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Characterizing the AFP Spin Flipper for the Nab Experiment

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The Nab experiment at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) aims to yield a precise measurement of the electron-neutrino correlation parameter, a, to $\Delta a/a = 1 \times 10^{-3}$ from the beta-decay of the free neutron. To achieve Nab's precision goal, polarization of the neutron beam must be near-zero. A polarizer/analyzer combination, neutron monitors, and an Adiabatic Fast Passage (AFP) spin flipper will be used to determine a beam polarization effectively less than 2×10^{-5}. Here, I will discuss the initial characterization efforts of the Nab spin flipper as well as plans for further testing.

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1. Introduction

A free neutron (that is, a neutron outside a nucleus) will undergo beta-decay within roughly fifteen minutes, in which one of the neutron's down quarks is transformed into an up quark, an electron, and an anti-neutrino [1]. The differential form of the neutron's decay rate is given in terms of a series of correlation parameters:

$$d\omega \propto \frac{1}{\tau} f(E_e) \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e \cdot E_\nu} + b\frac{m_e}{E_e} + A\frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + B\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} \right], \tag{1}$$

where $\vec{p}_e$ and $\vec{p}_\nu$ are the outgoing electron and neutrino momenta, respectively; $\vec{\sigma}_n$ is the spin vector of the decaying neutron; E_e and E_ν are the electron and neutrino energies, respectively; and $f(E_e)$ is the electron energy spectrum[2].

Flavor mixing between quark states is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix. According to the Standard Model of particle physics, the CKM matrix must be unitary. At present, discrepancies between experimental measurements suggest deviation from CKM unitarity. One way to probe the CKM matrix is through experimental determinations of a, the electron-neutrino correlation parameter, in neutron beta-decay. Determinations of a can be used to make determinations of λ, the ratio between the axial vector coupling constant g_A and the vector coupling constant for quarks g_V, through

$$a = \frac{1-\lambda^2}{1+\lambda^2} \tag{2}$$

where $\lambda = g_A/g_V$ [3].

The Nab (Neutron a and b) experiment is a high-precision free neutron beta decay experiment mounted at the Fundamental neutron Physics Beamline (FnPB) at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) [4]. The goal of Nab is to make the most precise determination of a. When taken with a separate measurement of the mean neutron lifetime, the determination of a will be used to determine λ and V_{ud}, probing the unitarity of the CKM matrix. Figure 1 shows the "teardrop" plot used to extract the value of a from the neutron decay data.

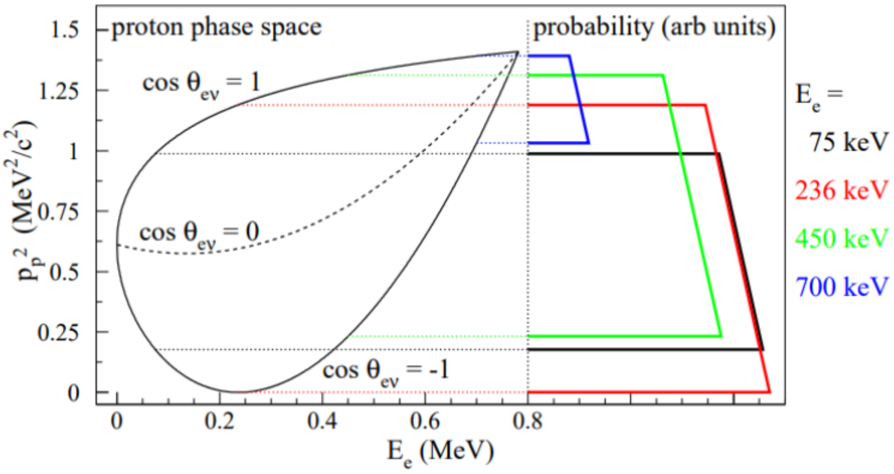

Figure 1: A plot of the phase space of the experiment using the squared proton momentum and the electron energy. The teardrop shape of the phase space is defined by the limits of $cos\theta_{e\nu}$. The trapezia slice individual electron energies. The slope of each trapezium is proportional to the value of a [5].

Nab's achievable precision of a is partially dependent on the neutron beam polarization. To make an unbiased determination of a, there must be zero polarization of the neutron beam. Non-zero polarization will contribute systematic error to a. While beam polarization of the FnPB is expected to be near-zero, this has not yet been confirmed. Should there be residual polarization, an Adiabatic Fast Passage (AFP) spin flipper will be used to flip the neutron spin pulse-by-pulse during data-taking to permit cancellation of the residual error.

2. Characterization of the AFP spin flipper

2.1 Spin flipper design

The spin flipper is made up of two main coil systems: the static coil and the RF coil. The static coil provides a gradually increasing static magnetic field along the length of the spin flipper. Since the Nab experiment uses a polychromatic beam, the field needs to increase gradually enough that all neutron spins can align themselves with the static field, regardless of their velocity. In this field, the neutrons precess at their Larmor frequency. The other field component, the RF field, is an oscillating magnetic field. At the location where the RF field oscillates in resonance with the Larmor frequency, the neutrons flip their spin [6].

