is crucial for cryostat operation and data analysis, particularly the thermal equilibrium NMR calibration. Resistance thermometers are thermally anchored to various parts of the refrigerator and measured using a four-lead bridge implemented on a personal computer running LabView software. Several types of resistors are needed to cover the temperature range from 300 K to 0.5 K. In addition, ^{3}He vapor pressure thermometry is used.

For thermometry above 70 K two 1000 Ω platinum resistors are utilized. For thermometry between 1.5 K to 4.5 K, three carbon resistors are used: a 220 Ω Speer, a 500 Ω carbon-glass, and a 1000 Ω carbon-glass. The carbon-glass resistors are calibrated against a germanium resistor. For thermometry below 1.5 K a commercially calibrated germanium resistor[8] and an RuO resistor are located in the ^{3}He cup directly below the target. The RuO resistor is calibrated against the germanium resistor. These two are located below the target in the ^{3}He cup and measure the temperature of the liquid ^{3}He in the cup. While the germanium resistor is highly accurate, it's resistance vs. temperature characteristic is sensitive to magnetic fields. Both resistors absorb rf and are useless when the microwaves are turned on for dynamic polarization.

To provide accurate thermometry during dynamic polarization, ^{3}He vapor pressure thermometry is used. In the temperature region from 0.3 K to a few K the vapor pressure of ^{3}He is strongly dependent on temperature [**?**]. To measure the vapor pressure, a 10 torr baratron head at room temperature is connected to the ^{3}He vapor by a 0.318 cm stainless-steel static pressure tube extending to just above the ^{3}He cup. Vapor-pressure thermometry is particularly important for the analysis of thermal equilibrium NMR signals (see [**?**]).

[8]Lake Shore Cryotronics, Inc., Westerville, OH.

4.4 Target Cup and Material

The target itself is made of the organic propanediol $C_3H_6(OH)_2$, chosen for the abundance of free hydrogen and high density (1.27 g/cm^3), which gives a hydrogen concentration of 5×10^{22} H/cm^3 (assuming a filling factor of 0.60). To aid in uniform cooling of the target, the propanediol is frozen into 1 mm beads [?]. The melting point of propanediol is around 100 K so that once the beads are formed they must be stored and loaded into the target cup while under liquid nitrogen.

The target cup is a 1.4 × 1.4 × 1.4 cm (inner dimensions) rectangular container, giving a nominal target thickness of 0.6 atoms/b. The cup is constructed from 0.0762 cm thick pieces of kel-F[9], a plastic chosen for the lack of polarizable free hydrogen, and epoxied together with A-12[10]. The NMR coil is wrapped tightly into grooves cut into the outside of the target cup. A diagram of the target cup is shown in Figure 4.8. The target cup is secured to the microwave horn located at the end of the target insert, a 0.635 cm diameter stainless-steel tube 92.6 cm long (see Figure 4.7), which allows the target to be inserted axially into the top of the refrigerator. The position of the target cup relative to the refrigerator is fixed by alignment pins. The target insert is also the microwave waveguide from room temperature down to the target cup. The insert also supports the NMR coaxial cable and the static pressure tube. Figure 4.9 shows detail of the target cup seated in the ^{3}He cup.

Free electrons required for DNP are provided by chemical doping. The target is doped with EHBA-Chromium(V) complex[11] which is prepared according to the recipe in [?]. The concentration of dopant is 0.375 g per 10 cm^3 of propanediol giving an electron density of 4×10^{19} electrons/cm^3.

The product of proton polarization and target thickness $P_T x$ is determined by a neutron transmission experiment described in Section 3.3. In addition the thickness of each target was determined by melting the beads after each experiment and finding their mass

[9] duPont Chemical Company, Wilmington, DE.

[10] Armstrong Products Company, Warsaw, IN.

[11] sodium bis (2-ethyl 2-hydroxy-butyrato) oxochromate (V) monohydrate.

and volume. This measurement, combined with an absolute NMR measure of polarization, allows a second measure of $P_T x$. Only the value of $P_T x$ measured by neutron transmission is used in calculating $\Delta\sigma_T$.

4.5 NMR for a Relative Measure of Target Polarization

Target (proton) polarization is measured with Nuclear Magnetic Resonance (NMR). NMR provides a relative polarization measurement, and must be calibrated to determine polarization absolutely. This calibration procedure will be described in [?], and is not used in the determination of $\Delta\sigma_T$. NMR is used to scale target polarization measured during a $\Delta\sigma_T$ measurement to the target polarization measured during the $P_T x$ calibration.

NMR is a technique to measure the change in inductance of a sample due to the nuclear polarization. The inductance L is given by

$$L = L_0[1 + 4\pi q\chi(\omega)] \tag{4.16}$$

where L_0 is a constant, q is the filling factor, and the complex magnetic susceptibility $\chi(\omega)$

$$\chi(\omega) = \chi'(\omega) - i\chi''(\omega) \tag{4.17}$$

is a function of an applied rf field. Polarization is proportional to the imaginary part of the susceptibility integrated over all frequencies

$$P \propto \int \chi''(\omega)d\omega \tag{4.18}$$

where in practice one only needs to integrate close to the proton Larmor frequency, ω_0.

The NMR electronics is shown in Figure 4.10 and includes a frequency synthesizer[12] controlled by a PC running LabView[13], a tuned LRC circuit of the Liverpool design [?], and a coil which contains the target. Response from the Liverpool box is recorded and displayed by LabView. Details of the NMR circuit are be given by [?].

[12] Model 5135A, Wavetek, Inc., San Diego, CA.
[13] National Instruments Corporation, Austin, TX.

The LRC circuit is tuned to 106.5 MHz, the Larmor frequency of protons in a 2.5 T magnetic field. The frequency synthesizer is programmed to sweep over the frequency range $\omega_0 \pm 0.250$ MHz. The LRC circuit is connected to the coil by a 1λ length of UT85 cryogenic coaxial cable. The coil is made from two loops of 0.051 cm diameter copper wire wrapped around the outside of the target cup, and thus 0.076 cm from the target material. The coil has an effective area of 5.52 cm^2 and a measured impedance of 0.18 μH.

Measurements of the circuit response (Q-curve) with the magnet tuned off resonance were made and saved to disk for use in a hardware background subtraction. A typical background Q-curve is shown in Figure 4.11. A typical circuit response with target polarization of $\approx$60% is shown without background subtraction in Figure 4.12 (note the change in scale) and with background subtraction in Figure 4.13. It was found that the Q-curve changed reproducibly with liquid helium level in the cryostat (probably due to a changing temperature gradient in the coaxial cable). Therefore, several background Q-curves were measured throughout the helium fill cycle and tagged with helium level. Measurements of the polarized target signal were similarly tagged with helium level and a background was accordingly subtracted.

Figure 4.5: Schematic of the ^{3}He gas handling system

Figure 4.6: Schematic of the ^{3}He pumping system

Figure 4.8: The ^{3}He cup showing the NMR coil

Figure 4.9: The target cup seated in the ^{3}He cup

Figure 4.10: The NMR System

Figure 4.11: A typical background NMR response

Figure 4.12: Measured NMR response for $P_T \approx 60\%$

Figure 4.13: NMR response for $P_T \approx 60\%$ after background subtraction

Chapter 5

The Polarized Neutron Beam

Measurements of $\Delta\sigma_T$ require a beam of polarized neutrons. Since it is not possible to accelerate neutral particles directly, the neutron beam is produced as a secondary beam from charged-particle reactions. A polarized proton beam is used for production of neutrons below 5 MeV via the ^{3}H($\vec{p},\vec{n}$)^{3}He reaction, and a polarized deuteron beam for production of neutrons above 5 MeV via the ^{2}H($\vec{d},\vec{n}$)^{3}He or ^{3}H($\vec{d},\vec{n}$)^{4}He reactions. A beam of negatively-charged polarized protons or deuterons is produced by TUNL's Atomic Beam Polarized Ion Source. The polarization axis of the beam can be selected with a Wien filter. This beam is then injected into a Van de Graaff electrostatic accelerator. Finally the beam is analyzed in energy and transported to the neutron production target.

5.1 The TUNL Polarized Ion Source

The TUNL Atomic Beam Polarized Ion Source (ABPIS) [**?**] can produce beams of vector-polarized protons, and vector- and tensor-polarized deuterons. For an ensemble of spin 1/2 particles, vector polarization is defined as

$$P_z = \frac{N^+ - N^-}{N^+ + N^-} \tag{5.1}$$

where N^+ (N^-) is the population of the $m_I = 1/2$ ($-1/2$) spin sub-state. For an ensemble of spin 1 particles, vector polarization is defined similarly, but where N^+ (N^-) is the population of the $m_I = 1$ (-1) spin sub-state. Tensor polarization is defined as

$$P_{zz} = \frac{1 - 3N^0}{N^+ + N^0 + N^-} \tag{5.2}$$

where N^0 is the population of the $m_I = 0$ spin sub-state. Vector and tensor polarizations of order 70% are typical from the ABPIS. Positive beam currents up to 100 μA are available for low energy ($<$ 80 keV, the source potential) experiments, and negative beam currents up to 4 μA are produced for injection into the accelerator.

A schematic diagram of the source is shown in Figure 5.1. The source is held floating at 80 kV below ground potential. High-purity hydrogen or deuterium gas (30 cc/min) flows into the dissociator, where an rf-induced plasma separates molecular H_2 or D_2 into atomic hydrogen or deuterium. This atomic beam exits the dissociator through a nozzle which is cooled to 30 K to slow down the beam. Before the dissociator, the H_2 or D_2 gas is mixed with nitrogen to minimize recombination of H or D on the cold nozzle.

Nuclear polarization is produced as the atomic beam passes through two permanent sextupole magnets and three rf transition units. The sextupoles selectively focus atoms with electronic spin projection $m_S = 1/2$ and defocus atoms with $m_S = -1/2$. The defocused atoms are pumped away by four turbo pumps. The transition units are cavities with a magnetic field to separate spin substates and an rf oscillator tuned to the frequency of a hyperfine transition. These units selectively induce spin-flip transitions. Two types of transition units are used on the ABPIS: a strong field unit (SF) and two medium field units (MF1 and MF2). The spin-quantization axis of these transition units is parallel to the momentum of the beam. These transition units can be rapidly toggled on and off ($\approx$ 10 ms), so proton- and deuteron-beam polarization can be rapidly reversed. In practice, beam polarization is reversed at 10 Hz by the TUNL spin-state controller, as discussed in Section 5.1.1.

A proton beam polarized spin up ($P_z > 0$) or spin down ($P_z < 0$) is produced as follows: The atomic hydrogen beam is polarized in electronic spin by the first sextupole, that is, states **1** and **2** are focused and states **3** and **4** are defocused (see Figure 5.2). Since

Figure 5.1: Schematic of the the TUNL Atomic Beam Polarized Ion Source

the first transition unit, MF1, is not used, the beam passes through the second sextupole unchanged. To produce spin-up polarization, the SF transition unit is tuned to induce the transition **2** $\rightarrow$ **4**. The final populated states are **1** and **4**, the $m_I = +1/2$ states, with theoretical maximum polarization $P_z = +1$. To produce spin-down polarization, MF2 is tuned to induce the transition **1** $\rightarrow$ **3**, so the remaining populated states are **2** and **3**, the $m_I = -1/2$ states, with theoretical maximum polarization $P_z = -1$.

Deuterons with maximum positive or negative vector polarization are produced in the following way: An atomic deuterium beam is polarized in electronic spin by the first sextupole, that is, states **1**, **2**, and **3** are focused and states **4**, **5**, and **6** are defocused (see Figure 5.2). The MF1 transition unit then induces the transition **3** $\rightarrow$ **4**, and the second sextupole then defocuses state **4**. For spin-up polarization, SF induces the transition **2** $\rightarrow$ **6**, so the states **1** and **6** are left populated. Theoretical maximum polarizations are $P_z = +1$ and $P_{zz} = +1$. For spin-down polarization, MF2 induces the transitions **1** $\rightarrow$ **4** and **2** $\rightarrow$ **3**, so the states **3** and **4** are left populated. Theoretical maximum polarizations are $P_z = -1$ and $P_{zz} = +1$. In both deuteron-beam polarization states, beam current is reduced by 1/3 as a result of the transitions.

The nuclear-spin polarized atomic beam then enters the electron cyclotron resonance (ECR) ionizer. The ionizer contains a plasma of high-energy electrons created by exciting N_2 molecules with microwaves. The plasma is contained in a magnetic bottle. Through atomic-electron collisions, the atomic beam is positively ionized. The beam is accelerated to 1.5 keV as it leaves the ionizer.

The beam then enters the cesium oven. In this region the beam passes through cesium vapor, and picks up two electrons through the cesium charge-exchange reaction. The negative-ionization process is approximately 10% efficient. Negative beam is then focused by a set of electrostatic lenses and is accelerated to 3/5 frame voltage (-24 keV) as it enters the Wien filter.

To accommodate experiments requiring a spin axis other than parallel to the axis of the transition units, or to compensate for spin precession through analyzing magnets

Figure 5.2: Hyperfine splitting of hydrogen and deuterium atoms in a magnetic field

further down stream, a Wien filter is used to orient the spin axis. The Wien filter uses a transverse magnetic field to precess the spin axis and a perpendicular electric field to compensate for beam deflection. In addition, the entire Wien filter cavity can be rotated, allowing arbitrary orientation of the spin in both planes. In this experiment, the proton and deuteron spin axis was precessed transverse to the beam axis and vertical (B = 430 G, $\phi = 0$). With the spin axis vertical, no compensation is required for precession through the analyzing magnets. After leaving the Wien filter the beam is focused through a set of lenses, accelerated to the source frame voltage (-80 keV), and enters the TUNL low-energy beam transport facility.

5.1.1 Fast Spin Flip

One of the techniques used to minimize instrumental asymmetries in the neutron-transmission asymmetry measurement is a rapid reversal of beam polarization. Beam polarization is reversed at a rate of 10 Hz in an 8-step sequence ($+--+-++-$) designed to cancel any effects due to detector drifts that are linear or quadratic in time [?]. Spin flipping is controlled by the TUNL Spin State Controller (SSC), which is driven by an external clock input. Spin-flip wiring is shown in Figure 5.3. SSC electronics are documented by Huffman [?].

