A measurement of parity-violating asymmetry in polarized cold neutron capture on $^3$He

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Abstract. The n$^3$He experiment measured the parity-violating directional asymmetry in the proton emission direction relative to the initial neutron polarization in the capture of polarized cold neutrons in the reaction $n + ^3$He $\rightarrow$ p $+ T$. Data taking was completed at the end of 2015 at the SNS, and two independent analyses of the proton parity asymmetry have since been completed and are in agreement. I will present the methods used to calculate the asymmetry, and the final results of the experiment.

1. Introduction

While strong force is known to be responsible for confining quarks into hadrons such as protons and neutrons, and for binding the individual nucleons into atomic nuclei, there is currently no consistent description of how this happens. The low energy interactions between proton and neutrons in nuclei are in principle calculable using quantum chromodynamics (QCD), but in practice the required non-perturbative calculations are not possible for many body systems. Instead models such as the DDH meson exchange model [1] or more modern effective field theory models are used to describe the interaction. The hadronic weak interaction can be used to probe the strong interaction between nuclei as it is sensitive to quark-quark correlation between the nuclei due to its short range. By examining how parity violating observables that arise due to the weak force are modified we can learn about the short-range strong interaction in the system.

The goal of the n$^3$He experiment was to measure the parity violating directional asymmetry in the emission of the proton, with respect to the neutron polarization, after capture of polarized cold neutrons on a gaseous $^3$He target, and the resulting spontaneous breakup in the reaction

$$\vec{n} + ^3\text{He} \rightarrow p + T + 765 \text{ keV}.$$  

 Calculations for the size of this asymmetry have been made using the DDH Reasonable range values for the weak coupling constants, and using more modern effective field theories (EFT). In the DDH model the predicted size of the parity violating asymmetry is $(−9.4 \rightarrow 2.5) \times 10^{-8}$. [2][3]

Using EFT formalism the asymmetry has been calculated using full four-body calculations of the strong scattering wave functions. Evaluation of the weak matrix elements in terms of $\chi$PT EFT:[4]

$$A^{PV}(Th) \approx 1.7 \times 10^{-8} \quad \Lambda = 500 \quad (2)$$

$$A^{PV}(Th) \approx 3.5 \times 10^{-8} \quad \Lambda = 600 \quad (3)$$
The goal accuracy for measuring these asymmetries was $2 \times 10^{-8}$ for the parity violating asymmetry, and $5 \times 10^{-8}$ for the parity conserving asymmetry.

2. Experiment Setup

The n$^3$He Experiment took place at the Spallation Neutron Source (SNS) of the Oak Ridge National Lab. The SNS is an accelerator driven spallation neutron source that provides neutron pulses at a 60 Hz repetition rate. The n$^3$He experiment ran on the Fundamental Neutron Physics Beamline (FnPB). For the FnPB the high energy spallation neutrons are moderated in a 20 K liquid hydrogen moderator. This produces cold neutrons that have a Maxwell-Boltzmann energy peaked around 5 Å. These low energy neutrons can then be transported in a neutron super mirror guide to the experiment cave. The guide is curved to remove line of sight to the moderator to reduce backgrounds in the experiment cave from gamma rays and fast neutrons. Two time of flight definition choppers were used to select the desired neutron energy range in each pulse to reduce overlap between the pulses. See reference [5] for more information on the FnPB. See figure 1 for an example of a series of chopped neutron pulses.

Figure 1. A series of neutron pulse spectra taken at a 1 Hz pulse rate over layed at a 60 Hz repetition rate to show the overlap between pulses. Neutrons from each pulse are shown with the same line color. The arrows indicate the neutron spin polarization sequence used during data taking.

Figure 2 shows a schematic layout of the n$^3$He experiment. A $^3$He neutron beam monitor was used to measure the neutron pulse intensity exiting the beam guide. Following is super mirror polarizer that was used to polarize the neutron beam which provided an wavelength dependent polarization of 90 – 95%.[6] A resonant frequency spin rotator was used to flip the neutron spin on alternating pulses. Due to the narrow energy range at each time of flight an average spin flip efficiency of greater than 99.5% was achieved for the neutron pulse.[6] Between the spin rotator and the target chamber a four-jaw collimator was used to give a well defined beam area on target. The collimator had two horizontal and two vertical plates that could be adjusted independently. Each jaw consisted of an aluminum plate with a cadmium sheet covered with a $^6$Li loaded plastic to define the collimator edge and to reduce the gamma ray background.

The target for the experiment was a multi-wire ionization chamber filled with pure $^3$He gas at a pressure of 0.47 atmospheres that also served as the detector for the proton emission direction by measuring the location of ionization in the chamber from the proton traveling through the fill gas. The target chamber contained 144 signal wires. Each signal wire is surrounding high
voltage wires that defined a volume around the signal wire within which the collection of the ionization charges will induce a net signal. See figures 3 and 4 for a picture and diagram of the target chamber respectively. Each wire was read out individually through one of four signal feed throughs.

