NPDGamma: a measurement of the parity-violating gamma asymmetry $A_\gamma$ in n-p capture

R C Gillis1,†, R Alarcon2, S Balascuta2, L Barrón-Palos3, J D Bowman4,*
R D Carlini5, W Chen1, T E Chupp6, C Crawford7, S Covrig5,
M Dabaghyan8, N Fomin9, S J Freedman10, T R Gentile11, M T Gericke12,
G L Greene10, F W Hersman8, T Ino14, G L Jones15, B Lauss16,
M Leuschner17, W R Lozowski18, R Mahurin15,12, Y Masuda14, J Mei1,
G S Mitchell17, S Muto14, H Nann1, S A Page12, S I Penttilä14,
W D Ramsay18, A Salas-Bacci19, S Santra1,a, M Sharma18, P-N Seo20,
E I Sharapov21, T B Smith22, W M Snow1, W S Wilburn19, V Yuan19

1 Indiana University, Bloomington, IN 47405, USA
2 Arizona State University, Tempe, AZ 85287, USA
3 Universidad Nacional Autónoma de México, C.P. 04510, D.F., Mexico
4 Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
5 Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
6 University of Michigan, Ann Arbor, MI 48104, USA
7 University of Kentucky, Lexington, Kentucky 40506, USA
8 University of New Hampshire, Durham, NH 03824, USA
9 University of Tennessee, Knoxville, TN 37996, USA
10 University of California, Berkeley, CA 94720-7300, USA
11 National Institute of Standards and Technology, Gaithersburg, MD 20899-0001, USA
12 University of Manitoba, Winnipeg, MB, R3T 2N2, Canada
13 High Energy Accelerator Research Organization, Oho 1-1, Tsukuba-shi, 305-0801, Japan
14 Hamilton College, Clinton, NY 13323, USA
15 Paul Scherrer Institut, CH-5232 Villigen, Switzerland
16 Department of Biomedical Engineering, University of California, Davis, CA 95616, USA
17 TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T 2A3, Canada
18 Los Alamos National Laboratory, Los Alamos, NM 87545, USA
19 Department of Physics, North Carolina State University, Raleigh, NC 27695, USA
20 Joint Institute for Nuclear Research, Dubna, Russia
21 University of Dayton, Dayton, OH 45469, USA
a Current address: Bhabha Atomic Research Center, Trombay, Mumbai 400085, India
* Principal investigator
E-mail: † rcgillis@indiana.edu

Abstract. The NPDGamma Experiment measures the parity-violating correlation $A_\gamma$ between neutron spin and photon momentum in the reaction $\vec{p} + p \rightarrow d + \gamma$. Knowledge of $A_\gamma$ and other parity-violating observables in few-body nuclear systems will provide constraints for a parameterized description of $\Delta S = 0$ parity-violating phenomena free from complications of nuclear structure. The NPDGamma experiment uses a polarized cold pulsed neutron beam, a liquid parahydrogen target, and a cylindrical array of 48 CsI(Tl) scintillation detectors operated in current mode to search for the asymmetry. NPDGamma recently completed the first phase of the program to measure $A_\gamma$ at the Los Alamos Neutron Science Center with the preliminary result $A_\gamma = (-1.2 \pm 2.1 \text{(stat.)} \pm 0.1 \text{(sys.)}) \times 10^{-7}$, reproducing the previous upper limit from a measurement at a reactor facility. We discuss the theoretical background and experimental method and report on preliminary analysis of the LANSCE data. The second phase of the
program to measure $A_\gamma$ is in progress at the Spallation Neutron Source at Oak Ridge National Laboratory.

1. An introduction to the theory
Measurements of parity violation (PV) in the nucleon-nucleon (NN) system at low energies can provide unique insight into the physics of QCD in the strongly interacting limit. Although PV comes from the weak interaction, its manifestation in hadronic systems at low energies necessarily involves the strong interaction, with nonperturbative QCD complicating the calculation of the observables. The weak interaction is in general hard to isolate experimentally at low energies in the NN system due to the presence of the dominant strong and electromagnetic interactions. While large nuclei provide mechanisms that enhance PV observables --- enough that many experimental observations have resolved PV effects --- the interpretation of such processes often calls for an ab initio understanding of many-body systems that does not yet exist. Experiments now emphasize few-nucleon systems which can possess a theoretically-clean interpretation. Recent reviews on this topic are found in [1, 2, 3].