2.2 Installation and devices

The spin flipper characterization measurement took place on the separate monochromatic beamline at FnPB (BL-13A). This second beamline uses a monochromator and choppers to select 4.45 Å and 8.9 Å neutrons [4]. Several devices were used to perform the characterization measurements. Neutrons first passed through a supermirror polarizer, which uses alternating layers of ferromagnetic and nonmagnetic materials to create a highly reflective polarizing mirror for one spin state [7, 8]. Neutrons exited the polarizer in the spin-up state. The polarized neutrons then passed through a pair of spin flippers (the Nab spin flipper and a Mezei spin flipper), each of which would flip the neutron spin if power were applied to the corresponding coils. Neutrons then passed through the S-bender analyzer, which filtered spin-down neutrons and allowed only spin-up neutrons to pass through to the 8-pack detector, an array of eight ^{3}He-filled proportional counters that measured the arrival time and transverse position of each neutron. Two adjustable collimators were used to center the beam through the Nab spin flipper.

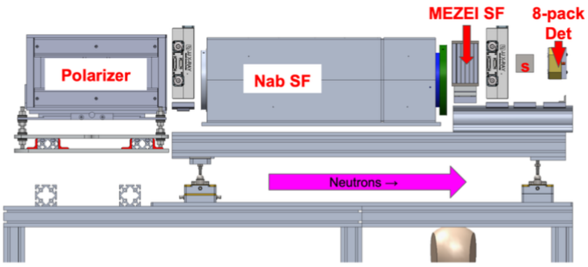

Figure 2: Schematic of experimental setup on BL-13A. Neutrons first pass through the polarizer, then through the first collimator, Nab spin flipper, Mezei spin flipper, and second collimator before filtering through the S-bender (labeled "s") and reaching the ^{3}He detector.

2.3 Measurements and results

A series of four transmission measurements were performed to extract the efficiency of the Nab spin flipper.

1. Both spin flippers off (N_0)
   N_0 is the number of neutrons that pass through the polarizer, maintain spin state, and pass through the S-bender. This number should be relatively high since the spin remains unchanged and passes through the identically oriented S-bender.

2. Nab spin flipper on, Mezei spin flipper off (N_1)
   N_1 is the number of neutrons that pass through the polarizer, flip in the Nab spin flipper, and maintain this flipped spin state. The number of neutrons detected is significantly reduced since the oppositely oriented S-bender will filter the flipped spin neutrons.

3. Nab spin flipper off, Mezei spin flipper on (N_2)
   N_2 is the number of neutrons that pass through the polarizer, flip in the Mezei spin flipper, and maintain this flipped spin state. As with N_1, this number is significantly reduced compared to N_0.

4. Both spin flippers on (N_{12})
   N_{12} is the number of neutrons that pass through the polarizer, flip in the Nab spin flipper, flip again in the Mezei spin flipper, and then pass through the S-bender. With both spin flippers on, the final spin state will be the same as when the neutrons exited the polarizer, so these neutrons should pass through the S-bender without much filtering.

The efficiencies of the individual flippers can then be obtained through

$$f = \frac{1}{2}\left(1 + \frac{N_{12} - N_1}{N_0 - N_2}\right) \tag{3}$$

$$f' = \frac{1}{2}\left(1 + \frac{N_{12} - N_2}{N_0 - N_1}\right) \tag{4}$$

where f and f' are the respective flipping efficiencies of the first and second spin flipper [9, 10]. The combined polarization efficiency is given by

$$P_{SM}P'_{SM} = \frac{(N_0 - N_1)(N_0 - N_2)}{N_{12}N_0 - N_1N_2} \tag{5}$$

where P_{SM} is the efficiency of the polarizer and P'_{SM} is the efficiency of the S-bender [9, 10].

The four-measurement sequence was performed in two configurations for two wavelengths. In the "upstream configuration," the high-static field end of the spin flipper was placed at the exit of the polarizer. In the "downstream configuration," the low-static field end of the spin flipper was placed at the exit of the polarizer. When ultimately installed on BL-13B, where there will be no polarizer, the Nab spin flipper will be in the "downstream configuration". However, due to the high field of the polarizer on BL-13A, it was decided to mount in the opposite configuration to improve spin transport.

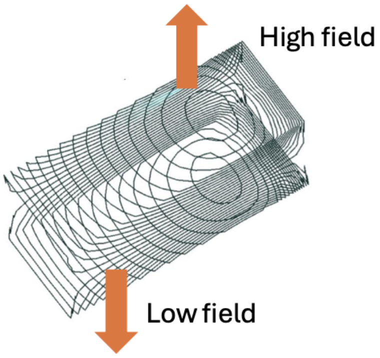

Figure 3: Locations of the high and low field sections of the Nab static field.

As expected, the neutrons experienced better spin transport in the upstream configuration. The number of neutrons detected in the flipped state (N_1, N_2) significantly decreased from the number of unflipped neutrons (N_0), verifying that the Nab spin flipper works. To ensure stability, the four-measurement sequence was performed twice and the time of flight (ToF) plots for each run were superimposed to compare results. ToF plots for the four-measurement sequence in the upstream configuration at 4.45 Å are shown in Figure 4.