At each clock pulse, the Fiber$^+$ and Scaler$^+$ outputs are toggled in the 8-step sequence, while the Fiber$^-$ and Scaler$^-$ outputs are toggled in the complementary way. The Fiber$^\pm$ outputs toggle the transition units at the ABPIS which cause the beam polarization to reverse. The Scaler$^\pm$ outputs (TTL) are used to provide spin-state information to the ADC for routing of charged-particle polarimetry data (see Section 5.3.1), and after conversion to NIM level signals, to the hit register for routing of neutron asymmetry data (see Section 5.5.2). The Preset Out output decrements a register in the countdown module. This register is used to index the on-line time-ordered spectra, and when it reaches zero the end of a run is signaled. A run is defined to be 1024 spin-flip sequences ($\approx$ 15 min) for a neutron run and 256 spin-flip sequences ($\approx$ 4 min) for a polarimetry run.

Figure 5.3: Fast spin-flip wiring diagram

Figure 5.4: Veto wiring diagram

Figure 5.5: Timing diagram for the fast spin-flip and veto circuits

Data are vetoed during the time it takes to flip spin. Vetoing is controlled by the polarized target veto module (PTVM) (see Figure 5.4 for a wiring diagram). The veto-module electronics are also documented by Huffman [**?**]. The veto signal proceeds the spin flip by 2 ms, and continues for 5 ms past the spin flip to allow the new polarization state to stabilize. The PTVM also sends a strobe signal 1 ms before the spin-flip to set a LAM in the hit register module to initiate the reading of scalers. A timing diagram of the spin-flip and veto circuits is shown in Figure 5.5.

5.2 Acceleration and Transport

The polarized charged-particle beam is transported from the ion source, through the accelerator, and to the neutron production target. In the low-energy beam transport facility, the beam is analyzed by a 30° bending magnet and focused by electrostatic quadrupoles, magnetic quadrupoles, and an Einzel lens, as shown in Figure 5.6. The beam is then injected into the accelerator.

Charged-particle acceleration is provided by a 10 MV FN tandem Van de Graaff accelerator.[1] Negative ions are accelerated toward the terminal of the accelerator, which is held at a positive potential [?]. In the terminal the beam passes through a thin (between 3 and 10 μg/cm^2) carbon foil, which strips two electrons from each hydrogen or deuterium ion. The positive ion is then accelerated away from the terminal. In this way, the beam is accelerated to an energy of $2eV_{Terminal}$. Transmission through the accelerator varies from 60% at the lowest energies to 90% at higher energies.

The terminal is enclosed in a large steel tank pressurized with a mixture of CO_2, N_2, and SF_6 as insulating gas. Two pelletron charging systems[2] provide charge to the terminal and establish an electrostatic gradient from the terminal to both ends of the tank through columns of alternating layers of stainless steel and glass. Fine terminal voltage stabilization ($\pm$ 50 V) is provided by the terminal stabilizer circuit [?].

After leaving the accelerator the beam enters the high-energy transport facility, shown in Figure 5.7. The beam is analyzed by a 59° bending magnet which fixes the energy of the beam on target. For this reason the magnetic field is regulated by an NMR feedback circuit. A left-right pair of tantalum slits is located after the analyzing magnet to provide feedback for the terminal voltage control circuit: the terminal voltage is adjusted to balance the current measured on these slits. The beam is then transported to the production target via magnetic steerers and magnetic quadrupoles for focusing. Three sets of steerers are controlled by feedback from pairs (left/right, up/down) of tantalum slits located further downstream.

At the entrance to the neutron-production cell is the last pair of feedback slits. A beam-profile monitor[3] allows monitoring of the beam cross section just before the cell. The final 94 cm of beam pipe is made of soft iron 3.2 mm thick to shield the charged-particle beam from fringe magnetic fields near the polarized target. The production cell itself is surrounded

[1] High Voltage Engineering Corporation, Burlington, MA.
[2] National Electrostatic Corporation, Middleton, WI.
[3] National Electrostatic Corporation, Middleton, WI.

by a length of 3.2 mm soft iron pipe. In addition, the last 30 cm of beam pipe and the production target are magnetically shielded with 2 layers of 1 mm thick μ-metal.[4] Deflection of the charged-particle beam due to the fringe field of the superconducting magnet, as observed in the beam scanner, was seen to be negligible.

5.3 Charged-Particle Polarimetry

Since $\Delta\sigma_T$ is proportional to neutron polarization, beam polarization must be accurately known. However, direct measurement of neutron polarization is time consuming and difficult.[5] But with knowledge of charged-particle beam polarization, which is relatively easy to measure, and of the polarization-transfer coefficients of the neutron-production reaction, neutron polarization can be calculated, as discussed in Section 3.2.3. This technique has been exploited throughout these measurements. Charged-particle beam polarization is measured by analyzing reactions and using the TUNL spin-filter polarimeter.

5.3.1 Elastic-Scattering Polarimetry

Scattering of a transversely-polarized beam from an unpolarized target exhibits a left/right asymmetry [?]. By measuring this scattering asymmetry one can deduce polarization of the incident beam (see Section 3.2). Proton-beam polarization is measured using $^4He(\vec{p},p)^4He$ elastic scattering, and deuteron-beam polarization is determined from the $^3He(\vec{d},p)^4He$ reaction.

The charged-particle polarimeter is a machined aluminum scattering chamber cylindrical in shape (30 cm diameter $\times$ 24 cm tall) and mounted on the 59° beamline with the symmetry axis of the chamber oriented 45° from vertical and perpendicular to the beamline axis. The beam passes through the center of the chamber along a diameter. This orientation allows access for left/right and top/bottom detector pairs. The top and bottom lids of the chamber are removable, with the gas cell and charged-particle detectors mounted to

[4] CO-NETIC AA, Magnetic Shield Corporation, Perfection Mica Company.

[5] One such measurement was made during the course of this experiment [?].

Figure 5.6: The TUNL low-energy beam transport facility

Figure 5.7: The TUNL high-energy beam transport facility

the top lid. The chamber is evacuated by the beamline pumping system.

The gas target[6] is a cylindrical cell 2.54 cm diameter $\times$ 3.81 cm long and is made of 2.29×10^{-4} cm thick Havar foil supported by a stainless-steel frame and sealed with A-12 epoxy[7]. The gas-cell frame limits detector access to lab angles of $\phi < 30°$ and $\phi > 75°$ for left/right detectors, and $\theta < 48°$ and $\theta > 133°$ for up/down detectors. The gas cell is fixed at 45° to a 0.953 cm diameter stainless-steel tube through which the cell is filled, and which supports the cell. The gas cell can be inserted and removed from the beam via a sliding o-ring seal, and is filled to slightly over 1 atm with ^{3}He or ^{4}He from a gas manifold. Figure 5.8 shows the scattering chamber, gas cell, and side detectors. The beam is tightly focused to pass through a 4 $\times$ 4 mm aperture formed by steerer feedback slits immediately before the scattering chamber. The beam forms a beamspot of approximately 2 mm diameter on the gas cell.

Scattered protons are detected at side angles and at 0° by positively biased, bottom mount, silicon detectors[8] of 50.0 mm^2 active area and 1000 μm depletion depth. Each side detector is mounted in a holder fixed to one of four (up, down, left, right) detector support arms. These detectors are 9.6 cm from the center of the target cell, but could be positioned at arbitrary angle in 3° increments. Solid-angle acceptance of the side detectors is defined by two tantalum collimating disks held by the detector holder. Tantalum foils are sometimes used to slow the scattered particles so they are fully stopped in the detectors and to stop unwanted heavier charged particles.

The 0° detector, required to measure deuteron-beam tensor polarization, is mounted to the bottom of the gas cell as shown in Figure 5.9. The solid angle of the 0° detector is defined by a tantalum collimating disk, and tantalum slowing foils are also mounted in front of the detector. Since these slowing foils absorbed a significant fraction of the beam energy, they were thermally isolated from the detector assembly by 2 stainless-steel screws, and thermally anchored to the chamber wall by a 2.54 cm wide copper braid. In addition, the

[6]A foil target could be mounted below the gas cell, but this configuration was not used during these measurements.

[7]Armstrong Products Company, Warsaw, IN.

[8]EG&G Ortec Inc., Oak Ridge TN.

beam	gas	ϕ_{lab}	solid angle	slowing foil	solid angle	slowing foil
3 MeV protons	^{4}He	111°	0.5 msrad	–	–	–
8 MeV deuterons	^{3}He	99°	1.5 msrad	20 mil	14 msrad	30 mil

Table 5.1: Operating parameters for the charged-particle polarimeter detectors

detector assembly is thermally isolated from the gas cell (to prevent melting of the A-12) and detector by 3 stainless-steel screws and heat sunk to the chamber by a 1.27 cm braid. Heating of the 0° detector proved to be problematic, and was monitored by observing the leakage current of the detector bias supply. The length of deuteron-beam polarization runs was reduced to minimize heating, and the number of polarimetry runs was reduced to allow the detector time to cool.

Signals from the three solid-state detectors are conditioned by Ortec 142 preamplifiers and Ortec 572 amplifiers, summed together, and fed into a 50 MHz, 1024 channel NS-621 ADC[9]. The ADC is read by the data acquisition computer (see Section 5.5.2 for more detail) when triggered by a LAM generated by the ADC.

Three bits containing detector routing information, obtained from gates generated by Ortec 551 single channel analyzers, are appended to the energy bits through an ADC interface panel. These events are also tagged with two spin-state routing bits and an ADC pile-up bit. Tagging the ADC with routing bits allows the use of just one ADC for all polarimeter detectors. The polarimeter wiring diagram is shown in Figure 5.10.

Polarization measurements were made at 3 MeV proton energy, corresponding to the neutron energy used for the $P_T x$ calibration, and at 8 MeV deuteron energy. Detectors were placed at the angle of maximum analyzing power for protons and at the angle of maximum figure of merit (analyzing power^2 $\times$ cross section) for deuterons. Table 5.1 summarized the operating parameters.

[9]Northern Scientific, Inc., Middleton, WI.

Figure 5.8: A beam's eye view of the polarimeter chamber without the 0° detector

Figure 5.9: Side view of the gas cell with the 0° detector mounted

Figure 5.10: Polarimeter wiring diagram

5.3.2 Spin-Filter Polarimetry

Polarization measurements at 18 MeV deuteron energy were performed with the TUNL spin-filter polarimeter [**?**]. The spin-filter polarimeter, recently installed in the ABPIS, works by exciting metastable atomic states in deuterium, and then quenching the beam. The populations of these atomic states reflect the nuclear polarization, and measurement of the metastable populations (from observing photons emitted during decays) yields the nuclear polarization of the beam.

5.4 Neutron Production

Polarized neutrons are produced by one of three neutron-production reactions. To produce neutrons below 5 MeV, the $^{3}\mathrm{H}(\vec{p},\vec{n})^{3}\mathrm{He}$ reaction with a Q-value of -0.764 MeV is used. For the production of neutrons between 5 and 20 MeV, the $^{2}\mathrm{H}(\vec{d},\vec{n})^{3}\mathrm{He}$ reaction with a Q-value of 3.269 MeV is used. To produce higher-energy neutrons, up to 35 MeV, the ^{3}H($\vec{d},\vec{n}$)^{4}He reaction with a Q-value of 17.590 MeV is used. These reactions have large polarization-transfer coefficients and are used extensively as sources of polarized neutrons. A deuterium gas cell, described in Section 5.4.1, and two tritiated-titanium foils, described in Section 5.4.2, were employed as neutron-production targets.

5.4.1 The Deuterium Gas Target

A gas cell is used to make polarized neutrons via the ^{2}H($\vec{d},\vec{n}$)^{3}He reaction, and is shown in Figure 5.11. A space 6.0 cm long × 1.9 cm diameter is filled with deuterium gas. This space is separated from the beamline vacuum by a 6.35×10^{-4} cm thick Havar window. At the back of the gas cell is a 0.51 mm thick tantalum beamstop to prevent charged particles from leaving the gas cell. A pair of steerer feedback slits immediately before the cell steers the beam on target. Beam current is measured by integrating charge accumulated on the production target. The beamstop is cooled by blowing compressed air on the back of the tantalum disk.

The cell was filled to 3 atm of deuterium gas (giving a deuterium thickness of 3.0 mg/cm^2) during the E_d = 8.0 MeV runs and 4 atm (giving a thickness of 4.0 mg/cm^2) during the E_d = 12.0 and 14.6 MeV runs. A typical count rate in the main neutron detector from this production cell was 15,000 s^{-1} with 300 nA of 8.0 MeV deuteron beam.

The energy of the neutron beam produced by the ^{2}H($\vec{d},\vec{n}$)^{3}He reaction is calculated from the deuteron energy at the center of the gas cell using the computer code RKIN [?]. Deuteron-beam energy losses due to the Havar and 1/2 the thickness of deuterium gas are calculated using the computer code BABEL [?]. Table 5.2 reports these energy-loss calculations. The spread in neutron energy is due mainly to neutron production throughout the length of the gas cell.

5.4.2 The Tritium Foil Target

Tritiated titanium evaporated onto a foil is used to make polarized neutrons via the ^{3}H($\vec{p},\vec{n}$)^{3}He or ^{3}H($\vec{d},\vec{n}$)^{4}He reactions. The production cell is shown in Figure 5.12. A

Figure 5.11: The deuterium gas cell neutron-production target

Beam Location	E_d	E_n	E_d	E_n	E_d	E_n
Havar Entrance	8.00	–	12.00	–	14.60	–
Havar Exit	7.70	–	11.78	–	14.41	–
D_2 Entrance	7.70	11.84	11.78	14.71	14.41	17.19
D_2 Center	7.55	10.70	11.64	14.58	14.29	17.08
D_2 Exit	7.40	10.55	11.50	14.45	14.17	16.96
$\bar{E}_n$ (ΔE_n)	10.70 (0.21)		14.58 (0.18)		17.08 (0.16)	

Table 5.2: Energy-loss calculations through the deuterium gas cell. Energies are in MeV

solid tritium target is used for radiation safety considerations, and as an additional safety precaution, the tritium is isolated from the beamline vacuum by a 3.0 cm buffer space and a 2.29×10^{-4} cm thick Havar window. The foil beamstop is cooled by blowing compressed air onto the back of the foil. The buffer space is filled with 1 atm of ^{4}He gas to provide cooling to the Havar window.

