Parity-Violating Gamma Asymmetry in np-Capture

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Abstract

The npdgamma Collaboration uses a pulsed polarized cold neutron beam, a para-hydrogen target, and an array of 48 CsI scintillation detectors to measure, in n+p $\rightarrow$ D + γ reaction, the parity-violating asymmetry A_γ of the photons emission along the neutron spin and opposite to it. The theory-predicted value is $A_\gamma \approx -0.5 \times 10^{-7}$. Knowledge of A_γ and other parity-violating observables in few-body nuclear systems should provide constraints for a parameterized description of the parity-violating phenomena free from complications of nuclear structure. We report final results of the first phase of the experiment, which took place at the spallation neutron source of the Los Alamos Neutron Science Center: $A_\gamma = -(1.2 \pm 2.1(\text{stat.}) \pm 0.1(\text{sys.})) \times 10^{-7}$, and the parity allowed, left-right (LR) asymmetry $A_\gamma^{LR} = -(1.8 \pm 1.9(\text{stat.}) \pm 0.2(\text{sys.})) \times 10^{-7}$. Our A_γ value reproduces the previous upper limit from a measurement at the Grenoble ILL reactor facility, while the A_γ^{LR} value is obtained for the first time. The second phase of the experiment, aimed at a better statistical accuracy, is presently started by the npdgamma Collaboration at another source − the Spallation Neutron Source of the Oak Ridge National Laboratory.

Introduction

The observable of interest in the polarized cold neutron capture $\vec{n} + p \rightarrow D + \gamma$ (E_γ=2.2 MeV) is the parity-violating (PV) asymmetry A_γ in the angular distribution of the 2.2-MeV photons with respect to the direction of the neutron polarization $\mathbf{P_n}$

$$\frac{d\omega}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_\gamma P_n(\mathbf{s_n}\cdot\mathbf{k}_\gamma)\right). \tag{1}$$

The scalar product in this equation reduces to $\pm\cos\theta$ where θ is the angle between the neutron spin $\mathbf{s_n}$ and gamma momentum $\mathbf{k}_\gamma$ ($\mathbf{s_n}$ and $\mathbf{k}_\gamma$ are unit vectors). In the absence of parity violation, $A_\gamma = 0$. A nonzero asymmetry A_γ results from an interference between regular M1 and the PV admixed E1 gamma transitions. The M1 transition connects the parity conserving ${}^1S_0$ np scattering state to the parity conserving ${}^3S_1$ deuteron state (labeling of states is ${}^{2J+1}L_I$ with $L = S,$or P as the orbital momentum, $I -$ the spin of the pair and $J -$ the total momentum). The E1 transition can be, for example, from the ${}^3S_1$ np-scattering state to the PV admixed ${}^3P_1$ deuteron state. The matrix elements $\langle {}^3S_1|\mathbf{M1}|{}^1S_0\rangle$ and $\langle {}^3P_1|\mathbf{E1}|{}^3S_1\rangle$ can be calculated in theory, see for example [1, 2, 3]. In the meson-exchange framework, the result for A_γ, which is essentially the ratio of of these quantities, is

$$A_\gamma = -0.1069h^1_\pi - 0.0014h^1_\rho + 0.0044h^1_\omega \approx -0.11h^1_\pi, \tag{2}$$

where the h^1_π, h^1_ρ, h^1_ω are weak meson-nucleon coupling constants. They have been calculated in Ref. [4] from the Standard Model using a valence quark model of QCD. In this meson exchange picture, the nucleon-nucleon weak interaction is modeled as a process in which the three lightest mesons (π, ρ, and ω) couple to one nucleon via the weak interaction at one vertex and to the second nucleon via the strong interaction at the other vertex. In the latest decade the effective field theory approach to the weak interaction has been also developed, e.g. in Refs. [5, 6, 7],. It reformulated the problem in terms of the parameters of the parity violating Lagrangian. This new approach, which thought to be less model dependent, invigorated the present study of parity violation in the npdγ reaction and few body systems.