3. Calculation of Asymmetries

The differential cross section for the proton emission direction can be expressed as:

\[
\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_0 \left( 1 + A_{PV} \cos \theta_{s_n, k_p} + A_{PC} \cos \theta_{s_n \times k_n, k_p} \right)
\]  (4)
Figure 4. Schematic cross section through the central axis of the target chamber. Linear dimensions are in centimeters.

where

\[ A_{PV} = \text{parity violating asymmetry} \]
\[ A_{PC} = \text{parity conserving asymmetry} \]
\[ P = \text{neutron beam polarization}. \]

The yield \( Y \) in a given wire number \( i \) is then

\[ Y^\uparrow/\downarrow_i = Y_0 \epsilon (1 \pm P A_{PV} G_{PV} \pm P A_{PC} G_{PC}) + p_i. \quad (5) \]

where

\( Y_0 \) = wire yield with no beam polarization
\( \epsilon \) = charge collection efficiency.
\( G \) = geometry factor
\( \uparrow / \downarrow \) = indicates the neutron polarization parallel or antiparallel to the magnetic field.
\( p_i \) = the electronic pedestal in wire \( i \)

The geometry factors relate the physical construction of the target, the gas, the spatial extent of the neutron beam, the relative location of the target and beam to each other. The geometry factors can be expressed as

\[ G = \frac{\langle E \cos \theta \rangle}{\langle E \rangle}. \quad (6) \]

and the values were determined by monte carlo simulation using Geant4.

The target chamber is not sensitive to where along the length of the wire that ionization occurs inside a cell, this allows the wires planes to be aligned either parallel or perpendicular to the neutron polarization so that it is sensitive to only one of the parity violating or the parity allowed asymmetries.
Physics asymmetry values were extracted by taking combinations of the measured wire yields over two neutron pulses of opposite polarization. Different combinations of the yields are sensitive to different systematic effects. For example using the yield from a single wire for two consecutive pulses with opposite neutron spins

\[ A_{exp} = \frac{Y_{↑} - Y_{↓}}{Y_{↑} + Y_{↓}} \]

\[ = \frac{P_{UV}G_{PV}}{1 + p/Y_{0}} \approx P_{UV}G_{UD} \]  

assuming that the pedestal is small compared to the neutron signal. This calculation is sensitive to variations in the neutron beam intensity between the pulses as \( Y_{0} \) is required to be identical for the pulse pair for it to cancel. By choosing pairs of wires labeled \( u \) and \( d \) that are opposite sides of the center of the target chamber such that \( G_{u} = -G_{d} \), a wire pair asymmetry can be calculated that is less sensitive to the beam fluctuations than the single wire asymmetry,

\[ A_{exp} = \frac{Y_{u}^↑ - Y_{u}^↓}{Y_{u}^↑ + Y_{u}^↓} - \frac{Y_{d}^↑ - Y_{d}^↓}{Y_{d}^↑ + Y_{d}^↓} \]

\[ \approx 2PG_{UV}P_{UV} + \frac{p_{u}^↑ - p_{u}^↓}{Y_{0,u}^↑ + Y_{0,u}^↓} - \frac{p_{d}^↑ - p_{d}^↓}{Y_{0,d}^↑ + Y_{0,d}^↓} \]

\[ A_{beam} = \frac{Y_{u}^↑ - Y_{u}^↓}{Y_{u}^↑ + Y_{u}^↓} + \frac{Y_{d}^↑ - Y_{d}^↓}{Y_{d}^↑ + Y_{d}^↓} \]

This two wire asymmetry is more sensitive to the electronic pedestal than the single wire asymmetry, but the pedestals were sufficiently stable over time that measurements of the pedestal in dedicated beam off runs were made to correct for those factors.

Each data run consisted of 24998 pulses. The SNS facility would use every 600th pulse for diagnostics purposes producing no neutrons, asymmetries in each run were calculated over the spin sequences between the diagnostic dropped pulses. For extracting the physics asymmetries the two wire method was used.

To examine the variation in the physics asymmetry over the data taking period the covariance weighted mean asymmetry was calculated for all wire pairs in the chamber in batches of consecutive runs, figure 5 shows the plot of these values. To look for effects specific to each wire pair the mean asymmetries were also calculated for all runs for each wire pair as is shown in figure 6. No unexpected deviations were seen. To correct for the beam asymmetry, \( A_{beam} \), that can occur if there is a correlation between the neutron spin and the beam intensity a linear regression was performed between the beam asymmetry calculated in the M1 monitor and the target chamber as it should be the same in each detector. This only had a small effect on the final calculated asymmetries. The central result for the asymmetry values are subject for a forthcoming publication, but the goal measurement accuracy was exceeded for the parity violating asymmetry, and met for the parity conserving asymmetry.

\[ \sigma_{APV} = \pm 0.97(stat) \pm 0.25(sys) \times 10^{-8} \]  

\[ \sigma_{APC} = \pm 5.9(stat) \pm 0.43(sys) \times 10^{-8} \]

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Figure 5. The mean wire pair parity violating asymmetry calculated for each run batch during data taking. Data is divided by between asymmetry calculations over 600 pulse sequences that where the polarization of the first pulse was parallel or antiparallel to the magnetic holding field.

Figure 6. The wire pair parity violating physics asymmetry calculated for all wires pairs in the target chamber.

References
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