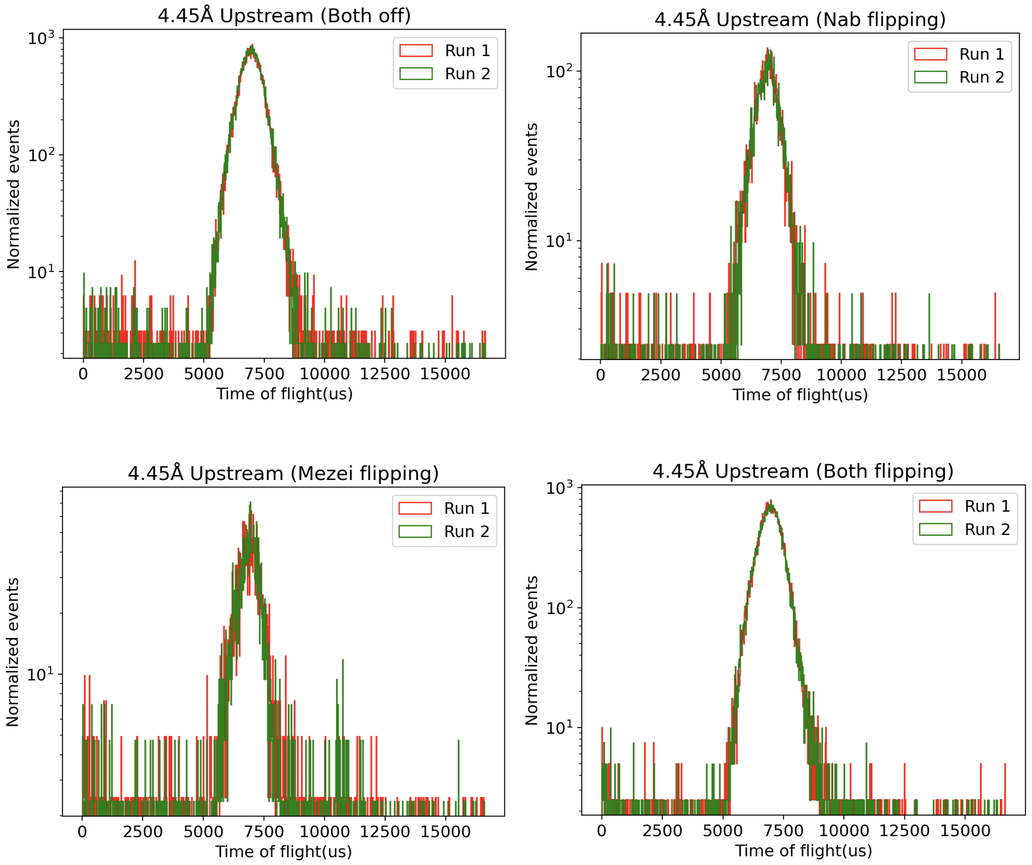

Figure 4: Time of flight plots for each measurement sequence (4.45 Å, upstream configuration). The four-measurement sequence was performed twice to confirm stability.

	Both off (N_0)	Nab on (N_1)	Mezei on (N_2)	Both on (N_{12})	f (Nab)
Normalized events (Run 1)	53775.7 ± 231.90	8186.3 ± 90.48	4103.6 ± 64.06	49750.1 ± 223.05	0.918 ± 0.003
Normalized events (Run 2)	54988.6 ± 234.50	8215.2 ± 90.64	3906.1 ± 62.50	50088.7 ± 223.81	0.910 ± 0.003

Table 1: Normalized neutron events and efficiencies for the four-measurement sequence (4.45 Å, upstream configuration). Neutron events were normalized with respect to the proton charge (neutrons/C) of the SNS at the time of data-taking. Uncertainty shown is purely statistical.

3. Conclusions and Future Work

These characterization efforts on BL-13A give an average Nab spin flipper efficiency of 91.4 ± 0.3%. Systematic uncertainty analysis is still ongoing. It is expected that this efficiency will change once installed on BL-13B due to the additional magnetic fields from the Nab spectrometer. Previous spin transport simulations suggest a spin flipper efficiency of 99% when installed on BL-13B. To reproduce the magnetic environment of BL-13B outside of the beamline, another characterization measurement will be conducted at the High Flux Isotope Reactor (HFIR) at ORNL. At HFIR, there will be enough space to characterize the spin flipper in the expected Nab magnetic field environment prior to installing the spin flipper on BL-13B.

In addition to further characterization measurements, several devices will need to be designed, built, and optimized before installing on BL-13B for the final beam polarization measurement. These devices include an S-bender, to act as our polarizing device; a ^{3}He-based absorber with in-situ polarization to act as our spin analyzer; and a ^{3}He-based neutron detector. Once these devices are ready, they can be installed on BL-13B for the final beam polarization measurement, which is expected to take place in late 2025.

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