In particular, the value of the h^1_π coupling constant is widely debated. With the 'best DDH' value of $h^1_\pi = 4.6 \times 10^{-7}$ the predicted A_γ value is $\approx -5 \times 10^{-8}$. Such a value is really small and has not been yet experimentally proved, only an upper limit of $\sim 10^{-7}$ was obtained in the npdγ experiment at Grenoble [8, 9]. Measurements of the circular polarization of the gamma ray decay in ^{18}F, e.g. [10], and of the parity-violating triton emission asymmetry in the ^{6}Li(n,α)T reaction [11] have been interpreted to indicate a rather small value $h^1_\pi \leq 1 \times 10^{-7}$ as compared to the theory expectation, while the anapole moment of ^{133}Cs from the parity violation in Cs atoms seem to favor a much larger value [12], $h^1_\pi = (9.5 \pm 2.1) \times 10^{-7}$. So the h^1_π remains to be proved experimentally.

The left-right asymmetry in the npdγ reaction is due to the parity-allowed interference of M1 and E1 capture amplitudes and is described by the form $A^{LR}\mathbf{s_n}\cdot[\mathbf{k_n}\times\mathbf{k}_\gamma] \propto 1 \pm A^{LR}P_n\sin\theta\sin\phi$. The angle ϕ is between $\mathbf{k_n}$ and $\mathbf{k}_\gamma$. The calculated value A^{LR} is 0.67×10^{-8} at energy of 3-meV [13] and increases linearly with the neutron energy.

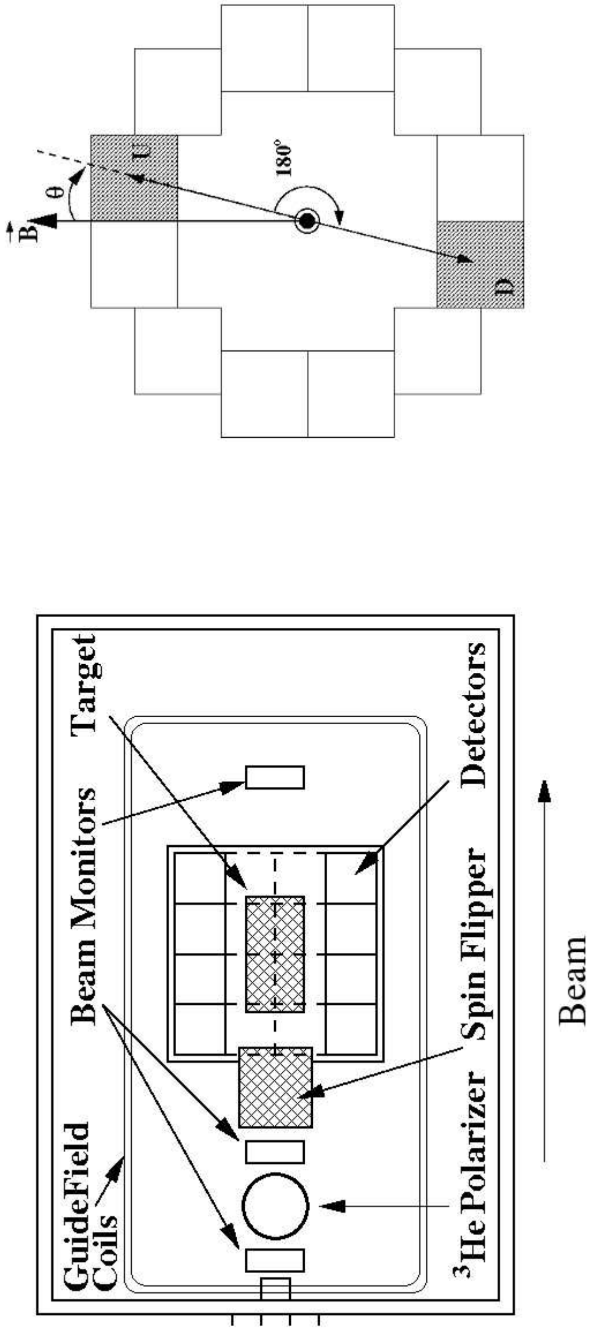

Figure 1: The experimental setup of the npDg experiment at LANSCE.

