PARITY-VIOLATING NEUTRON SPIN-ROTATION MEASUREMENTS AT NIST

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Abstract

In order to constrain weak coupling constants between nucleons, the Neutron Spin Rotation (NSR) collaboration has placed an experimental upper bound on the parity-violating spin rotation of transversely polarized neutrons transmitted through liquid helium. These measurements also place limits on the existence of possible long-range parity-odd forces [1]. Particular attention has been paid to reducing possible systematic errors below the statistical precision of the measurement. In addition, simulations of the beam transport and target interactions have been used to investigate systematic errors from small-angle scattering in the target and help plan the next generation experiment. The recent experiment performed on the NG6 neutron beam at the NIST Center for Neutron Research (NCNR) yielded a statistically-limited rotation angle of $d\phi/dz = [+1.7 \pm 9.1(stat.) \pm 1.4(sys.)] \times 10^{-7}$ rad/m [2]. The NSR collaboration is currently upgrading the apparatus to accept the higher flux and increased phase-space of the new NGC beam at the NCNR.

Introduction

The Neutron Spin Rotation (NSR) collaboration seeks to constrain hadronic weak coupling constants by measuring parity violating neutron spin rotation in liquid ^{4}He [2,3].

Longstanding uncertainty in details of the hadronic weak interaction (HWI) stems largely from the very short range of the quark-quark weak interaction (∼0.01 fm) compared with the range of nucleon-nucleon interactions (∼1 fm) and the relative strength of the weak to strong force between strongly interacting particles ($\sim 10^{-6}$). Experimentally one uses parity violation to isolate the weak contribution.

The primary analysis tool over the last 25 years has been the meson exchange model of Desplanques, Donoghue, and Holstein (DDH) [4], which models the HWI between nucleons as via an exchange of a light meson (π, ρ, ω) where the meson couples to the nucleons via strong coupling at one vertex and weak coupling at the other. This model leads to six meson coupling constants which need to be fixed by measurement. Different experiments are sensitive to different linear combinations of the coupling constants. For instance, neutron spin rotation in combination with existing (p,α) longitudinal analyzing powers [5,6] and photon asymmetry in radiative decays in ^{19}F [7,8] help isolate the isovector from the isoscalor contributions. Theoretical progress is also being made using effective field theories to parameterize the HWI in a model-independent way based on underlying symmetries [9]. A calculation of the isovector coupling, f_π, using lattice QCD has also recently been published [10]. Thus, a suite of parity-violating measurements, of which neutron spin rotation is a part, is needed to constrain ongoing theoretical efforts to understand the HWI.

Spin rotation in neutron transmission through matter arises from the dependence of the neutron's index of refraction on the forward scattering amplitude, $f(0) = f_{PC} + f_{PNC}$, which itself has parity conserving (PC) and parity non-conserving (PNC) terms,

$$n = 1 + \left(\frac{2\pi}{k^2}\right) \rho \left[f_{PC} + f_{PNC}\left(\vec{\sigma}_n \cdot \vec{k}_n\right)\right], \tag{1}$$

where ρ is the target density, k is the neutron wavenumber, and σ_n is the neutron spin. For the case of a polarized neutron incident on an unpolarized target the dependence on this forward scattering amplitude leads to a helicity dependence in the index of refraction. A transversely polarized beam carries with it a superposition of both helicity states which each acquire different phases. This effect causes the polarization axis to rotate about the beam direction ($\hat{z}$-axis) as the neutron travels through the medium. The PNC rotation angle is given by

$$\phi_{PNC} = \phi_+ - \phi_- = 4\pi\rho z f_{PNC}, \tag{2}$$

where z is the distance traveled through the target.

Given the small expected rotation value of $\frac{d\phi}{dz} \sim 10^{-7}$ rad/m, any experiment will need to contend with rotations due to precession about longitudinal fields, such as the earth's magnetic field. The NSR experiment uses three layers of magnetic field suppression to reduce longitudinal fields to 100 μG in the target region. Even at this level, however, parity conserving rotations from precession about longitudinal fields are on the order of 2 mrad/m.