PV in the NN system is traditionally described in terms of the DDH model, a quark model calculation that uses symmetry arguments and information from nonleptonic hyperon decays to deduce estimates of PV couplings in a single-meson-exchange theory [4, 5]. This approach is similar to successful meson-exchange descriptions of the parity-conserving (PC) NN interaction. In the PV theory the three lightest mesons are used, with neutral pseudoscalar mesons excluded since in their case P violation also entails CP violation and such amplitudes are at best highly suppressed. One vertex of the meson exchange violates parity and corresponds to the coupling that is unique to the DDH theory. The other coupling is determined from measurements of PC observables. The PV couplings are labeled by $h^{\Delta I}_{\mu}$ where $\Delta I = 0, 1$ or 2 is the isospin change, and $\mu$ is the meson type. There are a total of six couplings: $h^1_\pi$, $h^0_\rho$, $h^1_\rho$, $h^0_\omega$, $h^1_\omega$ and $h^1_\omega$ (a seventh coupling $h^1_\rho$ is considered negligible [6]). To reflect the considerable strong interaction uncertainties involved, DDH presented their work in the form of a set of best values with corresponding reasonable ranges.

More recently an effective field theory (EFT) approach is being developed for the PV NN interaction for the low energies and momenta relevant for most experiments [3, 7, 8, 9, 10]. The EFT approach is constructed to take into account all of the relevant symmetries and degrees of freedom in low energy QCD, in particular chiral symmetry. Since the perturbative expansion is in terms of the ratio of momentum to the QCD scale $\Lambda$, the unknown physics is hidden in the vertices. The theory then depends on parameters that can be determined from experiment. It is in principle possible to calculate the EFT parameters, however the physical insight associated with a model-based explanation is not as immediately apparent with the EFT approach.

The EFT approach has been expressed in different forms: one with pions fully integrated out, relevant for lower energies, and others with dynamical pions, including a possibility for two-pion exchange. The parameters of the pionless theory reduce at sufficiently low energies to a total of five independent $S \leftrightarrow P$ transition amplitudes. In the pionful theories, the same five parameters remain but incorporate different dynamics, and extra parameters that explicitly incorporate the pion dynamics are introduced.

The observable of interest in this experiment is the coefficient $A^{\gamma P}_{\gamma PV}$ ($A_\gamma$ when there is no ambiguity) of the PV correlation between neutron spin $s_n$ and gamma momentum $k_\gamma$ in the distribution $d\omega/d\Omega$ of gamma radiation from the capture reaction $\vec{n} + p \rightarrow d + \gamma$ (2.2 MeV):

$$\frac{d\omega}{d\Omega} \propto 1 + A_\gamma \frac{s_n \cdot k_\gamma}{|s_n| |k_\gamma|} + \cdots \quad (1)$$
An examination of the quantum numbers associated with initial and final states shows that \( A_\gamma \) depends entirely on \( \Delta I = 1 \) [11, 12].

By a symmetry argument (discussed e.g. in [1]), charged-current \( \Delta I = 1 \) processes are suppressed relative to neutral-current \( \Delta I = 1 \) processes by a factor of \( \tan^2 \theta_C \) where \( \theta_C \) is the Cabibbo angle. Neutral-current processes are therefore expected to dominate \( \Delta I = 1 \) channels. Neutral-current processes are of particular interest since they do not occur in \( \Delta S = 1 \) processes. \( \Delta S = 0 \) processes, and the \( \Delta I = 1 \) portion in particular, therefore give access to a missing piece of the as-yet incomplete picture of nonleptonic weak interactions.

The pion is expected to play a dominant role in the \( \Delta I = 1 \) part of the interaction. According to the DDH model, \( A_\gamma \) is expected to depend almost exclusively on \( h^1_\pi \) [1]:

\[
A_\gamma = -0.107 h^1_\pi - 0.001 h^1_\rho + 0.004 h^1_\omega,
\]

(2)
corresponding to a DDH best (most probable) value of \( A_\gamma \approx -5 \times 10^{-8} \). The dependence of \( A_\gamma \) on the EFT parameters has been calculated to be [9]:

\[
A_\gamma = -0.27 \tilde{C}^{\pi}_{60} - 0.09 m_N p_t,
\]

(3)

for a six-parameter theory valid at lab energies under 40 MeV, where \( \tilde{C}^{\pi}_{60} \) incorporates single-pion exchange and is proportional to \( h^1_\pi \); and \( m_N p_t \) is one of the five \( S \leftrightarrow P \) amplitudes.