The apparatus and experiment

The np→Dγ experiment has been performed at the spallation neutron source of the Los Alamos Neutron Science Center (LANSCE) [14]. The spallation neutrons, produced by 20 Hz 250 ns-long 800 MeV proton pulses on a tungsten target, are moderated by a 5 cm-thick liquid hydrogen moderator. The neutron flight path FP12 and the apparatus were developed by the Collaboration. The FP12 neutron supermirror guide ends at about 20 m from the moderator. Fig. 1 shows a schematic side view and the cross section of the apparatus. Not shown are magnetic field coils providing a vertical guide field. There are three beam monitors. The distance from M1 to M3 is about 1.7 m. Besides the guide, the flight path beam line consists of a shutter, and a beam chopper. The chopper is used to define the neutron time of flight region within the 50 msec time of flight frame set by the 20 Hz source frequency. This corresponds to energy range from 2 to 15 meV and prevents neutrons from different frames from mixing. For this energy range, the integrated neutron current at the end of the guide was measured to be 1.0×10^9 n/s s at an average proton current of 100 μA. An instantaneous intensity was about four order of magnitude higher, therefore the gamma-detector array, as well as monitors, were run in current mode [15].

The neutrons were vertically polarized by passing through a 12 cm diameter glass cell containing polarized ^{3}He [17, 18, and references there]. The ^{3}He polarization was monitored using NMR. The beam polarization was measured with the beam monitors using neutron transmission through the polarized and unpolarized ^{3}He target. The neutron energy averaged polarization was 55±7 %. The beam polarization was reversed with each spallation pulse using a radio frequency (RF) spin rotator [16] − a solenoid positioned coaxially with the beam that operates by magnetic spin resonance. In this device, the neutron spin precesses in the presence of the static 10 G holding field and RF field of the solenoid. To make RF field proportional to the neutron velocity, the amplitude of the RF field was varied in time as 1/TOF, so that all neutrons within the measured time-of-flight (TOF) region were rotated by 180° while moving inside the solenoid.

The proton target was a 16-liter parahydrogen in a cryogenic vessel [19]. About 60% of the polarized neutrons that enter the target are captured on hydrogen. The parahydrogen is required to ensure that the neutrons are not depolarized in the liquid hydrogen before capture. Ortho-H_2 depolarizes cold and thermal neutrons, while in para-H_2 only thermal neutrons with energies greater than 16 meV are depolarized. The thermal equilibrium fraction of ortho-H_2 is known to be low at liquid hydrogen temperatures ($\approx$ 17 K), however the rate of conversion is slow. In our experiment, the para-H_2 concentration higher than 99.9% was achieved and maintained by circulating the liquid hydrogen through a chamber of iron oxide catalyst.

The 2.2-MeV gamma rays were measured using the detector described in [20]. This is an array of 48 CsI(Tl) scintillator cubes, each with a 15-cm side length. It was designed to have sufficient spatial and angular resolution, high efficiency, and large solid angle coverage. There are four rings of detectors, arranged in a cylindrical fashion. Each ring has twelve detectors, as shown in the cross sectional view of Fig. 1. Current mode detection is performed by converting the scintillation light from CsI(Tl) to current signals using vacuum photo diodes, and the photocurrents are converted to voltages and amplified by low-noise solid-state electronics [15].

Asymmetries were measured in TOF bins for 55 different neutron energies between 2 and 16 meV. The analysis of data was performed separately in this bins on each of the six detector pars in each ring. Geometry of pairs in one ring is shown in Fig. 1. The raw asymmetry A_{raw} for an Upper (U), Down (D) pair was defined by

$$A_{raw} = \frac{N_{U,\uparrow}(\theta) - N_{D,\uparrow}(\theta) - N_{U,\downarrow}(\theta) + N_{D,\downarrow}(\theta)}{N_{U,\uparrow}(\theta) + N_{D,\uparrow}(\theta) + N_{U,\downarrow}(\theta) + N_{D,\downarrow}(\theta)} \tag{3}$$

and the physics asymmetry A_γ was calculated from equation

$$A_\gamma P_n \; cos\theta = A_{raw}. \tag{4}$$

Here N is the detector signal. Symbols ↑ and ↓ refer to the direction of beam polarization. To suppress detector gain drifts, one such raw asymmetry was calculated (summed) over one eight step secuence (↑↓↓↑↓↑↑↓) and raw asymmetries were formed from all 'valid sequences' in the run. Typical run lengths were $\simeq$ 8.3 minutes and included 10000 beam pulses or 1250 eight step sequences. One successful week of measurements resulted in about 700 runs.