The approach to reduce this false effect by nearly five orders of magnitude takes two basic steps. As shown in Fig. 1 the target has two chambers upstream and downstream of a 5-cm long region of vertical magnetic field supplied by a π-coil. Vertically polarized neutrons will rotate about the beam axis ($\hat{z}$-axis) from either longitudinal magnetic fields

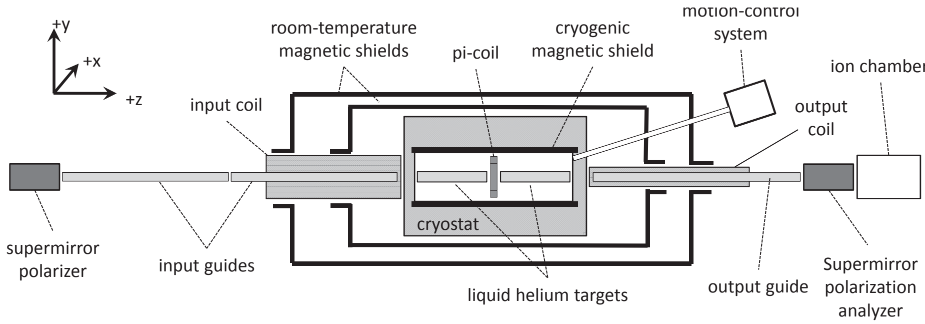


Figure 1: Layout of NSR apparatus. Neutrons enter from the left, exit a supermirror polarization filter, proceed through glass waveguides and magnetic spin transport, enter the upstream target, are rotated 180° about the $\hat{y}$-axis (π-coil), enter the downstream target, proceed through glass wave guides and magnetic spin transport which rotates the neutron spin ±90° about the $\hat{z}$-axis (output coil), analyzed by the supermirror analyzer and are detected in a ^{3}He ionization chamber (Adapted from Ref [2])

or parity-violating interactions with the target itself. The field of the π-coil is designed to rotate the neutron polarization direction rotation by 180° about the vertical axis ($\hat{y}$-axis). This changes the sign of any horizontal component of the polarization which neutrons acquired from PC or PNC rotations. We first consider the PC rotations which are independent of which target chamber is filled. Because the two chambers are machined to equal lengths (fractional difference $\sim 10^{-4}$), the target-chamber related PC rotation, ϕ_{PC}, is effectively canceled by the action of the π-coil. That is, the neutron could rotate clockwise in the first half of the target region, have its horizontal component flipped by the π-coil, and then rotate the same amount clockwise in the second half of the target, thereby rotating back to zero. In practice there is a non-zero PC rotation for neutrons emerging from the target region due to fringing fields and the fact that while the target chambers themselves are nearly identical, the total distance traveled by a neutron before and after the π-coil in the low-field region is not identical.

The second step, switching whether the upstream or downstream target is filled with liquid helium, removes the rest of the PC rotation and simultaneously isolates the PNC rotation. Because filling the upstream versus downstream chambers does not affect the PC rotation, subtracting the rotations for the two cases further reduces ϕ_{PC}. At the same time, the sign of the PNC rotation, ϕ_{PNC}, depends on which target is filled. When the upstream chamber is filled, the sign of the rotation acquired in that target is flipped by the π-coil and no additional PNC rotation is added in the empty second half of the target. Conversely, when the downstream target is filled, no PNC rotation is acquired in the first half of the target and the resulting rotation from the filled second half has a sign opposite to that of the case when the upstream target is filled. Thus, by alternately filling the upstream and downstream chambers and subtracting the results, one can isolate ϕ_{PNC}.

The difficulty with this second step is that the incoming neutron flux may vary during the time between target position changes, and since our experiment is a counting experiment, beam fluctuations would result in additional noise in the subtracted rotations. To address this additional noise, the experiment is divided horizontally to produce two side-by-side experiments, where target states are given by filling chambers UpStream-Left and DownStream-Right followed by filling UpStream-Right and DownStream-Left. Since the left and right experiments see essentially the same reactor fluctuations, through the double subtraction of Up-Down and Left-Right, we are able to reduce effects of reactor noise by a factor of 10, reducing the random fluctuations to within $\sim 10\%$ of pure counting statistics.

Experimental Details

Fig. 1 shows a schematic of the NSR Apparatus. A cold neutron beam with a peak wavelength of 5 Å from the ^{58}Ni NGC waveguide with a critical angle 2.1 mrad/Å at the NIST Center for Neutron Research (NCNR) is vertically polarized by a 4.5 cm$\times$4.5 cm supermirror polarizer. It then travels through a float-glass waveguide with a critical angle of 0.68 mrad/Å which includes guide fields to preserve the vertical spin as the neutron passes from the magnetic field of the supermirror polarizer to the 100-μG target region. The helium targets are cooled to 4.2 K in a non-magnetic cryostat [11] which includes a layer of cryoperm surrounding the four target chambers and the π-coil. Two additional layers of mu-metal keep the ambient fields in the target region to less than 100-μG.