Initially (Aug-Dec 1995), the production foil was a 1.9 cm diameter copper disk 0.051 cm thick onto which was evaporated a 1.1 mg/cm^2 thick layer of titanium that contained "5 Ci/in^2" of tritium ($\approx$ $TiT_{1.4}$). This gives a tritium thickness of 0.03 mg/cm^2. This foil was used during the $K_y^{y'}(0°)$ measurement and during the $P_T x$ calibration for the $\Delta\sigma_T$ measurements at $E_n = 11$, 15, and 17 MeV. A typical neutron count rate with this foil was 2,500 s^{-1} with 700 nA of proton beam.

A second production foil was utilized later (Jan 1996), consisting of a molybdenum disk onto which was evaporated a 2.2 mg/cm^2 layer of titanium which contained "10 Ci/in^2" of tritium ($\approx$ $TiT_{1.4}$), giving a tritium thickness of 0.11 mg/cm^2. This foil was used during the $\Delta\sigma_T$ measurement at $E_n = 35$ MeV and the $P_T x$ calibration for that run. Typical neutron count rates with this foil were 7,000 s^{-1} with 700 nA of 3 MeV proton beam, and 300 s^{-1} with 850 nA of 17.0 MeV deuteron beam.

Energy of the neutron beam produced by the tritium foils is calculated from the charged-particle beam energy at the center of the tritiated titanium layer after accounting for energy loss in the Havar, helium buffer gas, and 1/2 the thickness of tritiated titanium[10]. Table 5.3 reports these energy loss calculations. Spread in neutron-beam energy is due to the finite thickness of the tritiated titanium layer. The energy of the proton beam, as reported by the high-energy analyzing magnet NMR controller, was calibrated against a known neutron cross-section resonance in ^{12}C, as described in [**?**]. Corrections of less than 100 keV were made to the energy given by the NMR setting, and are reflected in Table 5.3.

[10] A uniform tritium density is assumed.

Figure 5.12: The tritiated titanium neutron-production target

Beam Location	E_p	E_n	E_p	E_n	E_p	E_n	E_d	E_n
Havar Entrance	2.91	–	2.95	–	2.99	–	17.08	–
Havar Exit	2.78	–	2.82	–	2.85	–	17.02	–
^{4}He Entrance	2.78	–	2.82	–	2.85	–	17.02	–
^{4}He Exit	2.71	–	2.75	–	2.79	–	16.99	–
$TiT_{1.4}$ Entrance	2.71	1.92	2.75	1.96	2.79	2.01	16.99	34.58
$TiT_{1.4}$ Center	2.66	1.87	2.70	1.91	2.70	1.91	16.95	34.54
$TiT_{1.4}$ Exit	2.61	1.82	2.65	1.86	2.61	1.82	16.91	34.50
$\bar{E}_n$ (spread)	1.87 (0.071)		1.91 (0.071)		1.91 (0.14)		34.54 (0.057)	

Table 5.3: Energy-loss calculations through the tritium cell. Energies are in MeV

Figure 5.13: Experimental setup from the neutron-production target to the detector

5.5 Neutron Detection

5.5.1 Detectors and Collimation

A schematic of the neutron-production cell, polarized target, and neutron detector is shown in Figure 5.13.

Neutrons are detected by a block of proton-rich scintillating material optically coupled to a photomultiplier tube (PMT). Incident neutrons scatter from protons in the scintillator, and the recoiling protons interact with the scintillator material by excitation or ionization. During de-excitation or recombination, light is emitted. When this light strikes the photocathode of the PMT electrons are produced. The number of electrons is increased by secondary emission of electrons through a chain of dynodes held at increasing potentials. This amplified current is collected by the anode.

Pulse height from the PMT is proportional to proton recoil energy[11] and is used to discriminate polarized neutrons from deuteron break-up and background neutrons which are at a lower energy. Since gammas are also detected, it is necessary to discriminate neutrons from gammas. This was done using pulse-shape discrimination [?], which exploits the different fall times for neutron and gamma pulses produced by the PMT.

The 0° (main detector) scintillator is a cylindrical aluminum cell (12.7 cm diameter × 12.7 cm long) with one end made of glass to allow light to exit. The inside of the cell is coated with white reflective paint to reduce light loss. The cell is filled with the liquid organic fluid BC−501[12]. The glass end of the cell is optically coupled to a 12.7 cm diameter R1250 photomultiplier tube[13] and powered by a 14 stage voltage dividing base typically biased to −2200 V.

The 0° detector is mounted in a polyethylene shield 50.8 × 50.8 cm and 55.9 cm long. The detector views a solid angle of 2.5 msrad as defined by a collimator located between the polarized proton target and the detector shield. The collimator is a rectangular block of polyethylene 50.8 × 50.8 cm and 128.3 cm long. The rectangular bore has an entrance aperture of 2.38 × 2.38 cm and an exit aperture of 8.99 × 8.99 cm. The collimator was designed based on a Monte-Carlo simulation using the computer code MCNP [?]. The collimator defines a beam spot at the polarized target of 1.2 × 1.2 cm. Both the collimator and detector shield are mounted separately on linear bearings riding on rails.

Alignment of the neutron-production cell, target cup cooled to 77 K (which contained a copper target for alignment purposes), and collimator was verified with radiography. An X-ray film positioned at the front of the detector shield was exposed with radiation pro-

[11] This is true if all of the recoil energy of the protons is deposited in the scintillator. In practice, pulse heights are observed up to the proton recoil energy.

[12] Bicron Corporation, Newbury, OH.

[13] Hamamatsu Corporation, Bridgewater, NJ.

duced at the production target via the ^{2}H($\vec{d},\vec{n}$)^{3}He reaction. It was verified that the solid angle seen by the detector was completely blocked by the copper target in the target cup.

A monitor detector directly measured the incident neutron flux during ^{2}H($\vec{d},\vec{n}$)^{3}He runs[14]. The monitor detector is a small (11.1 $\times$ 22.2 $\times$ 25.4 mm thick) liquid organic scintillator contained in an aluminum box with a single glass window. The scintillator is located directly after the production target and coupled to a 0.51 cm diameter PMT[15] via a 1 m long light pipe [**?**]. This geometry places the PMT outside the fringe fields of the superconducting magnet.

5.5.2 Neutron-Detector Electronics

Neutron-transmission and polarimetry data were acquired by NIM and CAMAC modules and interfaced to the data acquisition computer, a μ-VAX 3200, by an MBD-11[16] multiple branch driver [**?**]. Data acquisition, sorting, and analysis are performed using the software package TUNL XSYS [**?**].

A diagram of the neutron data acquisition wiring is shown in Figure 5.14. Analog signals from the main neutron detector are fed into a commercially available pulse-shape discrimination module PSD 5020[17]. In addition to pulse-shape discrimination, the Link module can set upper and lower thresholds. Separate output signals corresponding to neutron and gamma events are available as output from the Link module. These signals are sent through a Philips 794 lower level discriminator, a Philips 706 veto module for inhibiting when the crate is disabled (see Section 5.1.1), and finally to a KS 3610[18] scaler module for reading by the computer. The monitor detector signal is fed directly into the Philips 794 for discrimination.

Since the Link module requires at least 300 ns to distinguish between neutrons and gammas [**?**], a dead-time correction is applied to the number of recorded neutron counts.

[14]Neutron flux was not monitored during ^{3}H($\vec{d},\vec{n}$)^{4}He runs due to the large flux of break-up neutrons.
[15]Model R329-02, Hamamatsu Corporation, Bridgewater, NJ.
[16]Bi-Ra Systems, Albuquerque, NM.
[17]Link Analytical Limited, Bucks, England.
[18]Kinetic Systems Corporation, Lockport, Il.

Figure 5.14: Schematic of neutron-detection electronics

The Link's live-time output is inhibited when the module is busy and is used to calculate this dead-time correction. The live-time signal is converted to NIM and then ANDed with a 100 kHz pulser. The "gated" and "ungated" pulser signals pass through the veto module and into the scaler.

Similarly, a 5 MHz pulser and the 500 kHz full scale output from the beam current integrator (BCI) [**?**] are sent to the veto module and into the scaler module. In addition, an inhibit signal from the BCI (inhibited when the beam current falls outside of a set window) is ANDed with the crate inhibit signal for vetoing data. The 5 MHz pulser is used to measure asymmetries in the data acquisition electronics (typically less than a few parts in 10^{-7}), and a BCI asymmetry is calculated and used to correct the measured neutron asymmetries.

Chapter 6

Experimental Procedures

6.1 Measurement of Neutron Asymmetries

Transmission asymmetries for a neutron beam and proton target are measured with beam and target polarizations anti-parallel and parallel. Data are averaged over one beam spin-flip sequence (800 ms of data). Beam-flip sequences with a pulser asymmetry of $> 0.5 \times 10^{-7}$ are vetoed off line. To be counted as valid, main detector events must meet pulse-shape discrimination (PSD) criteria to distinguish neutrons from gammas, and must exceed an energy threshold to distinguish "good" neutrons (produced in the neutron production cell) from "bad" neutrons (deuteron break-up and background neutrons). In particular, when using the $^3\mathrm{H}(\vec{d},\vec{n})^4\mathrm{He}$ reaction to produce 35 MeV neutrons, the break-up of 17 MeV deuterons in the beamstop produces copious quantities of 15 MeV neutrons, which can pile-up in the ADC to nearly 35 MeV. Monitor events only must exceed a threshold.

The effect of this neutron selection process can be seen in energy spectra from the main neutron detector at $E_n = 35$ MeV. Figure 6.1(a) shows a full neutron energy spectrum from the $^3\mathrm{H}(\vec{d},\vec{n})^4\mathrm{He}$ reaction without PSD turned on and without an energy threshold set. Neutrons produced by the $^3\mathrm{H}(\vec{d},\vec{n})^4\mathrm{He}$ reaction extend up to the recoil edge at channel 350. The large low-energy background extending up to around channel 250 is mostly from

(a) Energy spectra without PSD and threshold set (note the log scale)

(b) Energy spectra with PSD and threshold set (note the log scale)

Figure 6.1: Effect of PSD and energy threshold on a neutron detector proton recoil-energy spectrum at $E_n = 35$ MeV. Note that the yields are not normalized

gammas and break-up neutrons piling up in the ADC. Figure 6.1(b) shows the effect of turning on PSD and a setting an energy threshold. The background has been removed, but only around 25% of the ^{3}H$(\vec{d},\vec{n})^4$He neutrons are being counted.

To verify the effectiveness of the neutron selection, a test run was performed using neutron time-of-flight (TOF) techniques. Since gammas will travel to the detector faster than the ^{3}H$(\vec{d},\vec{n})^4$He neutrons, break-up neutrons will be slower, and background events will be uncorrelated, examining a TOF spectra provides insight into the nature of particles getting into the detector. TOF requires a pulsed beam: for this test a pulsed unpolarized beam from the TUNL Direct Extraction Negative Ion Source (DENIS) was used. Otherwise, experimental conditions for the TOF test duplicated the conditions during the $E_n = 35$ MeV $\Delta\sigma_T$ measurement. The flight path was from the neutron production cell to the main neutron detector ($\approx$ 2 m). Figure 6.2(a) shows a TOF spectra with no PSD and no energy threshold cut. The peak at channel 430 is gammas produced at the production target, the peak at channel 240 is 35 MeV neutrons produced by the ^{3}H$(\vec{d},\vec{n})^4$He reaction,

(a) Time-of-flight spectra without PSD and threshold

(b) Time-of-flight spectra with PSD and threshold set

Figure 6.2: Effect of PSD and energy threshold on time of flight (time increasing to the left). Note that yields are not normalized and the time-of-flight delay was changed

and the peak at channel 180 is break-up neutrons. After setting PSD and the energy threshold to the values used during the $\Delta\sigma_T$ measurement, the TOF spectra became as shown in Figure 6.2(b). Both the gammas and break-up neutron peaks have been reduced to negligible levels. Based on this test, we conclude that cutting neutrons based on PSD and recoil energy are satisfactory conditions for selecting $^3\mathrm{H}(\vec{d},\vec{n})^4\mathrm{He}$ neutrons.[1]

With the low-energy background from pile-up of break-up neutrons extending so near the recoil edge, the gain drift of the neutron detectors (discussed in Section 3.1) can cause extraordinary problems. As the gain of the detector increases with count rate the energy threshold effectively decreases. The threshold was routinely set as low (close to the end of the pile-up tail) as possible to maximize count rate. Therefore, an increase in gain (decrease in threshold) could allow pile-up neutrons to exceed the threshold cut. Break-up

[1] More recent TOF tests using pulsed polarized beam which allow examining a 2-dimensional spectrum of recoil energy vs. TOF suggest that cutting with PSD and a threshold will allow a background as large as 100% of the $^3\mathrm{H}(\vec{d},\vec{n})^4\mathrm{He}$ neutrons to be counted as valid. These are events widely scattered in time-of-flight and are probably pile-up.

neutrons have a lower polarization than $^3\mathrm{H}(\vec{d},\vec{n})^4\mathrm{He}$ neutrons[?], and since $\Delta\sigma_T$ is slowly varying with energy down to $E_n = 10$ MeV, this leakage would cause a dilution of the measured transmission asymmetry.

In an effort to minimize this effect, the neutron yield (number of neutrons per BCI) was monitored during the 35 MeV $\Delta\sigma_T$ measurement. Since an increase in neutron yield signals that part of the break-up tail is making the threshold cut, the main detector threshold was adjusted periodically (several times a day) during the run to maintain a neutron yield below a predetermined value.

