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Status of the NPDGamma Experiment at the SNS

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Abstract The main goal of the NPDGamma experiment is to measure the gamma-ray asymmetry with respect to the neutron spin direction in the nuclear reaction $\vec{n} + p \to d + \gamma$. The up-down asymmetry A_γ has a predicted size of the order of $5 \cdot 10^{-8}$, and the NPDGamma experiment is designed to measure it with an uncertainty of about 10^{-8}. To test the entire apparatus the gamma-ray asymmetry from neutron capture was measured using a Cl target followed by measurements on Al to establish the relevant background levels. At present the experiment is taking data with a liquid H_2 target to measure the parity violation on the $\vec{n} + p \to d + \gamma$ reaction and extract the $\Delta I = 1$ part of the hadronic weak interaction.

Keywords weak interation · parity violation · neutron capture · gamma rays

1 Introduction

While the strong and electromagnetic forces conserve parity, the weak force does not. The weak force between quarks is 10^{-7} times smaller than the

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strong force and is responsible for parity-violating effects in the nucleon-nucleon system. The main goal of the NPDGamma experiment is to measure the gamma-ray asymmetry with respect to the neutron spin direction in the $\vec{n} + p \to d + \gamma$ reaction. The differential cross section for the capture of polarized neutron by nuclei is proportional to the factor:

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi} \left(1 + A_\gamma \cos\theta + B_\gamma \sin\theta\right) \tag{1}$$

In the above equation θ is the angle between the neutron spin direction and the gamma ray initial momentum. For a neutron beam polarized in the vertical direction normal to the axis of the beam, the up-down asymmetry A_γ violates parity and the left-right B_γ conserves parity. The maximum parity-violating and parity-conserving terms are measured for gamma rays emitted along the neutron spin direction aligned with the magnetic field and along the horizontal direction normal to the beam axis, respectively. If the misalignment angle between the vertical detector axis and the direction of gravity is smaller than 1° then there is very little mixing between the two asymmetries [1]. The up-down asymmetry A_γ has a predicted size of the order of $5 \cdot 10^{-8}$, and the NPDGamma experiment is designed to measured it with an uncertainty of about 10^{-8}.

In the absence of any systematic effects, a non-zero asymmetry A_γ comes from the small parity non-conserving admixture of the P-wave states in the initial S -wave singlet and the final S-wave triplet states. The only significant contribution to the A_γ asymmetry comes from the weak pion exchange. The measured asymmetry and the weak meson couplings are related [2–7] with three coupling constants:

$$A_\gamma = -0.1069 h_\pi^1 - 0.0014 h_\rho^1 + 0.0044 h_\omega^1 \,. \tag{2}$$

The hadronic weak interaction probed by measuring A_γ is therefore almost purely $\Delta I = 1$. The effect of the D- wave state admixture in the deuteron ground state on these coefficients is negligible. A calculation of the weak meson-nucleon couplings from the Standard Model was first performed by Desplanques, Donoghue, and Holstein (DDH) by using a valence quark model in 1980 [8] and more recently in reference [2]. The predicted DDH best value for h_π^1 is 4.7×10^{-7} [9]. Recently, the first lattice QCD calculation for this coupling gives a value of $(1.011 \pm 0.505) \times 10^{-7}$ [10].

The most sensitive experiments designed to measure the parity violation in the $\Delta I = 1$ channel used the ^{18}F gamma ray circular polarization [11]. These results and the arguments of the meson model [12] suggest that $h_\pi^1 \leq 1.2 \times 10^{-7}$. The non-zero measurement of the anapole moment of ^{133}Cs [13] has been used to calculate $h_\pi^1 = (9.6 \pm 2.2 \text{ (exp.)} \pm 3.6 \text{ (theor.)}) \times 10^{-7}$ [14]. Because the two values do not agree in the limits of experimental errors, the $\Delta I = 1$ part of the hadronic weak interaction remains undetermined.