Neutrons leave the target region and enter a float-glass waveguide surrounded by coils that adiabatically precess the polarization by $\pm 90°$ about the beam axis. This process converts any acquired horizontal component of the polarization axis to a vertical component, which can be analyzed by the vertical analyzing supermirror. A segmented ^{3}He ion chamber detects the neutrons in four spatial quadrants (U/D,L/R) as well as four separate longitudinal sections in order to separate neutrons as a function of energy based on the energy-dependent mean free path in ^{3}He gas. Since the PC rotation depends on neutron energy and the PNC rotation does not, data collected by these four chambers can be used to further isolate the PNC rotation. In addition, the energy dependence of the non-zero PC rotation given by these four sections of the ion chamber are used to infer the average longitudinal field in the target region which are compared to flux gate measurements [3].

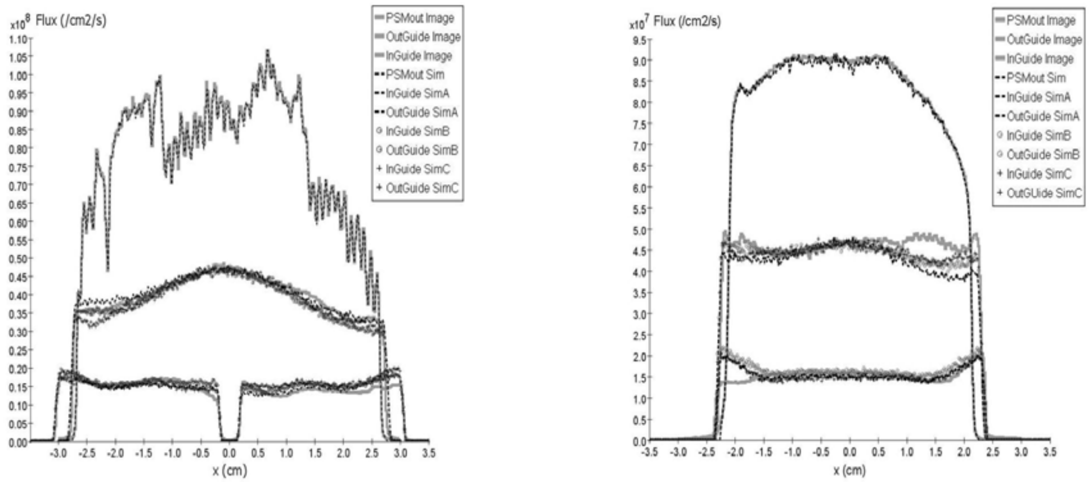
The direction of the 90° rotation in the output waveguide is flipped at 1-Hz to form an asymmetry in the neutrons detected after the analyzing supermirror. Thus, a spin rotation angle is determined from this asymmetry every two seconds,

$$\phi = \frac{1}{PA} \frac{N^+ - N^-}{N^+ + N^-}, \tag{3}$$

where N^+ and N^- are the counts for the two different states of the output coils and PA is the product of the polarization and analyzing power of the apparatus. The product PA has been determined to 5% accuracy as described in Ref. [12].

Simulations

A number of possible systematic errors are discussed in [2,3,12]. The most significant class of such effects are those coupled to both longitudinal fields in the target region



(a) (b)

Figure 2: Measured and simulated flux of the NSR apparatus on the NG6 beamline at NIST for a 1-cm wide horizontal slice (a) and a 1-cm wide vertical slice (b). The solid lines show neutron activation measurements for three beam positions, after the polarizing supermirror, after the input guides, and after the output guide. Dotted lines show simulations for slight adjustments to beam alignment.

and target-dependent effects. One such systematic that has been investigated by simulation is counting asymmetries due to non-forward scattering. Since the targets are different distances from the detector, energy changes, path-length differences, and detection solid-angle differences for neutrons scattered from the upstream and downstream target positions can lead to different average rotation values. A Monte-Carlo simulation of the apparatus chooses neutron trajectories from the measured output phase space of the polarizing supermirror and transports the neutrons through the waveguides, air gaps, and Al windows. Neutrons also interact with the liquid helium targets where non-isotropic small angle scattering is simulated. The overall neutron transport agrees with measurements of neutron flux at different positions along the beamline [12] and shows sensitivity to the types of slight misalignment (~ 1 mrad) that are possible [14]. Fig. 2 shows profiles of vertical and horizontal slices of beam images using neutron activation of Dy foils normalized to capture flux measured with calibrated fission chambers [12] at the output of the polarizing supermirror, the output of the input guides and the output of the output guide. Included in the figure are results of simulations for various slight changes in alignment of the beamline.