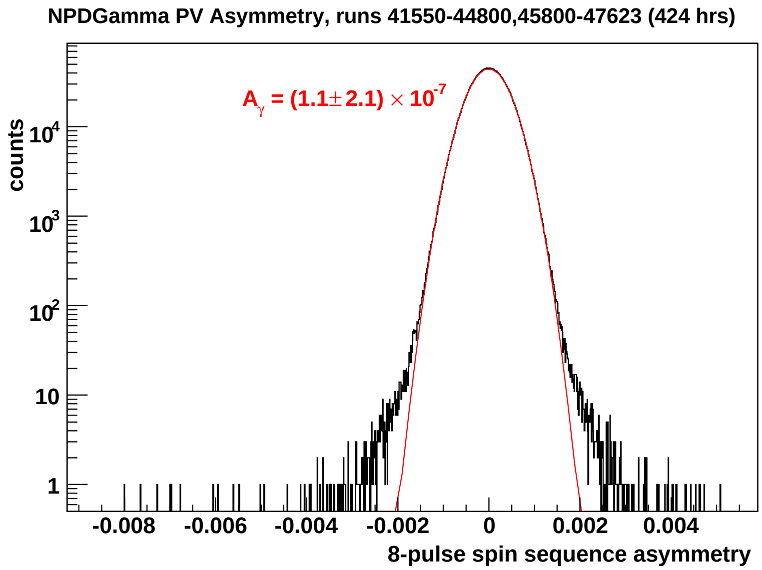

Figure 2: An example of measured row asymmetries for hydrogen.

The Results

Prior to the main experiment, the control measurements of the PV asymmetry in cold neutron capture on a 1-cm thick CCl_4 target have been performed. The obtained result

Table: PV asymetries results and their statistical uncertainties σ

Ring	ϵ	Direction	A_{raw} (ppm)	σ_{raw} (ppm)	A_γ (ppm)	σ_γ (ppm)
1	0.5	UD	-0.27	0.29	-0.38	0.49
		LR	-0.20	0.28	-0.20	0.49
2	0.4	UD	-0.015	0.24	0.01	0.36
		LR	-0.29	0.24	-0.33	0.35
3	0.2	UD	-0.17	0.33	-0.19	0.40
		LR	-0.38	0.27	-0.42	0.33
4	0.12	UD	-0.02	0.43	-0.013	0.48
		LR	0.41	0.40	0.48	0.45
Combined		UD	-0.12	0.15	-0.12	0.21
		LR	-0.23	0.14	-0.18	0.19

$A_\gamma(Cl) = -(19.0 \pm 2.0) \times 10^{-6}$ is in an agreement with that of $-(21.2 \pm 1.7) \times 10^{-6}$ in Ref. [21]. The left-right asymmetry is much smaller and cannot be seen in this measurement.

An example of measured row asymmetries for hydrogen is shown in Fig. 2. Detailed results are presented in Table. They are statistically limited. The final statistical uncertainties are higher than the uncertainties for the raw asymmetries due to a $\simeq$30% background. The main source of background were capture gamma rays from the aluminum wall of the cryogenic vessel. The quantity $\epsilon = Y_{bgr}/Y_p$ is the fractional background to hydrogen yield. The total asymmetry A_γ is a sum of a left-right parity-allowed term and an up-down PV term which were extracted from a fit to the angular dependence of $A_\gamma(\theta) \equiv A_\gamma^{UD} cos\theta + A_\gamma^{LR} sin\theta$.
The uncertainties on the beam polarization and spin flip efficiency were measured to be 5% and 1% respectively. Possible systematic uncertainties are discussed elsewhere [22].

Summary

The final result for the parity-violating asymmetry $A_\gamma = -(1.2 \pm 2.1(\text{stat.}) \pm 0.1(\text{sys.})) \times 10^{-7}$ reproduces the previous upper limit from a measurement at the Grenoble ILL reactor facility. The result for the parity allowed left-right (LR) asymmetry $A_\gamma^{LR} = -(1.8 \pm 1.9(\text{stat.}) \pm 0.2(\text{sys.})) \times 10^{-7}$ is obtained for the first time. The second phase of the experiment, aimed at a better statistical accuracy, is presently under preparation at the SNS of the Oak Ridge National Laboratory. The beam line FNPB with a supermirror polarizer is built there. The installed npDγ apparatus is currently undergoing modifications for running at FNPB. Both LANSCE and SNS are pulsed spallation sources, but SNS is expected to provide an average neutron intensity of about 30 times greater than at LANSCE. A main modification is the change of the Helium neutron polarizer to a supermirror FeSi bender having a 95% polarizing efficiency.

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