2 The NPDGamma experimental set-up

Figure 1 shows a schematic view of the NPDGamma experimental setup at the fundamental neutron physics beam line (BL13) of the pulsed, spallation neutron source (SNS) at Oak Ridge National Laboratory (ORNL). Cold neutrons from the SNS are polarized by passing through a Super Mirror Polarizer (SMP). After the SMP the neutron polarization is aligned with the vertical main magnetic field. The direction of the neutron spin just before the target can be rotated by a radio-frequency (RF) resonant neutron spin rotator (SR) [17] . To control the drifts in the efficiency of the experiment, the neutron spin is rotated within an eight pulse sequence: during the 2^{nd}, 3^{rd}, 5^{th} and 8^{th} pulse the spin is rotated 180^o and in the other pulses the spin direction stays unchanged. Flipping the spin this way also takes care of gain differences between detector pairs used to form the photon asymmetries. Since in a pulse the neutrons with different energy arrive to the experiment at different time of flight, the amplitude of the RF field is varied to reverse the spins at all neutron energies with high efficiency.

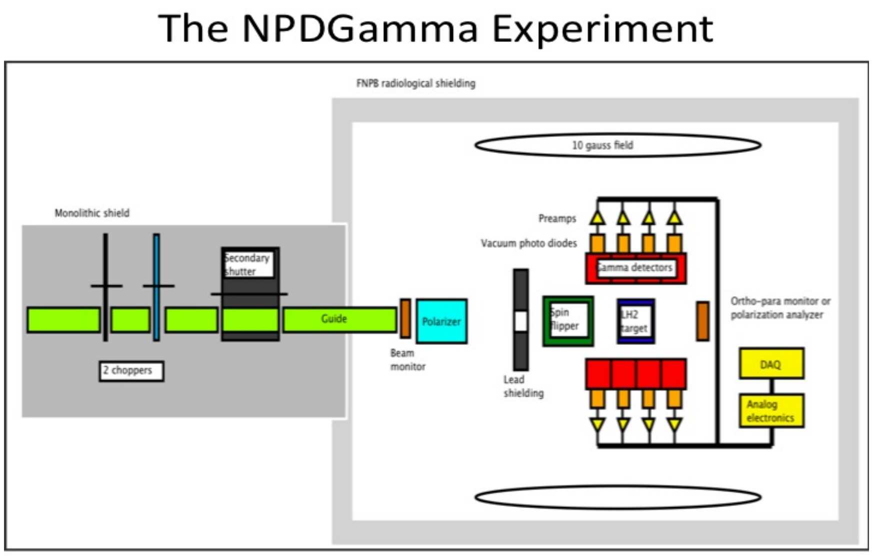

Fig. 1 A schematic view of the NPDGamma setup. Cold neutrons are polarized after passing a super mirror polarizer (SMP), the neutron spins are flipped by a resonant spin rotator (SR), and their polarization is maintained by a highly uniform field. The 16-liter liquid hydrogen target is surrounded by an array of CsI detectors.

The polarized neutrons that exit the SMP are guided through the 10 G main vertical magnetic field produced by four main rectangular horizontal coils installed symmetrically with respect to beam axis with auxiliary coils wound around the four main coils. In addition to the main and auxiliary coils there are two pairs of vertical coils named "shim coils" located on the front, back, left and right sides of the aluminum main support frame. By adjusting the current in these shim coils the tilt angle of the magnetic field in the center of the detector can be decreased. The polarized neutrons move through the magnetic field of the guide coils passing through the RF-resonant Spin Rotator and arrive to the target surrounded by the four rings of detectors. Soft low carbon steel plates are attached on the surface of the floor, ceiling and the two lateral walls of the BL13 enclosure to provide magnetic and radiological shielding. These plates form a return yoke for the field flux and attenuate the residual magnetic fields outside the BL13 enclosure to less than 25 mG. The plates also decrease the variations in the magnetic fields generated outside the enclosure, to assure a stable magnetic field inside the main coils. The optimum distance between the two middle main coils and between the top main coil and the shield was calculated using a finite-element model in Opera 3D, and the optimum ratio of the currents in the top-bottom and middle coils was adjusted with the goal of minimizing the average field gradient in the y direction dB_y/dy over the volume between the SR and the end of the liquid H_2 target.

The liquid hydrogen target system includes the 16-liter target vessel which is thermally connected to two mechanical refrigerators, filled through a combined fill/vent line, and thermally isolated inside an intermediate temperature radiation shield and a vacuum vessel. Helium gas surrounds the weld joints and o-ring seals in the vacuum vessel and the hydrogen piping system, which lie inside the experimental cave. The target must absorb as much of the polarized cold neutron beam flux as possible without depolarizing the neutron beam before capture. The need to prevent neutron depolarization requires the target to be in the para-hydrogen state at temperatures no higher than 17 K. The target system therefore is equipped with a cryostat to liquefy gaseous hydrogen at room temperature and an ortho-para converter (OPC) to catalyze the formation of para-hydrogen. The target system meets the national hydrogen safety codes as well as the laboratory safety standards.