While the PV NN interaction is characterized by total isospin change \( \Delta I = 0 \oplus 1 \oplus 2 \), in \( \Delta S = 1 \) decays we have \( \Delta I = \frac{1}{2} \oplus \frac{3}{2} \). In the \( \Delta S = 1 \) case, there is an empirical preference for \( \Delta I = \frac{1}{2} \) (known as the \( \Delta I = \frac{1}{2} \) rule), but this preference is of unclear dynamical origin. It’s possible that an understanding of the isospin dependence of the NN interaction could give us new insight into this problem. Particularly relevant to the \( \Delta I = 1 \) portion of \( \Delta S = 0 \), a question has arisen from the interpretation of two measurements: the anapole moment of \(^{133}\text{Cs} \), and the polarization of gamma radiation from \(^{18}\text{F} \) decays [3, 13, 14]. The \(^{18}\text{F} \) measurement suggests a value for \( h^1_\rho \) that is at the very low end of the DDH reasonable range. It would be interesting to see if this apparent suppression of a \( \Delta I = 1 \) weak NN amplitude relative to theoretical expectations is confirmed. The \(^{133}\text{Cs} \) measurement on the other hand can be interpreted to give a relatively large value for \( h^1_\rho \). A model-independent few-body approach may be helpful in addressing the questions arising from this issue.

2. The apparatus

The NPDGamma apparatus was installed at the Los Alamos Neutron Science Center (LANSCE) at Flight Path 12 (FP12) where the first phase of the \( A_\gamma \) measurement was conducted. The apparatus is currently being installed in preparation for the second phase of the measurement at the Fundamental Neutron Physics Beamline (FNPB) at the newly-built Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. Both facilities are pulsed spallation sources, but the FNPB will provide an average neutron rate incident on the target that is about 50 times greater than what was available at FP12.

Figure 1 shows a schematic side view of the NPDGamma apparatus as set up at FP12. The spallation neutrons are produced by 20 Hz, 250 ns long, 800 MeV proton pulses incident on a tungsten target [16] and are backscattered from a 5 cm thick cold hydrogen moderator into the FP12 neutron guide [17]. The average proton current for analyzed data runs was 87 \( \mu \)A. The end of the FP12 neutron guide is located 21 m from the moderator. Due to the high beam flux (a peak instantaneous rate of \( \approx 10^{10} \) neutrons/s exiting the FP12 guide) and the impracticality of finely segmenting detectors, the gamma detector array and beam monitors are run in current mode.

The beam monitors are parallel plate ionization chambers containing a mixture of \(^3\text{He}, \ ^4\text{He} \) and \( \text{N}_2 \) gases and are placed directly in the beam. The cross section for the exothermic reaction
Figure 1. A schematic side view of the NPDGamma apparatus during hydrogen data taking on FP12. Only two opposite detectors of each ring are shown. Not shown are field coils surrounding the entire apparatus which provide a vertical static magnetic field. M1, M2 and M3 are the three beam monitors. The distance from M1 to M3 is about 1.7 m. About 60% of the beam incident on the target is captured by hydrogen, and most of the remainder is absorbed in $\text{^6Li}$-enriched plastic outside the vessel. Only a small fraction of the beam passes through to M3.

$n + ^3\text{He} \rightarrow p + ^3\text{H}$ has a well-known $1/\sqrt{E}$ energy dependence. At FP12 and the FNPB there is a direct relationship between time of flight (TOF) and neutron energy since a beam chopper is used to prevent consecutive pulses from significantly overlapping. For fixed beam monitor properties and TOF, the output current is proportional to the rate of neutrons incident on the monitor. Ratios of monitor signals are used to measure relative changes in the transmission of the beam through the apparatus.

The protons for the $\text{n} + ^3\text{He} \rightarrow p + ^3\text{H}$ reaction are provided by a 16 liter cryogenic liquid hydrogen vessel [18]. Aluminum was chosen for the cryostat and vessel material because it has small neutron capture and scattering cross sections. Given the 15 meV energy difference between the para and ortho nuclear spin states of the $^1\text{H}_2$ molecule, the beam will depolarize in orthohydrogen but will only depolarize significantly in parahydrogen at energies above 15 meV. The equilibrium fraction of orthohydrogen is low enough at operating temperatures ($\approx 17$ K) that spin-flip scattering is negligible for neutrons below 15 meV. The ortho-to-para conversion rate is increased by circulating the liquid hydrogen through a catalyst. Using data on the energy dependence of scattering cross-sections for orthohydrogen and parahydrogen molecules, the parahydrogen fraction was measured to be $99.9 \pm 0.7\%$ from observations of the energy-dependent transmission of the beam through the target. A description of this measurement and an updated value of the parahydrogen fraction will be given in an upcoming publication [19].