6.2 Measurement of Beam Polarizations

6.2.1 Proton Polarization

Figure 6.3 are typical energy spectra from one polarimeter detector (the left detector) for both proton spin states. The elastically-scattered proton peak at channel 380 shows an asymmetry. To determine the number of counts in the peak a linear background is fit and subtracted from the spectrum. A gate is then set around the peak and the area within the gate is calculated. A channel-by-channel asymmetry, like the one in Figure 6.4(a) is a useful tool for determining where to set the gates. In this figure, an asymmetry is calculated for each energy bin and plotted with statistical error bars.

6.2.2 Deuteron Polarization

Figure 6.5 are typical energy spectra from one polarimeter detector (the left detector) for both deuteron spin states($\pm P_d$) and the 0° detector for $+P_d$. The peaks at channel 500 in the side detectors are protons produced by the $^3\mathrm{He}(\vec{d},p)^4\mathrm{He}$ reaction and show an asymmetry. The background in the 0° detector spectra is rather mysterious and probably due to excessive count rate and heating, and is not physical. To determine the number of counts in the peak an exponential background is fit and subtracted from the spectrum. A gate is then set around the peak and the area within the gate is calculated. A channel-by-

(a) Left polarimeter detector, $+P_p$

(b) Left polarimeter detector, $-P_p$

Figure 6.3: Energy spectra for 3 MeV protons elastically scattered from ^{4}He into the left polarimeter detector for spin-up and spin-down beam polarizations. The smaller peak at higher energy is protons scattering from Havar

(a) Channel-by-channel proton asymmetry

(b) Channel-by-channel deuteron asymmetry

Figure 6.4: Channel-by-channel asymmetries calculated with the left polarimeter detector. Error bars are from counting statistics. The region with small error bars corresponds to the proton peaks

channel asymmetry, like the one in Figure 6.4(b) was used to determining where to set the gates.

(a) Left polarimeter detector, $+P_d$

(b) Left polarimeter detector, $-P_d$

(c) Center polarimeter detector

Figure 6.5: Energy spectra for protons produced by the $^3\mathrm{He}(\vec{d},p)^4\mathrm{He}$ reaction with 8 MeV incident deuterons. The left detector with spin-up and spin-down beam polarizations and the 0° detector are shown

Chapter 7

Results

This chapter presents results of the $\Delta\sigma_T$ measurements. Neutron asymmetry measurements are summarized in Section 7.1. Beam polarization measurements are summarized in Section 7.2. In Section 7.3 target polarization $\times$ thickness $P_T x$ is computed for the two targets used during these measurements, and in Section 7.4 $\Delta\sigma_T$ is calculated.

7.1 Neutron Asymmetries

Neutron asymmetries were measured at the neutron energies listed in Table 7.1. The two lowest energy measurements, at $E_n = 1.91$ MeV and $E_n = 1.92$ MeV, were made to calibrate target polarization $\times$ thickness $P_T x$ of the targets: the target used for $\Delta\sigma_T$ measurements at $E_n = 10.70$, 14.58, and 17.08 MeV[1] was calibrated at $E_n = 1.92$ MeV, and the target used to measure $\Delta\sigma_T$ at $E_n = 34.67$ MeV[2] was calibrated at $E_n = 1.91$ MeV. The number of valid beam spin-flip sequences measured at each energy is listed as n in Table 7.1, with roughly 1/2 the counts in each target polarization state. A spin-flip sequence is defined as an 8-step beam polarization sequence $+--+-++-$, which is 800 ms of data. To be considered a valid spin-flip sequence the *time* spent in the $\pm$ spin states must form an asymmetry less than 0.0005×10^{-4}. All neutron asymmetry analysis is performed on 8-step

[1] These measurements were made in December 1995.

[2] This measurement was made in January 1996.

E_n (MeV)	Use	n	P_T Sequence
1.91	$P_T x$	48,103	$-++-$
1.92	$P_T x$	24,526	$+-$
10.70	$\Delta\sigma_T$	71,385	$-++-$
14.58	$\Delta\sigma_T$	62,837	$-++$
17.08	$\Delta\sigma_T$	67,568	$+--+$
34.67	$\Delta\sigma_T$	450,058	$+--+-++-+--$
			$++-+--+-++-$
			$+--+-++--+-$
			$++-+--+-++-$

Table 7.1: Summary of neutron asymmetry measurements

sequences. Data were collected in $\pm$ target polarization pairs in the order indicated by pluses and minuses in Table 7.1 to minimize systematic effects due to time drifts. Approximately 4 hours of data were collected during each target polarization state.

Results of the neutron asymmetry measurements are given in Tables 7.2 through 7.5. These tables report the measured neutron transmission asymmetries $\varepsilon_{\tilde{N}}$ (obtained from the intercept of the $(\varepsilon_{\tilde{N}} - \varepsilon_\delta)$ vs. ε_I plot in Figure 3.4) and ξ' (slope in Figure 3.4) for the main detector ($\varepsilon_{\tilde{N}_n}$ and ξ'_n) and for the monitor detector ($\varepsilon_{\tilde{N}_m}$ and ξ'_m) when it was used. Statistical uncertainty $\Delta\varepsilon_{\tilde{N}}$ and standard deviation $\sigma_{\varepsilon_{\tilde{N}}}$, as defined by Equations 3.63 and 3.64, are reported for each measured asymmetry. The uncertainty in $\xi'_{n,m}$ is from the least squares determination of the slope. The average slopes ξ'_n for asymmetries measured at both of the $P_T x$ calibration energies are consistent with a linear detector behavior $[\bar{\xi_n}' = 1.01 \pm 0.010\ (0.028)]$, and so ξ'_n is taken to be 1.0 for these calculations.

Figure 7.1 shows typical plots of $(\tilde{N}_n - \varepsilon_\delta)$ vs. ε_I for the main detector at the neutron energies where measurements were made. Figure 7.1 shows similar plots of $\tilde{N}_m$ vs. ε_I for the monitor detector. Each plot represents data from measurement of one target polarization state.

The neutron asymmetries corrected for dead-time asymmetries, detector gain drifts,

E_n (MeV)		$\varepsilon_{\tilde{N}_n} \pm \Delta\varepsilon_{\tilde{N}_n} (\sigma_{\varepsilon_{\tilde{N}_n}})$	$\xi'_n \pm \Delta\xi'_n$	$\varepsilon_{\tilde{N}_m} \pm \Delta\varepsilon_{\tilde{N}_m} (\sigma_{\varepsilon_{\tilde{N}_m}})$	$\xi'_m \pm \Delta\xi'_m$	$(\varepsilon_n)_+ \pm \Delta^{stat}_{\varepsilon_n} \pm \Delta^{sys}_{\varepsilon_n}$
1.91	A_-	70.92 ± 0.850 (0.838)	1.000 ± –	– ± – –	– ± –	70.92 ± 0.850 ± –
	B_-	73.32 ± 0.892 (1.007)	1.000 ± –	– ± – –	– ± –	73.32 ± 0.892 ± –
					average:	72.06 ± 0.615 ± –
1.92	A_+	72.66 ± 1.423 (1.388)	1.000 ± –	– ± – –	– ± –	72.66 ± 1.423 ± –
10.70	A_+	45.51 ± 0.495 (0.500)	1.023 ± 0.0137	48.57 ± 0.238 (0.260)	1.168 ± 0.0066	2.907 ± 0.525 ± 0.642
	B_+	43.68 ± 0.497 (0.511)	1.000 ± 0.0289	45.24 ± 0.254 (0.261)	1.120 ± 0.0148	3.307 ± 0.547 ± 1.371
					average:	3.099 ± 0.379 ± 0.581
14.58	A_+	49.26 ± 0.713 (0.531)	1.191 ± 0.0089	16.84 ± 0.201 (0.146)	1.092 ± 0.0025	25.94 ± 0.626 ± 0.309
17.08	A_+	46.68 ± 0.514 (0.560)	1.209 ± 0.0104	24.84 ± 0.198 (0.226)	1.249 ± 0.0040	18.72 ± 0.454 ± 0.337
	B_+	42.83 ± 0.498 (0.533)	1.264 ± 0.0054	18.19 ± 0.195 (0.224)	1.296 ± 0.0021	19.85 ± 0.422 ± 0.146
					average:	19.33 ± 0.309 ± 0.134

Table 7.2: Neutron asymmetries for $+P_T$ at $E_n \approx 2, 11, 15,$ and 17 MeV. Asymmetries are $\times 10^{-4}$

E_n (MeV)		$\varepsilon_{\tilde{N}_n} \pm \Delta\varepsilon_{\tilde{N}_n} (\sigma_{\varepsilon_{\tilde{N}_n}})$	$\xi'_n \pm \Delta\xi'_n$	$\varepsilon_{\tilde{N}_m} \pm \Delta\varepsilon_{\tilde{N}_m} (\sigma_{\varepsilon_{\tilde{N}_m}})$	$\xi'_m \pm \Delta\xi'_m$	$(\varepsilon_n)_- \pm \Delta^{stat}_{\varepsilon_n} \pm \Delta^{sys}_{\varepsilon_n}$
1.91	A₋	−92.39 ± 0.882 (0.909)	1.000 ± –	– ± – –	– ± –	−92.39 ± 0.882 ± –
	B₋	−92.13 ± 0.882 (0.938)	1.000 ± –	– ± – –	– ± –	−92.13 ± 0.882 ± –
					average:	−92.26 ± 0.624 ± –
1.92	A₋	−108.2 ± 1.440 (1.454)	1.000 ± –	– ± – –	– ± –	−108.2 ± 1.440 ± –
10.70	A₋	87.82 ± 0.481 (0.560)	1.031 ± 0.0097	52.65 ± 0.235 (0.401)	1.176 ± 0.0048	40.39 ± 0.507 ± 0.825
	B₋	83.69 ± 0.643 (0.522)	1.057 ± 0.0199	46.84 ± 0.322 (0.267)	1.161 ± 0.0100	38.83 ± 0.668 ± 1.532
					average:	39.82 ± 0.402 ± 0.726
14.58	A₋	90.61 ± 0.590 (0.636)	1.196 ± 0.0106	15.21 ± 0.167 (0.215)	1.104 ± 0.0030	61.98 ± 0.517 ± 0.675
	B₋	89.74 ± 0.697 (0.632)	1.162 ± 0.0113	15.21 ± 0.195 (0.178)	1.080 ± 0.0032	63.15 ± 0.627 ± 0.753
					average:	62.45 ± 0.399 ± 0.503
17.08	A₋	85.39 ± 0.520 (0.574)	1.282 ± 0.0058	22.89 ± 0.201 (0.245)	1.273 ± 0.0022	50.22 ± 0.444 ± 0.318
	B₋	83.00 ± 0.519 (0.660)	1.268 ± 0.0062	18.97 ± 0.202 (0.307)	1.299 ± 0.0024	50.88 ± 0.438 ± 0.320
					average:	50.55 ± 0.312 ± 0.227

Table 7.3: Neutron asymmetries for $-P_T$ at $E_n \approx 2, 11, 15$, and 17 MeV. Asymmetries are $\times 10^{-4}$

E_n (MeV)		$\varepsilon_{\tilde{N}_n} \pm \Delta\varepsilon_{\tilde{N}_n}\,(\sigma_{\varepsilon_{\tilde{N}_n}})$	$\xi'_n \pm \Delta\xi'_n$	$(\varepsilon_n)_+ \pm \Delta^{stat}_{\varepsilon_n} \pm \Delta^{sys}_{\varepsilon_n}$
34.67	A_+	102.66 ± 6.287 (6.502)	2.396 ± 0.1137	42.82 ± 2.624 ± 2.032
	B_+	113.47 ± 5.168 (4.982)	2.282 ± 0.1474	49.72 ± 2.264 ± 3.212
	C_+	111.76 ± 7.317 (7.259)	1.980 ± 0.1964	56.43 ± 3.695 ± 5.597
	D_+	110.22 ± 4.692 (4.837)	2.108 ± 0.0976	52.27 ± 2.225 ± 2.420
	E_+	105.44 ± 4.469 (6.330)	1.588 ± 0.1673	66.39 ± 4.074 ± 6.994
	F_+	117.48 ± 6.530 (6.646)	2.300 ± 0.1250	51.05 ± 2.839 ± 2.775
	G_+	106.26 ± 8.370 (7.267)	1.887 ± 0.1983	56.30 ± 4.434 ± 5.916
	H_+	96.32 ± 6.566 (7.217)	2.248 ± 0.1570	42.82 ± 2.921 ± 2.991
	I_+	95.60 ± 5.217 (5.221)	2.561 ± 0.1512	37.31 ± 2.037 ± 2.203
	J_+	116.43 ± 5.906 (5.950)	3.174 ± 0.1940	36.66 ± 1.891 ± 2.241
	K_+	117.38 ± 7.505 (6.783)	3.095 ± 0.2108	37.93 ± 2.425 ± 2.583
	L_+	108.54 ± 9.079 (6.490)	2.904 ± 0.2308	37.42 ± 3.126 ± 2.974
	M_+	97.89 ± 8.253 (7.211)	2.355 ± 0.2029	41.63 ± 3.504 ± 3.587
	N_+	104.04 ± 6.109 (5.619)	2.646 ± 0.2095	39.31 ± 2.309 ± 3.112
	O_+	140.32 ± 5.502 (5.542)	2.939 ± 0.2145	47.40 ± 1.872 ± 3.459
	P_+	111.14 ± 5.914 (5.936)	2.424 ± 0.1893	45.83 ± 2.439 ± 3.579
	Q_+	133.62 ± 4.876 (4.944)	1.846 ± 0.1599	72.34 ± 2.641 ± 6.266
	R_+	141.43 ± 5.461 (5.309)	2.298 ± 0.1720	61.53 ± 2.376 ± 4.605
	S_+	129.73 ± 4.875 (5.158)	2.386 ± 0.1529	54.36 ± 2.043 ± 3.484
	T_+	85.99 ± 5.938 (6.019)	2.722 ± 0.2069	31.59 ± 2.182 ± 2.401
	U_+	88.21 ± 6.559 (6.689)	2.915 ± 0.2137	30.26 ± 2.250 ± 2.218
	V_+	72.71 ± 7.201 (8.260)	2.961 ± 0.2862	24.54 ± 2.432 ± 2.372
			average:	44.59 ± 0.526 ± 0.626