The gamma rays from neutron capture are detected by an array of 48 CsI crystals grouped in four rings and each crystal is viewed by a vacuum photodiode. Each ring has 12 detectors arranged in a circular pattern around the target (see Fig. 2). The array covers a solid angle of about 3π. The centers of the detectors are at about 29 cm from the beam axis. The detectors are opperated in current mode because of the high neutron and gamma rays flux.

3 Status of the NPDGamma Experiment

The $\vec{n} + p \rightarrow d + \gamma$ parity-violating up-down asymmetry A_γ was measured in the first phase of the NPDGamma experiment at the Neutron Scattering Center LANSCE at Los Alamos National Laboratory [15]. The experimental result did not have enough statistical precision to test the theoretical prediction. After the completion of this experiment the entire experimental setup was moved to the SNS at ORNL. Some of the main modifications needed to

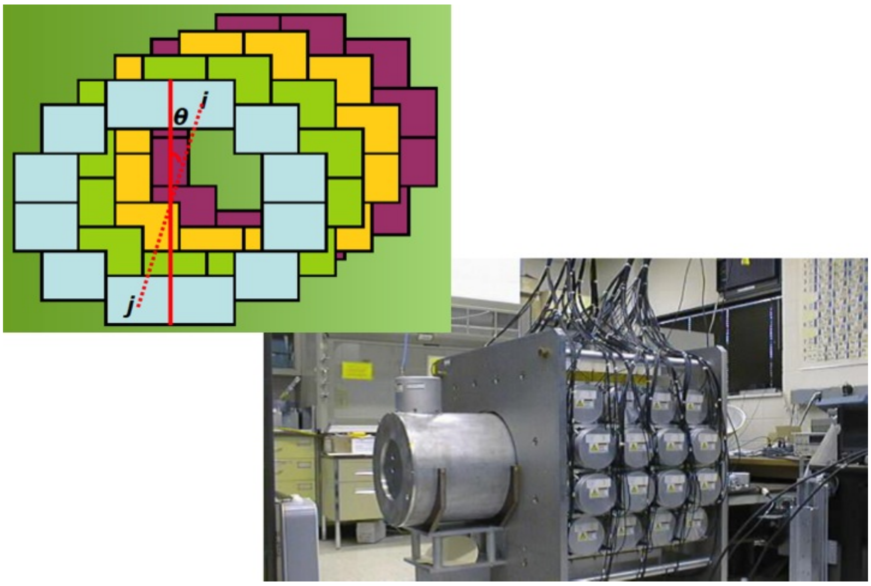

Fig. 2 Left: a sketch of the four rings consisting of 12 detectors each. Right: a photograph of the array in a testing room. In the experiment beam enters from the left into the SR, enclosed in a cylindrical Al can, and then interacts with the liquid hydrogen vessel to be located at the center of the detector array.

run the experiment at the SNS were the implementation of a Super Mirror Polarizer (SMP) and the building of a Compensation Magnet (CM) around the SMP to decrease their total fringe field at the center of the detector array [16]. Prior to the installation of the new hydrogen target the entire apparatus was commissioned and the first measurements of neutron capture on nuclear targets were performed. In addition, the target vessel was rebuilt with thinner Al windows and it was successfully commissioned at the new location. Since the proton target is liquid Hydrogen (H_2) contained in an Al vessel the parity violation asymmetry from Al has to be known with a precision smaller than $4 \cdot 10^{-8}$. At the time of this writing the experiment had started to run with a liquid H_2 target to measure the parity violation on the $\overrightarrow{n} + p \rightarrow d + \gamma$ reaction.