By selection of the appropriate TOF range, the asymmetry measurement excludes data from neutrons with energies that give rise to significant depolarization of the beam in the target.

The beam was polarized at FP12 by transmission through a cell of polarized $^3\text{He}$ [20, 21]. The beam polarization is neutron energy dependent [22] and is extracted from fits to in situ beam monitor measurements of the transmission of the beam through the cell. The average beam polarization for analyzed data runs was $53 \pm 3\%$. The beam at the FNPB will be polarized using a supermirror polarizer which provides for an improved beam polarization.

The 2.2 MeV gamma rays are detected using a cylindrical array of 48 CsI(Tl) detectors. There are four rings of twelve detectors each arranged contiguously in a cylindrical fashion (see figures 1 and 2). Each 15 cm x 15 cm x 15 cm CsI crystal is coupled to a battery-powered vacuum photodiode connected to a low-noise solid state preamplifier. The vacuum photodiodes and beam monitors use the same preamplifier design which is described in [23]. Vacuum photodiodes were
used since they possess small nonlinearities ($< 10^{-4}$) when operated in current mode and their gain is insensitive to changes in magnetic field ($< 10^{-3}$/mT). The average detector photoelectron yield was 1300 photoelectrons per MeV [24].

The entire apparatus exists in a static, vertical $\approx 1$ mT magnetic field, with vertical gradients in the beam volume less than 0.1 $\mu$T/cm. The beam polarization is reversed pulse-by-pulse with efficiency 98.8 $\pm$ 0.5 % using the RF spin rotator [25], a solenoid positioned coaxially with the beam that operates by magnetic spin resonance. The neutron spin direction is rotated in the presence of the static field and RF field of the solenoid. The amplitude of the RF field is ramped as 1/TOF so that neutrons of different energies all rotate by the required $\pi$ radians while traveling down the fixed length of the RF solenoid.

3. The gamma asymmetry measurement

The gamma asymmetry measurement is made using eight consecutive beam pulses with beam polarization ordered temporally according to the sequence $\uparrow\downarrow\downarrow\uparrow\downarrow\uparrow\uparrow\downarrow$. A raw asymmetry $A_{\text{raw}}$ is extracted for a given detector pair at each of $\approx 50 \times 0.4$ ms-wide time-of-flight bins between $\approx 2$ and 15 meV neutron energy using:

$$A_{\text{raw}} = \frac{\Sigma_{\uparrow} [N_U - N_D] - \Sigma_{\downarrow} [N_U - N_D]}{\Sigma_{\uparrow} [N_U + N_D] + \Sigma_{\downarrow} [N_U + N_D]}$$

where $N$ is the pedestal-corrected detector signal. U and D refer to opposing detectors as shown in figure 2. Each sum is performed over one of the two opposite polarization states in the sequence. This 8-step sequence cancels linear and quadratic time dependences of detector properties. To make best use of the dynamic range of the ADCs, the detector signal is read for each ring as one average and twelve differences from the average.

![Figure 2. A gamma asymmetry is measured using opposite detectors in a ring which are labeled U and D. U is positioned at angle $\theta$ from the direction of beam polarization in the state $\uparrow$. $\vec{B}$ is the static magnetic holding field.](image)

A data run typically consists of 1250 8-step sequences. The result presented in this writeup incorporates data from 4966 beam shutter-open, hydrogen target-full data runs. Cuts were made on 1% of the data due to invalid 8-step sequences. At $\approx 32$-34 ms TOF, the beam chopper closes the beam, allowing for $\approx 6$ ms of data that are used to study prompt background (the last 10 ms of the 50 ms pulse are used by acquisition electronics to transfer data). The prompt background was found to be primarily due to activation from neutron capture on aluminum [26]. Separate
beam shutter-closed runs were used to observe long-term background and to measure electronic signal offsets (pedestals).