Table 7.4: Neutron asymmetries for $+P_T$ at $E_n \approx 35$ MeV. The standard deviation of the distribution is $\sigma_{\varepsilon_n} = 2.429$. All asymmetries are $\times 10^{-4}$

E_n (MeV)		$\varepsilon_{\tilde{N}_n} \pm \Delta\varepsilon_{\tilde{N}_n} (\sigma_{\varepsilon_{\tilde{N}_n}})$	$\xi'_n \pm \Delta\xi'_n$	$(\varepsilon_n)_- \pm \Delta^{stat}_{\varepsilon_n} \pm \Delta^{sys}_{\varepsilon_n}$
34.67	A_-	130.64 ± 4.516 (4.978)	2.422 ± 0.0760	53.90 ± 1.864 ± 1.691
	B_-	113.27 ± 5.030 (4.870)	1.925 ± 0.1268	58.80 ± 2.613 ± 3.873
	C_-	116.68 ± 6.452 (5.897)	2.253 ± 0.1525	51.77 ± 2.864 ± 3.504
	D_-	126.64 ± 8.105 (8.276)	1.984 ± 0.1862	63.79 ± 4.085 ± 5.987
	E_-	139.47 ± 4.779 (5.282)	2.275 ± 0.0993	61.30 ± 2.101 ± 2.676
	F_-	113.92 ± 7.117 (6.405)	2.436 ± 0.1077	46.68 ± 2.922 ± 2.064
	G_-	132.33 ± 6.677 (6.867)	2.315 ± 0.1765	57.15 ± 2.885 ± 4.357
	H_-	125.68 ± 6.248 (4.840)	2.614 ± 0.1809	48.07 ± 2.391 ± 3.327
	I_-	156.63 ± 5.338 (5.336)	2.711 ± 0.1711	57.71 ± 1.969 ± 3.642
	J_-	153.88 ± 5.901 (5.849)	2.603 ± 0.2035	59.02 ± 2.267 ± 4.614
	K_-	142.91 ± 7.144 (5.675)	2.921 ± 0.2008	48.89 ± 2.445 ± 3.361
	L_-	151.33 ± 6.987 (7.593)	3.109 ± 0.1443	48.66 ± 2.248 ± 2.259
	M_-	131.41 ± 7.386 (6.381)	2.451 ± 0.2463	53.59 ± 3.014 ± 5.852
	N_-	119.11 ± 6.094 (4.913)	2.605 ± 0.1506	45.72 ± 2.339 ± 2.643
	O_-	136.77 ± 5.216 (5.669)	2.990 ± 0.1783	45.65 ± 1.745 ± 2.722
	P_-	140.49 ± 6.168 (5.614)	1.929 ± 0.2252	72.73 ± 3.197 ± 8.491
	Q_-	165.25 ± 5.414 (5.762)	2.365 ± 0.1762	69.85 ± 2.289 ± 5.204
	R_-	177.85 ± 5.818 (6.467)	2.438 ± 0.1636	72.93 ± 2.387 ± 4.894
	S_-	131.54 ± 5.761 (6.201)	2.345 ± 0.1693	56.08 ± 2.457 ± 4.049
	T_-	101.06 ± 6.052 (5.722)	2.600 ± 0.2185	38.86 ± 2.328 ± 3.266
	U_-	109.22 ± 6.489 (6.233)	3.264 ± 0.2244	33.46 ± 1.988 ± 2.300
	V_-	101.50 ± 6.985 (7.546)	2.966 ± 0.0736	34.19 ± 2.355 ± 0.848
			average:	52.43 ± 0.504 ± 0.528

Table 7.5: Neutron asymmetries for $-P_T$ at $E_n \approx 35$ MeV. The standard deviation of the distribution is $\sigma_{\varepsilon_n} = 2.319$. All asymmetries are $\times 10^{-4}$

E_n (MeV)		$(\varepsilon_n)_+ \pm \Delta\varepsilon_n$	$(\varepsilon_n)_- \pm \Delta\varepsilon_n$	$\bar{\varepsilon}_n \pm \Delta\bar{\varepsilon}_n$
34.67	A	53.90 ± 2.517	42.82 ± 3.319	5.54 ± 2.083
	B	58.80 ± 4.672	49.72 ± 3.930	4.54 ± 3.053
	C	51.77 ± 4.526	56.43 ± 6.707	−2.33 ± 4.046
	D	63.79 ± 7.248	52.27 ± 3.287	5.76 ± 3.979
	E	61.30 ± 3.402	66.39 ± 6.994	−2.55 ± 3.889
	F	46.68 ± 3.578	51.05 ± 3.970	−2.19 ± 2.672
	G	57.15 ± 5.226	56.30 ± 7.393	0.42 ± 4.527
	H	48.07 ± 4.097	42.82 ± 4.181	2.63 ± 2.927
	I	57.71 ± 4.140	37.31 ± 3.004	10.20 ± 2.558
	J	59.02 ± 5.141	36.66 ± 2.932	11.18 ± 2.959
	K	48.89 ± 4.156	37.93 ± 3.543	5.48 ± 2.731
	L	48.66 ± 3.187	37.42 ± 4.315	5.62 ± 2.680
	M	53.59 ± 6.583	41.63 ± 5.014	5.98 ± 4.138
	N	45.72 ± 2.643	39.31 ± 3.875	3.21 ± 2.345
	O	45.65 ± 3.233	47.40 ± 3.933	−1.03 ± 2.546
	P	72.93 ± 9.073	45.83 ± 4.331	13.45 ± 5.027
	Q	69.85 ± 5.685	72.34 ± 6.800	−1.25 ± 4.432
	R	72.93 ± 5.445	61.53 ± 5.182	5.70 ± 3.758
	S	56.08 ± 4.736	54.36 ± 4.039	0.86 ± 3.112
	T	38.86 ± 4.011	31.59 ± 3.244	3.64 ± 2.579
	U	33.46 ± 3.040	30.26 ± 3.159	1.60 ± 2.192
	V	34.19 ± 2.503	24.54 ± 3.389	4.83 ± 2.107
			average:	3.97 ± 0.62

Table 7.6: Neutron asymmetry differences $\bar{\varepsilon}_n$ computed pairwise for $E_n = 35$ MeV. The standard deviation of the distribution is $\sigma_{\varepsilon_n} = 0.923$. All asymmetries are $\times 10^{-4}$

(a) $E_n = 1.91$ MeV; $\xi'_n = 1.029$

(b) $E_n = 10.70$ MeV; $\xi'_n = 1.031$

(c) $E_n = 14.58$ MeV; $\xi'_n = 1.196$

(d) $E_n = 17.08$ MeV; $\xi'_n = 1.282$

(a) $E_n = 10.70$ MeV; $\xi'_m = 1.176$

(b) $E_n = 14.58$ MeV; $\xi'_m = 1.104$

(c) $E_n = 17.08$ MeV; $\xi'_m = 1.273$

Figure 7.2: Plots of the measured neutron asymmetry for the monitor detector binned in beam current asymmetry [$\varepsilon_{\tilde{N}_m}$ vs. ε_I] and the weighted least-squares fit. Error bars are obtained from counting statistics

and normalized to the monitor detector $(\varepsilon_n)_\pm$ are calculated according to Equation 3.60

$$(\varepsilon_n)_\pm = \left(\frac{\varepsilon_{\tilde{N}_n} - \varepsilon_\delta}{\xi'_n} - \frac{\varepsilon_{\tilde{N}_m}}{\xi'_m} \right)_\pm$$

for each target spin state, where $\varepsilon_{\tilde{N}_m} = 0$ when no monitor was used. The $(\varepsilon_n)_\pm$ are listed in the right-most column of Tables 7.2 through 7.5. Dead-time asymmetries ε_δ are typically less than 0.05×10^{-4} at $E_n = 2, 11$, and 35 MeV, and less than 0.5×10^{-4} for $E_n = 15$ and 17 MeV.

Uncertainty in the $(\varepsilon_n)_\pm$ due to counting statistics is identified as $\Delta^{stat}_{\varepsilon_n}$. Uncertainty in $(\varepsilon_n)_\pm$ due to the $\Delta\xi'_{n,m}$ is a systematic uncertainty and is identified as $\Delta^{sys}_{\varepsilon_n}$. For the purpose of reporting the overall uncertainty in the neutron asymmetry measurement, these uncertainties are added in quadrature and labeled $\Delta\bar{\varepsilon}_n$ in Table 7.7.

For measurements of $\Delta\sigma_T$ below 20 MeV, neutron asymmetries were measured for one or two target polarization pairs. When two measurements of a particular asymmetry $(\varepsilon_n)_\pm$ were made, a statistically weighted average is calculated with the uncertainty in the average computed in the usual way. From these average plus and minus target polarization asymmetries at each energy, the average asymmetry $\bar{\varepsilon}_n$, defined $\bar{\varepsilon}_n = \frac{1}{2}[(\varepsilon_n)_+ - (\varepsilon_n)_-]$ is calculated at each energy.

In the case of $\Delta\sigma_T$ at $E_n = 35$ MeV, where 22 measurements were made for each target polarization state, pairwise average asymmetries $\bar{\varepsilon}_n$ are calculated and are listed in Table 7.6. These pairwise averages are then averaged over all target polarization pairs. This pairwise method is used to more closely correlate in time measurements of the $+/-$ target polarization asymmetries and therefore reduce the effect of systematics which drift in time. The standard deviation $\sigma_{\varepsilon_{\tilde{N}}}$ of the distribution of pairwise $\bar{\varepsilon}_n$ is given in the caption of Table 7.6. In contrast, the standard deviation of the distribution of the ε_n obtained from averaging separately the $\pm P_T$ asymmetries $(\varepsilon_n)_\pm$ and then calculating $\bar{\varepsilon}_n$ (as the lower energy data was analyzed) is 35% larger.

However, the standard deviation of the distribution of 35 MeV neutron asymmetries is still 50% larger than expected from counting statistics. Examining a histogram of the

E_n (MeV)	$\bar{\varepsilon}_n \pm \Delta\bar{\varepsilon}_n$
1.91	-82.2 ± 0.44
1.92	-90.4 ± 1.01
11.70	18.4 ± 0.54
14.58	18.3 ± 0.47
17.08	15.6 ± 0.47

Table 7.7: Final neutron asymmetry averages $\bar{\varepsilon}_n = \frac{1}{2}[(\varepsilon_n)_+ - (\varepsilon_n)_-]$. Asymmetries are $\times 10^{-4}$

22 target polarization pairs, as in Figure 7.3 demonstrates why this is so. The gaussian curve in the figure has a mean neutron asymmetry based on the VPI partial-wave analysis prediction of $\Delta\sigma_T$ (SAID, FA95 solution) and a width based on the counting statistics of our measurement. Clearly, the neutron asymmetry measurement at 35 MeV was not replicate sampling: the Shapiro-Wilk W normality test [?] indicates only a 23% probability that the data is taken from a gaussian distribution. We conclude then that there were systematic effects which were not eliminated or accounted for during the measurement, for example fluctuations in the deuteron beam tensor polarization, in determining ξ_n, or in neutron selection.[3]

For this reason the measurement of $\Delta\sigma_T$ at 35 MeV will not be included in subsequent analysis. However, another measurement near 35 MeV is currently underway. For this new measurement we are using a pulsed polarized beam to allow neutron selection using time-of-flight techniques, the neutron detector bases have been transistorized [?] to address the non-linear gain issue, and refinements to the high-energy deuteron polarimeter now allows reliable polarimetery.

Finally, Table 7.7 summarizes the neutron asymmetry averages $\bar{\varepsilon}_n$ used in subsequent calculations. The uncertainty $\Delta\varepsilon_n$ includes $\Delta^{stat}_{\varepsilon_n}$ and $\Delta^{sys}_{\varepsilon_n}$ from both target polarization states added in quadrature.

[3]Chapter 6 details neutron selection techniques used in these measurements.

Figure 7.3: Histogram of 35 MeV neutron asymmetries calculated pairwise. The gaussian curve is a distribution with a mean neutron asymmetry based on $\Delta\sigma_T$ predicted by SAID (FA95 solution) and a width based on counting statistics of the 35 MeV measurement

7.2 Beam Polarization

Neutron-beam polarization was determined from measurements of charged-particle beam polarization and from measured or previously known polarization transfer-coefficients of neutron production reactions. Charged-particle beam polarization was determined by measuring a left/right scattering asymmetry and from the known analyzing powers of analyzing reactions, or with the TUNL spin-filter polarimeter. In this section, determination of the polarization-transfer coefficients (Section 7.2.1) and analyzing powers (Section 7.2.2) is discussed, and results of charged-particle beam polarization measurements are presented (Section 7.2.3). Finally, calculation of the neutron-beam polarizations are reported (Section 7.2.4).

7.2.1 Polarization-Transfer Coefficients

The ^{3}H($\vec{p},\vec{n}$)^{3}He reaction as a source of polarized neutrons has been well studied above $E_n = 2$ MeV.[4] Since we are interested in producing transversely-polarized neutrons below 2 MeV for the P_Tx calibration, a measurement of $K_y^{y'}(0°)$ was performed at $E_n = 1.88$ MeV [?]. Our measured value of $K_y^{y'}(0°) = 0.655 \pm 0.0214$ is consistent with an earlier measurement of Wilburn [?] at $E_n = 1.94$ MeV, which determined the transfer coefficient to be $K_y^{y'}(0°) = 0.656 \pm 0.036$. Since these two measurements agree and bracket the energies used for both P_Tx calibrations, our measured value of $K_y^{y'}(0°)$ will be used in subsequent calculations.