To test the entire apparatus the gamma ray asymmetry from neutron capture was measured using a Cl target, which has a well known and large parity-violating asymmetry (see Fig. 3). This was followed by measurements on Al to establish the relevant background levels since the main contributions to the gamma ray asymmetry in the Hydrogen target come from the neutrons captured in the liquid Hydrogen and in the Al entrance windows [18]. The measured asymmetry A_{raw} with the H_2 target is the weighted sum of the background asymmetry A_b of the gamma rays emitted from Al and the asymmetry A_p from the neutrons captured in liquid Hydrogen.

$$A_p = A_{raw}(1 + \epsilon) - A_b \epsilon \tag{3}$$

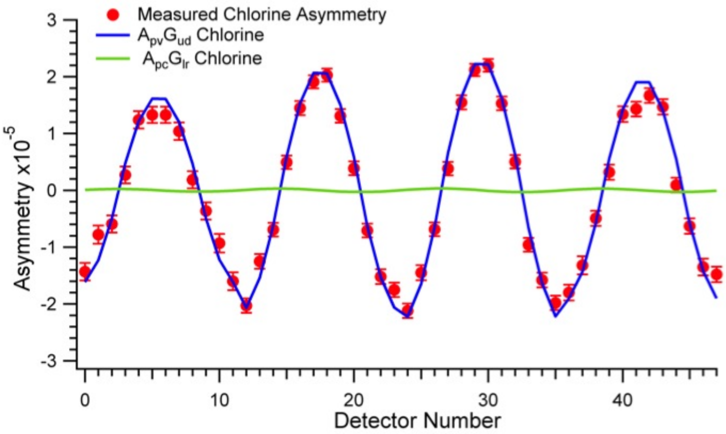

Fig. 3 The raw Cl asymmetries as a function of the detector number. The blue curve corresponds to the contribution from the parity violating term and the green curve to the contribution from the parity allowed term.

The fractional detector background is $\epsilon = N_b/N_p$ where N_b and N_p are the number of detected γ rays emitted from Al and H_2 respectively, per unit time. The uncertainty in the background correction σ_b increases the uncertainty σ_{raw} in the total raw asymmetry measured with the H_2 target:

$$\sigma_p^2 = (1+\epsilon)^2\sigma_{raw}^2 + \epsilon^2\sigma_b^2 \tag{4}$$

To control the systematic errors due to beam fluctuations and gain mismatch the neutron spin is flipped from up to down by passing through the Spin Rotator. The optimum size of the CsI crystals (15 cm) was determined from Monte Carlo calculations of the energy absorbed in the detectors, for 2.2 MeV gamma rays emitted from $\vec{n} + p \rightarrow d + \gamma$ reaction. Geometrical factors G_{ud} and G_{lr} were determined to take into account the finite size of the beam, targets, and detectors.

The raw Al asymmetries are shown in Fig. 4 as a function of the detector number. The shape of the parity-violating (A_{pv}) and parity-conserving (A_{pc}) asymmetries are given by the blue and green curves, respectively. The Al plot shows that the A_{pc} asymmetry is non-zero and that any A_{pv} asymmetry is small compared to the parity A_{pc} asymmetry. Final refinements to the data analysis are underway to obtain the A_{pv} and A_{pc} asymmetries. The data shown in Fig. 4 indicates that the A_{pv} and A_{pc} asymmetries in Al are small enough to not cause any systematic uncertainty in the $\vec{n} + p \rightarrow d + \gamma$ asymmetry when the Al background is subtracted.

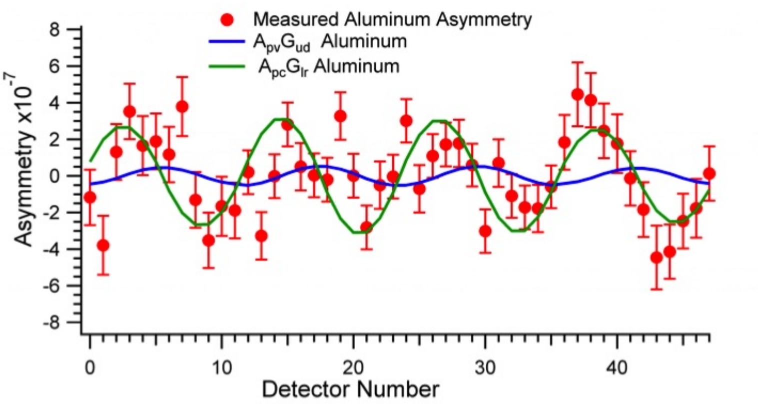

Fig. 4 The raw Al asymmetries as a function of the detector number. The blue curve corresponds to the contribution from the parity violating term and the green curve to the contribution from the parity allowed term.

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