Given the cylindrical symmetry of the detector array, two orthogonal $\theta$-dependent terms are observed simultaneously:

$$A_{\text{raw}} = P_n (A_{UD} \cos \theta + A_{LR} \sin \theta),$$

where $P_n$ is the beam polarization which has been averaged over the 8-step sequence and corrected for spin-flip efficiency and depolarization ($\approx 2\%$ from calculations) in the target. A measurement of $A_{UD}$ or $A_{LR}$ involves averaging over all detector pairs and over many 8-step measurements. Beam intensity fluctuations combined with unequal detector gains contribute to $A_{\text{raw}}$ but average to zero with a statistical width an order of magnitude smaller than that of the desired signal.

The appropriate value of $\theta$ for each pair was determined from simulations combined with measurements during which the detector array was moved transverse to the beam axis with the target in place. The capacity of the apparatus to observe a $\theta$-dependent $\gamma$ distribution has been demonstrated by a measurement of the previously-observed large PV asymmetry from polarized neutron capture on $^{35}$Cl. Figure 3 demonstrates how this measurement was extracted from 24 individual detector-pair asymmetry measurements. Figure 4 shows a histogram of 8-step $A_{UD}$ measurements that were taken with the parahydrogen target in full production mode.

**Figure 3.** The measured $\theta$ dependence of the gamma asymmetry from capture on $^{35}$Cl [27]. The $\cos \theta$ dependence of the large UD contribution is extracted from a fit while the LR contribution is too small to be seen.

**Figure 4.** Individual 8-step $A_\gamma$ measurements histogrammed over many data runs, with a least-squares fit to a Gaussian distribution. The broad wings at low count levels are likely attributable to cosmic ray background.

Effects that mimic $A_\gamma$ can be separated into beam-on or beam-off effects. Beam-off effects (detector gains and offsets that are correlated with the state of the spin rotator) were measured to be zero at the $10^{-9}$ level over the period of approximately a day [24]. Beam-on effects are catalogued by considering all cartesian invariants that involve the neutron spin direction and other vectors associated with all of the reaction products that can influence the energy deposition in the detectors. The apparatus is designed to render all such systematic effects from other interactions negligible. The gamma asymmetries from other materials in the apparatus (Al, Cu, In) were measured to confirm the absence of asymmetries from background [28].

Limits on some important beam-on systematic effects are shown in Table 1. The items in the table refer to the mixing of the parity-allowed asymmetry $A_{LR} = (-1.8 \pm 1.9\text{(stat.)}) \pm 0.6\text{(syst.)}$
0.1(sys.) \times 10^{-7} into A_{UD} from imperfect detector alignment (good to \pm 20 \text{ mrad}), polarization-dependent $\gamma$ scattering, up-down steering of the beam due to vertical holding field gradients, and directional asymmetries associated with background processes including neutron decay and capture on materials of the apparatus. Systematic effects are discussed in more detail in an upcoming publication [26]. With systematic effects accounted for, $A_{UD} = A_\gamma$.

### Table 1. Limits on important beam-on systematic effects.

| Effect                                | Limit    |
|---------------------------------------|----------|
| Left-right asymmetry                  | $1 \times 10^{-8}$ |
| $\gamma$-ray circular polarization   | $7 \times 10^{-13}$ |
| Stern-Gerlach steering                | $8 \times 10^{-11}$ |
| Beta decay from $^{28}$Al              | $4 \times 10^{-9}$ |
| Beta decay in flight                  | $3 \times 10^{-11}$ |
| Radiative beta decay                  | $2 \times 10^{-12}$ |
| Capture on $^{6}$Li                   | $2 \times 10^{-11}$ |

According to a combination of target-empty measurements and MCNPX simulations, a relatively large background contribution of $\approx 25\%$ of the total signal (averaged over all detectors) comes from capture on the aluminum walls and entrance windows of the hydrogen target vessel and cryostat. The asymmetry from aluminum was measured to be consistent with zero with statistical uncertainty at the $2 \times 10^{-7}$ level. This result was weighted by intensity and subtracted from the hydrogen target-full asymmetry, with statistical uncertainties also appropriately weighted and added in quadrature. Preliminary analysis of the FP12 data [29] indicates an upper limit for $A_\gamma$:

$$A_\gamma = ( -1.2 \pm 2.1 \text{(stat.)} \pm 0.1 \text{(sys.)} ) \times 10^{-7}$$

(6)

that matches the precision of the previous measurement $A_\gamma = (0.6 \pm 2.1) \times 10^{-7}$ that was performed in 1977 at the ILL [30, 31]. The goal for the FNPB is to achieve a statistics-limited measurement with uncertainty $1 \times 10^{-8}$.

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