The ^{2}H($\vec{d},\vec{n}$)^{3}He reaction is a prolific source of polarized neutrons between 5 and 20 MeV. The transverse vector and tensor polarization-transfer coefficients $K_y^{y'}(0°)$ and $A_{yy}(0°)$ for the ^{2}H($\vec{d},\vec{n}$)^{3}He reaction were obtained from Lisowski [?]. To determine the coefficients at the deuteron energies of interest, a least-squares linear fit in deuteron energy is made to the published $K_y^{y'}(0°)$ data above $E_d = 4$ MeV. The published $A_{yy}(0°)$ data above $E_d = 3$ MeV appear energy independent, a weighted average value of $A_{yy}(0°)$ is calculated. The average $A_{yy}(0°)$ and interpolated values of $K_y^{y'}(0°)$ at $E_d = 8.0$, 12.0, and 14.6 MeV are listed in Table 7.8. Uncertainty in $K_y^{y'}(0°)$ is obtained from uncertainty in the fit parameters, and uncertainty in $A_{yy}(0°)$ is the standard deviation of the distribution of measurements.

The ^{3}H($\vec{d},\vec{n}$)^{4}He reaction, with a Q-value of 17.6 MeV, is used to produce polarized neutrons above 20 MeV. Transverse vector and tensor polarization-transfer coefficients for the ^{3}H($\vec{d},\vec{n}$)^{4}He reaction were obtained from Broste [?]. In this paper, measurements were made up to $E_d = 15$ MeV. To extrapolate to $E_d = 17.0$ MeV, a spline is fit [?] to the $K_y^{y'}(0°)$ data which is rapidly approaching the theoretical maximum value of 2/3, and a least-squares linear fit is made to the $A_{yy}(0°)$ data. Extrapolated values of $K_y^{y'}(0°)$ and $A_{yy}(0°)$ at $E_d = 17.0$ MeV are listed in Table 7.8. Uncertainty in $K_y^{y'}(0°)$ is estimated from the "goodness" of the spline fit, and uncertainty in $A_{yy}(0°)$ is determined from uncertainty

[4] Measurements of $K_y^{y'}(0°)$ from LANL and TUNL are tabulated in [?].

reaction	$E_{p(d)}$ (MeV)	E_n (MeV)	$K_y^{y'}(0°)$	$\pm\ \Delta K_y^{y'}$	$A_{yy}(0°)$	$\pm\ \Delta A_{yy}$
^{3}H($\vec{p},\vec{n}$)^{3}He	2.99	1.91	0.655	± 0.0227	–	± –
	2.95	1.92	0.655	± 0.0227	–	± –
^{2}H($\vec{d},\vec{n}$)^{3}He	8.0	10.70	0.638	± 0.0077	0.231	± 0.0011
	12.0	14.58	0.624	± 0.0094	0.231	± 0.0011
	14.6	17.08	0.615	± 0.0107	0.231	± 0.0011
^{3}H($\vec{d},\vec{n}$)^{4}He	17.00	34.67	0.58	± 0.01	0.32	± 0.08

Table 7.8: Polarization-transfer coefficients for the three neutron-production reactions ^{3}H($\vec{p},\vec{n}$)^{3}He, ^{2}H($\vec{d},\vec{n}$)^{3}He, and ^{3}H($\vec{d},\vec{n}$)^{4}He

in the least squares fit parameters.

7.2.2 Analyzing Powers

The analyzing power A_y for the ^{4}He($\vec{p},p$)^{4}He reaction was calculated from the explicit partial-wave expansion of the elastic scattering amplitude for spin 1/2 particles found in Satchler [?] using the FORTRAN code PHE4 (see Appendix A). Phase shifts were obtained from the effective-range parameterization provided in Schwandt [?]. This code allows the phase shifts to be determined at arbitrary energy and angle. Figure 7.4 is a contour plot of the calculated ^{4}He($\vec{p},p$)^{4}He analyzing power, with the energy and angle of our measurements indicated by the $\odot$. Values of A_y for proton energies at the center of the polarimeter gas cell ($E_p = 2.79$ MeV corresponding to $E_n = 1.92$ MeV, and $E_p = 2.83$ MeV corresponding to $E_n = 1.91$ MeV) at $\theta_{lab} = 99°$ are listed in Table 7.9. Uncertainty in A_y arises from estimates of the uncertainties in proton energy and detector angle.

^{3}He($\vec{d},p$)^{4}He analyzing powers were calculated from Legendre-polynomial coefficients found in Bittcher [?]. The analyzing powers at $E_d = 8.0$ MeV are listed in Table 7.10. T_{22}^C (which is 0 at 0°) and T_{20}^C were computed by integrating T_{22} and T_{20} over the solid angle subtended by the 0° detector ($\Delta\theta = 7°$). Since uncertainties in the individual ^{3}He($\vec{d},p$)^{4}He analyzing power measurements from [?] were typically 0.005, the uncertainty in calculating analyzing powers from the Legendre-polynomial fit is considerably lower, and therefore neglected in calculating deuteron-beam polarization.

E_p (MeV)	$A_y \pm \Delta A_y$
2.79	0.897 ± 0.005
2.83	0.898 ± 0.005

Figure 7.4: Contour plot of ^{4}He$(\vec{p},p)^4$He analyzing power. Measurements were made at the points indicated by the $\odot$

Table 7.9: ^{4}He$(\vec{p},p)^4$He analyzing powers at the angle $\theta_{lab} = 99^\circ$

E_d (MeV)	iT_{11}	T_{20}	T_{22}	T_{20}^C	T_{22}^C
8.0	0.658	−0.0323	−0.294	−1.131	−0.00932

Table 7.10: Analyzing powers for the ^{3}He$(\vec{d},p)^4$He reaction at $E_d = 8.0$ MeV and $\theta_{lab} = 111^\circ$

7.2.3 Charged-Particle Beam Polarization

Recall from Section 3.2.1 that the average of spin-up and spin-down proton polarization is calculated from

$$P_p = \frac{1}{A_y}\frac{\sqrt{\gamma}-1}{\sqrt{\gamma}+1},$$

where γ is a ratio of counts in the left and right polarimeter detectors. Proton-beam polarization was measured with the $^4\mathrm{He}(\vec{p},p)^4\mathrm{He}$ reaction at $E_p = 2.95$ MeV (producing 1.92 MeV neutrons) and at $E_p = 2.99$ MeV (producing 1.91 MeV neutrons) for the $P_T x$ calibration of two separate targets. Beam polarization was measured every 90 min with 4 min of data ($\approx$ 200,000 total counts) collected during each measurement. Proton-beam polarization was then averaged over the measurements separately for both calibrations. Since the statistical uncertainty of each measurement was negligible, the standard deviation of the distributions was taken to be a systematic uncertainty. Table 7.11 lists the measured and average proton-beam polarizations P_p for both targets. Uncertainty in P_p includes systematic uncertainty in the term $\frac{\sqrt{\gamma}-1}{\sqrt{\gamma}+1}$ (upper $\pm$) and systematic uncertainty in the analyzing power A_y (lower $\pm$). In subsequent calculations these uncertainties will be added in quadrature.

From Section 3.2.2, vector P_d and tensor P_{dd} deuteron-beam polarizations are given by

$$P_d = \sqrt{\frac{2}{3}}\frac{\left(\frac{\tilde{\epsilon}_L^{\pm}}{\tilde{\epsilon}_L^{(0)}} - \frac{\tilde{\epsilon}_R^{\pm}}{\tilde{\epsilon}_R^{(0)}}\right)\left[1-\frac{1}{2}\,\hat{t}_{20}^{\pm}(\,T_{20}^C\,+\sqrt{6}\,T_{22}^C\,)\right]}{2\sqrt{2}\,iT_{11}}$$

$$P_{dd} = \sqrt{2}\frac{2-\left(\frac{\tilde{\epsilon}_L^{\pm}}{\tilde{\epsilon}_L^{(0)}} + \frac{\tilde{\epsilon}_R^{\pm}}{\tilde{\epsilon}_R^{(0)}}\right)}{(\,T_{20}\,+\sqrt{6}\,T_{22}\,)-\frac{1}{2}\left(\frac{\tilde{\epsilon}_L^{\pm}}{\tilde{\epsilon}_L^{(0)}} + \frac{\tilde{\epsilon}_R^{\pm}}{\tilde{\epsilon}_R^{(0)}}\right)(\,T_{20}^C\,+\sqrt{6}\,T_{22}^C\,)}$$

where the normalized detector efficiencies $\tilde{\epsilon}$ are expressed in terms of ratios of counts in the left, right, and center detectors. The deuteron-beam polarization at $E_d = 8.0$ MeV was measured every 2 hr using the $^3\mathrm{He}(\vec{d},p)^4\mathrm{He}$ reaction, with 4 min of data ($\approx$ 100,000 counts in the left and right detectors) collected during each measurement.

E_p (MeV)		P_p
2.95	A	0.742
	B	0.741
	C	0.732
	D	0.751
	E	0.749
	average:	$0.743\pm^{0.0033}_{0.0041}$

(a) Proton-beam polarization measurements during $P_T x$ calibration at $E_n = 1.92$ MeV

E_p (MeV)		P_p
2.99	A	0.711
	B	0.711
	C	0.706
	D	0.705
	E	0.711
	F	0.703
	G	0.706
	H	0.709
	I	0.706
	average:	$0.707\pm^{0.0011}_{0.0039}$

(b) Proton-beam polarization measurements during $P_T x$ calibration at $E_n = 1.91$ MeV

Table 7.11: Measured and average proton-beam polarizations

Vector and tensor polarizations averaged over $\pm P_d$ spin state are calculated for each measurement, and are listed in Table 7.12. P_d and P_{dd} are then averaged over all the measurements, with the average also reported in Table 7.12. Since the statistical uncertainty in each measurement is negligible, the standard deviations of the distributions are taken as a systematic uncertainty in the average deuteron-beam polarizations (upper $\pm$). Systematic uncertainty from knowledge of analyzing powers is negligible. However, since determining the number of counts in the detectors (the $0°$ detector in particular) depends on background fitting and the choice of gates, a systematic uncertainty is assigned to the P_d and P_{dd} based on the distribution of polarizations obtained from various combinations of backgrounds and gates (lower $\pm$). In subsequent calculations these uncertainties will be added in quadrature.

The vector P_d and the tensor P_{dd} deuteron-beam polarizations (averaged over $\pm P_d$ spin states) at $E_d = 17.0$ MeV were measured every 2.5 hr with the TUNL spin-filter polarimeter [?]. Results of these measurements and the polarizations averaged over all measurements are listed in Table 7.12. Statistical uncertainty in each measurement is neg-

E_d (MeV)		P_d	P_{dd}
8.00	A	0.731	0.697
	B	0.778	0.935
	C	0.763	0.859
	D	0.745	0.812
	E	0.736	0.731
	F	0.771	0.946
	G	0.768	0.907
	H	0.761	0.832
average:		$0.757 \pm \frac{0.0061}{0.005}$	$0.82 \pm \frac{0.032}{0.02}$

(a) Deuteron-beam polarization measurements during the $\Delta\sigma_T$ measurement at $E_n = 10.70$ MeV using the $^3\text{He}(\vec{d}, p)^4\text{He}$ reaction

E_d (MeV)		P_d	P_{dd}
17.0	A	0.771	0.766
	B	0.796	0.806
	C	0.788	0.792
	D	0.796	0.800
	E	0.782	0.784
	F	0.815	0.803
	G	0.779	0.776
	H	0.771	0.785
	I	0.771	0.786
	J	0.780	0.785
	K	0.793	0.821
	L	0.807	0.793
	M	0.789	0.790
	N	0.823	0.807
	O	0.795	0.803
	P	0.780	0.791
average:		$0.790 \pm \frac{0.0038}{0.004}$	$0.793 \pm \frac{0.0034}{0.004}$

(b) Deuteron-beam polarization measurements during the $\Delta\sigma_T$ measurement at $E_n = 34.67$ MeV using the TUNL spin-filter polarimeter

Table 7.12: Measured and average deuteron-beam polarizations

ligible, the standard deviation of the distributions is taken to be a systematic uncertainty. This systematic uncertainty (upper $\pm$) and an estimate of the systematic uncertainty from instrumental effects (estimated to be 0.5%, lower $\pm$) are reported in Table 7.12. In subsequent calculations, these uncertainties will be added in quadrature.

7.2.4 Neuton-Beam Polarization

Neutron-beam polarization can be calculated from the charged-particle beam polarization and polarization-transfer coefficients for the $^3\text{H}(\vec{p}, \vec{n})^3\text{He}$ neutron production reaction

E_n (MeV)	$P_n \pm \Delta P_n$
1.91	0.463 ± 0.0164
1.92	0.487 ± 0.0171
10.70	0.662 ± 0.0165
14.58	0.647 ± 0.0171
17.08	0.638 ± 0.0169
34.67	0.610 ± 0.0204

Table 7.13: Neutron-beam polarizations used in subsequent calculations

according to Equation 3.90

$$P_n(0^\circ) = P_p K_y^{y'}(0^\circ)$$

and for the $^2\mathrm{H}(\vec{d},\vec{n})^3\mathrm{He}$ and $^3\mathrm{H}(\vec{d},\vec{n})^4\mathrm{He}$ reactions from Equation 3.92

$$P_n(0^\circ) = \frac{\frac{3}{2} P_d K_y^{y'}(0^\circ)}{1 + \frac{1}{2} P_{dd} A_{yy}(0^\circ)}.$$

Using beam polarization and polarization-transfer coefficient values summarized in the previous sections, neutron-beam polarizations are calculated and listed in Table 7.13. The reported uncertainties include the total uncertainties in charged-particle beam polarizations and polarization-transfer coefficients. For the calculation of neutron-beam polarization at $E_n = 14.58$ and 17.08 MeV an additional uncertainty of 1% is assigned to the deuteron-beam polarization, since neutron-beam polarization at these energies is calculated from deuteron-beam polarization measurements made during earlier runs.

7.3 Target Polarization × Thickness

Target polarization × thickness was determined by a transmission experiment according to Equation 3.95

$$P_T x = \frac{2\bar{\varepsilon}_n}{P_n \Delta\sigma_T}$$

for the two targets used. The target calibrated at $E_n = 1.91$ MeV was used for measurements of $\Delta\sigma_T$ at $E_n = 35$ MeV, and the target calibrated at $E_n = 1.92$ MeV was used for

Model	$\Delta\sigma_T$ (E_n=1.908 MeV) (mb)	$\Delta\sigma_T$ (E_n=1.915 MeV) (mb)
SAID FA95	0.947	0.941
SAID VZ40	0.948	0.941
Nijm PWA	0.944	0.938
Nijm 93	0.946	0.939
Full Bonn	0.946	0.939
average:	0.946±0.002	0.940±0.002

Table 7.14: Predicted values of $\Delta\sigma_T$ at the $P_T x$ calibration energies

E_n (MeV)	$P_T x$ (b^{-1})
1.91	0.0375±0.00286
1.92	0.0396±0.00293

Table 7.15: Polarization × thickness of targets used in $\Delta\sigma_T$ measurements

measurements of $\Delta\sigma_T$ below 20 MeV.