The simulations can also be used to study the affects of magnetic fields in the target region and magnetic field gradients [3]. Results from various simulations with and without magnetic field gradients suggest false rotations due to small angle scattering are less than 4×10^{-8} rad/m for a 100-μG field.

Results and Future Work

The NSR collaboration has developed a neutron polarimeter which is sensitive to minute rotations from interactions between polarized neutrons and matter (order 10^{-7} rad per meter of target material). Parity-violating interactions via the hadronic weak interaction induce such rotations, and an upper limit of $d\phi/dz = [+1.7 \pm 9.1(stat.) \pm 1.4(sys.)] \times 10^{-7}$ rad/m [2] has been placed on the rotation of neutrons in liquid helium by the NSR collaboration. Intense effort has been placed on constraining a variety of systematic errors to the 1.4×10^{-7} level [2,3]. The upper limit presented here helps constrain the strength of the hadronic weak interaction, but a more precise measurement is possible to achieve tighter limits. In addition, these results place the most stringent limits to date on parity-violating long-range fifth-force interactions [1].

In order to reduce the statistical error in this statistics-limited measurement, the NSR collaboration is building an improved apparatus to take advantage of the larger-aperture (11 cm×11 cm), higher-flux (2.5×10^9/cm^2/s) [13], NGC beam at the NCNR which will become operational in 2014. Two new 10 cm×10 cm polarizing supermirrors will polarize and analyze the beam. To retain a greater faction of the more divergent beam on NGC than was done on NG6 with glass wave-guides, m=2 non-magnetic supermirror wave-guides are being built. An enlarged target chamber is being built which will employ a more efficient liquid He pumping system to reduce down time. A He re-liquifier will also reduce down time by improving the management of the liquid He target. With improved magnetic shielding in the target region, the NSR collaboration hopes to maintain magnetic fields below 10 μG in the target region. A new 10-cm diameter ion chamber of similar design to the existing chamber is currently being constructed. With the higher NGC flux, a larger area for neutron throughput, and supermirror waveguides, we expect the new experiment to reach a statistical precision of 2×10^{-7}rad/m for the extracted parity-violating spin rotation.

The increased divergence of the NGC beam coupled with supermirror waveguides which retain more of these divergent neutrons increases the possibility of systematic errors due to small angle scattering from the upstream versus downstream target positions. Simulations used for the NG6 experiment have been adapted to the new setup on NGC. In addition, the neutron phase space from simulations of the new supermirror polarizer placed after the simulated NGC beam is used as input to the transport code of the spin-rotation apparatus. These simulations confirm the expected flux increase at the detector over the previous experiment ($\sim 7 \times 10^7$ /cm^2/s) as well as better spatial uniformity. Preliminary simulation results indicate that we can expect a systematic error from small angle scattering from the two positions of the liquid He targets to be below the desired statistical accuracy [14].

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References

[1] H. Yan, W. M. Snow, Phys. Rev. Lett. **110**, 082003 (2013).
[2] W. M. Snow, *et* al., Phys. Rev. C **83**, 022501(R) (2011).
[3] W. M. Snow, *et* al. (in preparation).
[4] B. Desplanques, J. F. Donoghue, B. R. Holstein, Ann. Phy. **124** (1980) 449–495.
[5] J. Lang, *et* al., PRL **54** (1985) ff. 170.
[6] R. Henneck, *et* al., PRL **48** (1982) ff. 725.
[7] E. G. Adelberger *et* al., PRC **27** (1983) ff. 2833.
[8] K. Elsener *et* al., PRL **52** (1984) ff. 1476.
[9] M. J. Ramsey-Musolf, S. A. Page, Annu. Rev. Nucl. Part. Sci. **56** (2006) 1–52.
[10] J. Wasem, PRC **85**, 022501(R)(2012).
[11] C. D. Bass, *et* al., NIM A **612** (2009) 69–82..
[12] A. M. Micherdzinska, *et* al., NIM A **631** (2011) 80–89.
[13] J. C. Cook, Rev. Sci. Instr **80**, 023101 (2009).
[14] B. E. Crawford *et* al., (in preparation).