Measurements of $\bar{\varepsilon}_n$ and P_n have been discussed in previous sections. The value of $\Delta\sigma_T$ at the calibration energies is taken to be the average value of potential-model and phase-shift analysis predictions which are listed in Table 7.14. At low energies (below 5 MeV) ε_1 is fixed by kinematics and properties of the deuteron. So in this energy range $\Delta\sigma_T$ is model independent and well understood. Uncertainty in $\Delta\sigma_T$ is assigned the standard deviation of the distribution of the predictions.

Finally, $P_T x$ is calculated and reported in Table 7.15 for the two targets used. Uncertainty in $P_T x$ includes all statistical and systematic uncertainties.

7.4 Calculation of $\Delta\sigma_T$

$\Delta\sigma_T$ is given by Equation 3.19 to be

$$\Delta\sigma_T = \frac{-2\bar{\varepsilon}_n}{P_n P_T x \left[\frac{P_T(\Delta\sigma_T)}{P_T(P_T x)}\right]}.$$

E_n(MeV)	Area	Area($\Delta\sigma_T$)/Area($P_T x$)
1.91	83.143	–
1.92	86.101	–
10.70	86.771	1.0078
14.58	87.372	1.0148
17.08	87.425	1.0154
34.67	82.220	0.9889

Table 7.16: Average NMR area and correction to $P_T x$ due to target polarization

E_n (MeV)	$\Delta\sigma_T$ (mb)
10.70	-140.4 ± 7.0
14.58	-143.0 ± 7.2
17.08	-123.9 ± 6.7

Table 7.17: Measured values of $\Delta\sigma_T$

$P_T x$ is corrected by the factor $\left[\frac{P_T(\Delta\sigma_T)}{P_T(P_T x)}\right]$ (from Equation 3.95) independently for each $\Delta\sigma_T$ measurement to account for the difference between target polarization (as measured by NMR) during a $\Delta\sigma_T$ measurement and the corresponding $P_T x$ target calibration. Target polarization is measured approximately every minute, and an average (though uncalibrated) target polarization is calculated. Table 7.16 lists the average area of the NMR circuit response, which is proportional to polarization, for each measurement. Assuming the tuning parameters of the NMR circuit are constant in time, the ratio of NMR areas is equivalent to the ratio of polarizations. This avoids having to calibrate absolutely the NMR response. Table 7.16 also lists the P_T correction factors $\left[\frac{P_T(\Delta\sigma_T)}{P_T(P_T x)}\right]$ for the $\Delta\sigma_T$ measurements.

The spin-dependent total cross-section difference $\Delta\sigma_T$ are calculated and listed in Table 7.17. The uncertainties listed include all statistical and systematic uncertainties. These values are plotted in Figure 7.4. Also shown for comparison are previous measurements of $\Delta\sigma_T$ by Wilburn *et al.* [**?**], and the curve is based on the partial-wave analysis of SAID.

Figure 7.4: Measured values of $\Delta\sigma_T$. Previous measurements by Wilburn *et al.* are included for comparison. The curve is from the partial-wave analysis SAID.

Chapter 8

Calculation of ε_1 and Summary

Measurements of $\Delta\sigma_T$ were made at 10.70, 14.48, and 17.08 MeV neutron energys. The phase-shift parameter ε_1 was determined at these energies from a single-energy, single-parameter phase-shift analysis. Fixed phase shifts are taken from SAID (FA95 solution) and ε_1 is allowed to vary to reproduce the measured values of $\Delta\sigma_T$. Best fit values of ε_1 are reported in Table 8.1.

Figure 8.1 summarizes the experimental and theoretical understanding of ε_1 with the addition of our recent measurements. We are encouraged by the excellent agreement at 11 MeV between our measurement and the previous measurement of Wilburn [**?**]. Our values at 15 and 17 MeV also support the trend predicted by both potential models and partial-wave analyses, and disagree with values of ε_1 from Erlangen at 13.7 MeV and Bonn at 17.4 MeV which indicate a weak tensor force. Our measurements have clarified the understanding of the strength of the tensor interaction at low energy and indicate there is

E_n (MeV)	$\varepsilon_1 \pm \Delta\, \varepsilon_1$
10.70	1.231 ± 0.291
14.48	2.160 ± 0.399
17.08	1.782 ± 0.434

Table 8.1: Values of ε_1 obtained from partial-wave analysis of experimental $\Delta\sigma_T$ data

Figure 8.1: Theoretical predictions and experimental data for ε_1 below 60 MeV including current measurements and including unpublished Karslruhe data

no anomaly in ε_1 values between 10 and 20 MeV.

Due to experimental difficulties with the measurement of $\Delta\sigma_T$ at 35 MeV we cannot offer insight into the disagreement between theory and data in this energy region. The discrepancy between data and predictions in the energy region between 25 and 40 MeV is large. However, it should be noted that the Karlsruhe data have not as yet been published in the refereed literature. Figure 8.2 shows our understanding of the tensor interaction without including the Karlsruhe data. It is somewhat surprising to see how few published measurements of ε_1 exist; there are no data between 25 and 50 MeV. Clearly, there is a need for measurements in this energy region in order to clarify the discrepancy between the VPI and Nijmegen predictions.

In summary, we have constructed a dynamically polarized proton target for use in neutron-transmission measurements. With dynamic polarization the target polarization can

Figure 8.2: Theoretical predictions and experimental data for ε_1 below 60 MeV including current measurements but excluding unpublished Karlsruhe data

rapidly be reversed, so that transmission asymmetry measurements are less susceptible to systematic asymmetries. The target is cooled to 0.5 K by a ^{3}He evaporation refrigerator. Proton polarization of 0.65 has been achieved, and was measured by NMR in addition to neutron-transmission calibration.

We have implemented a new scattering polarimeter for measurements of proton- and deuteron-beam polarization. Fast, reliable measurements of vector and tensor beam polarizations are possible with this chamber from the $^4\text{He}(\vec{p},p)^4\text{He}$ and $^3\text{He}(\vec{d},p)^4\text{He}$ reactions. Difficulties due to beam heating of the 0° solid-state detector were addressed.

We have shown that the expression for the spin-dependent neutron-transmission asymmetry is derivable from a spin-dependent cross section term which includes beam and target polarizations. We have recognized systematic asymmetries due to count-rate dependent neutron detector gains and other effects. An analysis scheme to parameterize these systematic effects was developed. This analysis enables these asymmetries to be isolated from the spin-dependent asymmetry.

Looking toward the future, experiments are underway at TUNL to measure $\Delta\sigma_L$ between 10 and 20 MeV. Such data will complement these $\Delta\sigma_T$ measurements and allow a model-independent determination of ε_1. In addition, there are plans to remeasure $\Delta\sigma_T$ (and $\Delta\sigma_L$) in the region near 35 MeV.

Appendix A

The Program AY

```
      program progay
c
c     bwr, 11/96
c     written for VMS, also runs on UNIX
c
c calculate p-4He analyzing power from phase shifts <= l=3
c coulomb interaction explicitly handled
c references: Satchler, Direct Nuclear Reactions
c             Schwandt, Nuclear Physics, Nuc Phys A163 (1971)
c             Abramowitz & Stegun
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
      implicit none
      real en,thetalab,thetacm,sigma(0:3)
      real thetamin,dtheta,thetamax,theta
      real ay,dcs
      real*8 enjcm,kcm,rad2deg
      complex fc,g,h,s(0:3,-1:1)
      real emin,emax,de
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
      rad2deg=180.0/3.1415927
c
      write(6,*) 'energy range (MeV) [min,max,inc]:'
      read(5,*) emin,emax,de
      write(6,*) 'lab angle range (deg) [min,max,inc]:'
      read(5,*) thetamin,thetamax,dtheta
c
      open(unit=2,file='phe4.out')
      write(2,*)'p-4He reaction'
      write(2,*)' E(lab)  theta(lab)  theta(cm)   Ay    dsigma/domega'
c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c     loop over energy and angle, calculating Ay
```

```
c
      do en = emin,emax,de
         do theta=thetamin,thetamax,dtheta
c
c           get cm energy and wavenumber
            call energy(en,enjcm,kcm)
c
c           get cm angle
            call angle(theta,thetalab,thetacm)
c
c           calculate Coulomb scattering amplitude fc
            call coulomb(kcm,thetacm,sigma,fc)
c
c           calculate scattering matrix elements s at energy e
            call calcs(en,s)
c
c           calculate g
            call calcg(thetacm,kcm,sigma,s,g)
c
c           calculate h
            call calch(thetacm,kcm,sigma,s,h)
c
c           calculate analyzing power
            call calcay(fc,g,h,ay,dcs)
c
            write(2,100) en,thetalab*rad2deg,thetacm*rad2deg,ay,dcs
         end do
      end do
      close(2)
 100  format(f8.2,3x,f8.2,3x,f8.2,3x,f8.4,3x,f8.2)
      end
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
      subroutine energy(en,enjcm,kcm)
c
c     input  -> en:    proton lab energy (MeV)
c     output -> enjcm: proton cm energy (J),
c               kcm:   proton cm wave number (inverse m)
c
      implicit none
c
      real en
      real*8 enj,enjcm,kcm,mp,mhe,hbar,u,jev
c
      data jev         /1.60219d-19/
      data mp          /1.67265d-27/
      data mhe         /6.64476d-27/
      data hbar        /1.05459d-34/
c
c     proton lab energy from MeV to joules
      enj = en*1d6*jev
c
c     proton lab energy to cm energy
```

```
      enjcm=enj*mhe/(mp+mhe)
c
c     reduced mass
      u=mp*mhe/(mp+mhe)
c     cm wave number in inverse m
      kcm=dsqrt(2.0*u*enjcm)/hbar
c
      return
      end
c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
      subroutine angle (theta,lab,cm)
c
c     input  -> theta: lab angle (degree)
c     output -> lab:   lab angle (rad)
c               cm:    center of mass angle (rad)
c
      implicit none
c
      real lab,cm,c1,c2,c3,T1overT0,mp,mhe
      real deg2rad,theta
c
c     masses in amu
      mp = 1.00727647
      mhe = 4.00150618
      deg2rad = 3.1415927/180.0
c
c     lab angle in radians
      lab=float(theta)*deg2rad

c     this to avoid pathology at 180 deg
      if (lab.ge.3.14) then
         lab=3.14
      end if
c
c     calculate theta in cm
c     from Marion&Thornton 8.87b
      c1=(mp/(mp+mhe))**2
      c2=(mhe/mp)**2
      T1overT0=c1*(cos(lab)+sqrt(c2-sin(lab)**2))**2
c     from M&T 8.87a
      c3=2.0*mp*mhe/(mp+mhe)**2
      cm=acos(1.0-(1.0-T1overT0)/c3)
c
      return
      end
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
      real function p(l,thetacm)
c
c     evaluate legendre polynomial P sub l for l <= 3
c     input  -> l:       order of legendre polynomial to calculate
c               thetacm: center of mass angle (rad)
```

```
c
      implicit none
c
      real thetacm
      integer l
c
      if (l.eq.0) then
         p=1.0
      else if (l.eq.1) then
         p=cos(thetacm)
      else if (l.eq.2) then
         p=0.5*(3.0*cos(thetacm)**2-1.0)
      else if (l.eq.3) then
         p=0.5*(5.0*cos(thetacm)**3-3.0*cos(thetacm))
      end if
c
      return
      end
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
      real function p1(l,thetacm)
c
c     evaluate associated legendre functions P sub l super 1 for l <=3
c     imput  -> l:       order of associated legendre polynomial to evaluate
c               thetacm: center of mass angle (rads)
c
      implicit none
c
      real thetacm
      integer l
c
      if (l.eq.0) then
         p1=0.0
      else if (l.eq.1) then
         p1=sqrt(1.0-cos(thetacm)**2)
      else if (l.eq.2) then
         p1=3.0*cos(thetacm)*sqrt(1.0-cos(thetacm)**2)
      else if (l.eq.3) then
         p1=1.5*(5.0*cos(thetacm)**2-1.0)*sqrt(1.0-cos(thetacm)**2)
      end if
c
      return
      end
c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
      subroutine calcs(en,sme)
c
c     calculate phase shifts ph(l,j) and scattering matrix element s
c     at an energy en
c
c     phase shifts are calculated from effective range parameterization
c     given by Schwandt
c
```

```
c     input  -> en:  proton lab energy (MeV)
c     output -> sme: scattering matrix elements s(l,+/-)
c                    where + >>> spin=+1/2, - >>> spin=-1/2
c
      implicit none
c
      real ph(0:3,-1:1),en,k,eta,c(0:3),h,euler
      real a(0:3,-1:1,0:3)
      integer s,n,l,j
      real pi,deg2rad,sum
      complex sme(0:3,-1:1),i
c
      data pi     /3.1415927/
      data i      /(0.0,1.0)/
      data euler  /0.577216/
      deg2rad =   pi/180.0
c
c     load in effective range expansion coefficients a(l,s,n)
c     s=-1 >>> l-1/2 ... s=+1 >>> l+1/2
c     taken from Schwandt
c
      data(a(0,-1,n),n=0,3)/ 0.0,     0.0,     0.0,       0.0/
      data(a(0,+1,n),n=0,3)/-0.19266, 0.019038,0.0,       0.0/
      data(a(1,-1,n),n=0,3)/ 0.06117,-0.001213,0.0008978,-0.00000026/
      data(a(1,+1,n),n=0,3)/ 0.02267,-0.005448,0.0005449,-0.00000317/
      data(a(2,-1,n),n=0,3)/ 1.1380,  0.10500, 0.0,       0.0/
      data(a(2,+1,n),n=0,3)/ 1.0205,  0.05235, 0.0,       0.0/
      data(a(3,-1,n),n=0,3)/ 1.690,   0.1730,  0.0,       0.0/
      data(a(3,+1,n),n=0,3)/ 1.412,   0.1188,  0.0,       0.0/
c
c     evaluate equation 3 in Schwandt
c
      k = 0.17540*sqrt(en)
      eta = 0.31614/sqrt(en)
c
      sum=0.0
      do s=1,20
         sum=sum+1.0/(s*(s**2+eta**2))
      end do
      h=eta**2*sum-log(eta)-euler
c
c     evaluate coefficients c
c
      c(0) = 2.0*pi*eta/(exp(2.0*pi*eta)-1)
      do l=1,3
         c(l)=c(l-1)*(1+(eta/l)**2)
      end do
c
c     calculate phase shifts ph(l,j)
c
      do l=0,3
         do j=-1,1,2
            sum=0.0
               do n=0,3
               sum=sum+a(l,j,n)*en**n
```

```
            end do
            ph(l,j)=atan(1.0/(sum/(c(l)*k**(2.0*l+1))-
     c           2.0*eta*h/c(0)))
            if (ph(l,j).lt.0.0) then
               ph(l,j)=pi+ph(l,j)
            end if
         end do
      end do
c
      ph(0,-1)=0.0
c
c     evaluate calculate scatering matrix elements s(l,s)
c     from Satchler appendix A
      do l=0,3
         do j=-1,1,2
            sme(l,j)=cexp(2.0*i*ph(l,j))
         end do
      end do
c
      return
      end
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
      subroutine coulomb(kcm,thetacm,sigma,fc)
c
c     calculate Coulomb phase shifts sigma(l) and the coulomb scattering
c     amplitude fc, from Satchler, equation 4.11a
c
c     input  -> kcm:     proton cm wave number (inverse m)
                thetacm: center of mass angle (rad)
c     output -> sigma:   coulomb phase shifts sigma(l) (rad)
                fc:      coulomb scattering amplitude
c
      implicit none
c
      real Zp,Zhe,n,sigma(0:3)
      real alpha,sum,x,y,euler,sin2,thetacm
      integer loop
      real*8 kcm,mp,mhe,hbar,c,u,v
      complex fc,i
c
      data Zp          /1.0/
      data Zhe         /2.0/
      data mp          /1.67265d-27/
      data mhe         /6.64476d-27/
      data hbar        /1.05459d-34/
      data c           /2.99793d8/
      data euler       /0.57721566/
      data i           /(0.0,1.0)/
c
      u=mp*mhe/(mp+mhe)
      alpha=1.0/137.036
c
c     find proton velocity in m/s
```

```
      v=kcm*hbar/u
c     find n, the Sommerfeld parameter
      n=sngl(Zp*Zhe*alpha/(v/c))
c
c     find sigma(l), the Coulomb phase shifts, from Satchler 4.16
c
c     get sigma(0) from Abramowitz & Stegun 6.1.27
c     (evaluate arg gamma(1+in))
      x=1.0
      y=n
      sum=0.0
      do loop=0,20
         sum=sum+((y/(x+loop))-atan(y/(x+loop)))
      end do
      sigma(0)=y*(-euler)+sum
c
c     get sigma(l>0) from recursive relation A&S 6.1.24
c     (evaluate arg gamma(l+1+in)
      do loop=1,3
         sigma(loop) = sigma(loop-1) + atan(n/loop)
      end do
c
c     calculate Coulomb scattering amplitude from Satchler 4.23
c
      sin2=sin(thetacm/2.0)**2
      fc= -n/(2.0*sngl(kcm)*sin2)*
     1        cexp(-i*n*log(sin2)+2.0*i*sigma(0))
c
      return
      end
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
      subroutine calcg(thetacm,kcm,sigma,s,g)
c
c     calculate the function g from Satchler, appendix A
c     input  -> thetacm: center of mass angle (rad)
c               kcm:     proton cm wave number (inverse m)
c               sigma:   Coulomb phase shifts sigma (rad)
c               s:       scattering matrix elements
c     output: g
c
      implicit none
c
      real     thetacm,sigma(0:50),p
      integer  l
      complex  g,i,s(0:3,-1:1),temp
      real*8   kcm
c
      data i  /(0.0,1.0)/
c
c     calculate g from Satchler, equation A.9
c
      g=(0.0,0.0)
      do l=0,3
```

```
         temp=i/(2.0*sngl(kcm))*((2.0*l+1.0)-(l+1.0)*s(l,1)-
     1        l*s(l,-1))*cexp(2.0*i*sigma(l))*p(l,thetacm)
         g=g+temp
      end do
c
      return
      end
c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
      subroutine calch(thetacm,kcm,sigma,s,h)
c
c     calculate the function h from Satchler, appendix A
c     input  -> thetacm: center of mass angle (rad)
c               kcm:     proton cm wave number (inverse m)
c               sigma:   Coulomb phase shifts sigma (rad)
c               s:       scattering matrix elements
c     output: h
c
      implicit none
c
      real    thetacm,sigma(0:50),p1
      integer l
      real*8  kcm
      complex h,i,s(0:3,-1:1),temp
c
      data i   /(0.0,1.0)/
c
c     calculate h from Satchler, equation A.9
c
      h=(0.0,0.0)
      do l=0,3
         temp=i/(2.0*sngl(kcm))*(s(l,-1)-s(l,1))*
     1        cexp(2.0*i*sigma(l))*p1(l,thetacm)
         h=h+temp
c
      end do
c
      return
      end
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
      subroutine calcay(fc,g,h,ay,dcs)
c
c     calculate analyzing power from Satchler, equation A.11
c     input  -> fc: Coulomb scattering amplitude
c               g:  g
c               h:  h
c     output -> ay: analyzing power
c               dcs: differential cross section (mb/sr)
c
      implicit none
c
      complex fc,g,h
```

```
      real ay,dcs
c
c     scale fc, g & h to avoid underflow warning
c
      fc=fc*1e10
      g =g* 1e10
      h =h* 1e10
      ay=2.0d0*aimag((fc+g)*conjg(h))/(abs(fc+g)**2+abs(h)**2)
      dcs=(abs(fc+g)**2+abs(h)**2)*10e10
      return
      end
```

Biography

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Personal

Born in West Chester, Pennsylvania, August 10, 1966

Married Donna Elizabeth Key, October 24, 1992

Education

B.S. Physics, West Chester University of Pennsylvania, 1989

Thesis Title: *A Dynamically Polarized Proton Target for Measurements of the Transverse Spin-Dependent Total Cross Section Difference,* $\Delta\sigma_T$

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Memberships

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American Association of Physics Teachers

Council on Undergraduate Research

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Publications

Test of Parity-Conserving Time-Reversal Invariance Using Polarized Neutrons and Nuclear Spin Aligned Holmium. P.R. Huffman, N.R. Roberson, W.S. Wilburn, C.R. Gould, D.G. Haase, C.D. Keith, B.W. Raichle, M.L. Seely, and J.R. Walston. Phys. Rev. Lett. **76**, 4681 (1996).

Test of parity-conserving time-reversal invariance using polarized neutrons and nuclear spin aligned holmium. P.R. Huffman, N.R. Roberson, W.S. Wilburn, C.R. Gould, D.G. Haase, C.D. Keith, B.W. Raichle, M.L. Seely, and J.R. Walston. Phys. Rev. C **55**, 2684 (1997).

Contributed Abstracts

Measurements of the Spin Dependent Total $\vec{n}-\vec{p}$ Cross Section Difference $\Delta\sigma_T$ and $\Delta\sigma_L$ for E_n = 11-35 MeV. B.W. Raichle, B.E. Crawford, C.R. Gould, D.G. Haase, D.S. Junkin, M.L. Seely, N.R. Roberson, W. Tornow, J.R. Walston, W.S. Wilburn, G.W. Hoffmann, and S.I. Penttilä. Bulletin of the American Physical Society **41**, 1653 (1996).

Measurements of the Spin Dependent Total $\vec{n}-\vec{p}$ Cross Section Difference $\Delta\sigma_T$ and $\Delta\sigma_L$ for E_n = 11-35 MeV. B.W. Raichle, C.R. Gould, D.G. Haase, M.L. Seely, J.R. Walston, B.E. Crawford, W. Tornow, W.S. Wilburn, D.S. Junkin, G.W. Hoffmann, and S.I. Penttilä. Bulletin of the American Physical Society **41**, 1267 (1996).

A Polarized Proton Target for Investigation $\Delta\sigma_T$ in $\vec{n}-\vec{p}$ Scattering. B.W. Raichle, C.R. Gould, D.G. Haase, M.L. Seely, N.R. Roberson, W. Tornow, J.R. Walston, W.S. Wilburn, G.W. Hoffmann, and S.I. Penttilä. Bulletin of the American Physical Society **41**, 1002 (1996).

A Polarized Proton Target for Investigating $\Delta\sigma_T$ in $\vec{n}-\vec{p}$ Scattering. B.W. Raichle, C.R. Gould, D.G. Haase, M.L. Seely, N.R. Roberson, W. Tornow, J.R. Walston, W.S. Wilburn, G.W. Hoffmann, and S.I. Penttilä. Bulletin of the American Physical Society **40**, 1602 (1995).

A Polarized Proton Target for Investigating $\Delta\sigma_T$ *in* $\vec{n}-\vec{p}$ *Scattering.* B.W. Raichle, C.R. Gould, D.G. Haase, M.L. Seely, N.R. Roberson, W. Tornow, J.R. Walston, W.S. Wilburn, G.W. Hoffmann, and S.I. Penttilä. Bulletin of the American Physical Society **39**, 1821 (1994).

Co-Authored Abstracts

Determination of the Polarization Transfer Coefficient, K_z^z*, for the* $^3H(\vec{p},\vec{n})$ *Reaction at Low Energies.* J.R. Walston, C.R. Gould, D.G. Haase, B.W. Raichle, M.L. Seely, W. Tornow, W.S. Wilburn, C.D. Keith, G.W. Hoffmann, and S.I. Penttilä. Bulletin of the American Physical Society **41**, 1653 (1996).

Measurement of K_z^z *for the* $^3H(\vec{p},\vec{n})$ *Reaction for Neutron Energies 0.5-1.9 MeV.* J.R. Walston, C.R. Gould, D.G. Haase, B.W. Raichle, M.L. Seely, W. Tornow, W.S. Wilburn, C.D. Keith, G.W. Hoffmann, and S.I. Penttilä. Bulletin of the American Physical Society **41**, 1267 (1996).

Measuring Target Polarization in a Low-Energy Polarized Neutron-Polarized Proton Transmission Experiment. M.L. Seely, C.R. Gould, D.G. Haase, B.W. Raichle, J.R. Walston, N.R. Roberson, W. Tornow, W.S. Wilburn, D.S. Junkin, G.W. Hoffmann, and S.I. Penttilä. Bulletin of the American Physical Society **41**, 1261 (1996).

A Test of Time-Reversal Invariance Using MeV Neutrons and Aligned Holmium. P.R. Huffman, N.R. Roberson, W.S. Wilburn, C.R. Gould, D.G. Haase, C.D. Keith, B.W. Raichle, M.L. Seely and J.R. Walston. Bulletin of the American Physical Society **41**, 964 (1996).

Calibrating Target Polarization in a Polarized Neutron-Polarized Proton Scattering Experiment. M.L. Seely, C.R. Gould, D.G. Haase, B.W. Raichle, J.R. Walston, N.R. Rober-

son, W. Tornow, W.S. Wilburn, G.W. Hoffmann, and S.I. Penttilä. Presented at the 8^{th} International Workshop on Polarized Target Materials and Techniques, Vancouver, BC (May 1996).

Some Questions Regarding Microwave Induced Optical Nuclear Polarization. M.L. Seely, C.R. Gould, D.G. Haase, B.W. Raichle, J.R. Walston, N.R. Roberson, W. Tornow, and W.S. Wilburn. Presented at the 8^{th} International Workshop on Polarized Target Materials and Techniques, Vancouver, BC (May 1996).

Polarized Neutron Source and Detectors for the TUNL Parity-Even Test of Time Reversal Invariance. P.R. Huffman, N.R. Roberson, W.S. Wilburn, C.R. Gould, D.G. Haase, C.D. Keith, B.W. Raichle, and M.L. Seely. Bulletin of the American Physical Society **40**, 1619 (1995).

A Polarized Deuteron Target for Investigation of $\Delta\sigma_T$ *and* $\Delta\sigma_L$ *in n-d Scattering.* J.R. Walston, C.R. Gould, D.G. Haase, B.W. Raichle, M.L. Seely, N.R. Roberson, W. Tornow, W.S. Wilburn, G.W. Hoffman, and S.I. Penttilä. Bulletin of the American Physical Society **40**, 2063 (1995).

New Experimental Test of Parity-Even Time Reversal Invariance with MeV Neutrons. P.R. Huffman, B.C. Crawford, C.R. Gould, D.G. Haase, D.S. Junkin, C.D. Keith, N.R. Roberson, B.W. Raichle, M.L. Seely, J.R. Walston, and W.S. Wilburn. Submitted to the International Nuclear Physics Conference, Beijing, China (August 1995).

A Dynamically Polarized Proton Target for n-p Scattering. M.L. Seely, C.R. Gould, D.G. Haase, B.W. Raichle, J.R. Walston, N.R. Roberson, G.W. Hoffmann, and S.I. Penttilä. Bulletin of the American Physical Society **39**, 1384 (1994).

Measurement of $\Delta\sigma_T$ *in Polarized Neutron/Polarized Proton Scattering.* W.S. Wilburn, P.R. Huffman, N.R. Roberson, W. Tornow, C.R. Gould, D.G. Haase, C.D. Keith, T.P. Murphy, and B.W. Raichle. Bulletin of the American Physical Society **38**, 1063 (1993).

Oral Presentations

An Experimental Determination of the $^3S_1-^3D_1$ *Mixing Angle* ϵ_1. B.W. Raichle. Presented at the Institute for Nuclear Theory Summer School, Seattle, WA (June 1995).