Test of Parity-Conserving Time-Reversal Invariance Using Polarized Neutrons and Nuclear Spin Aligned Holmium

P. R. Huffman,* N. R. Roberson, and W. S. Wilburn
Physics Department, Duke University, Durham, North Carolina 27708-0305
and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308

C. R. Gould, D. G. Haase, C. D. Keith,† B. W. Raichle, M. L. Seely, and J. R. Walston
Physics Department, North Carolina State University, Raleigh, North Carolina 27695-8202
and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308

(Received 12 January 1996)

A test of parity-conserving, time-reversal noninvariance (PC TRNI) has been performed in 5.9 MeV polarized neutron transmission through nuclear spin aligned holmium. The experiment searches for the T-violating fivefold correlation via a double modulation technique—flipping the neutron spin while rotating the alignment axis of the holmium. Relative cross sections for spin-up and spin-down neutrons are found to be equal to within 1.2×10^{-5} (80% confidence). This is a 2 orders of magnitude improvement compared to traditional detailed balance studies of time reversal, and represents the most precise test of PC TRNI in a dynamical process. [S0031-9007(96)00497-8]

PACS numbers: 24.80.+y, 24.70.+s, 25.40.Dn, 28.20.Cz

Parity-conserving, time-reversal noninvariance (PC TRNI) arises only through second-order weak effects within the standard model. As such, observables from these interactions are expected to be extremely small [1]. Nevertheless, experimental bounds are much less stringent. Previously, the most precise dynamical bound came from the detailed balance studies of the reaction $^{24}\mathrm{Mg}(\alpha, p)^{27}\mathrm{Al}$ and its inverse [2], where relative differential cross sections were found to be equal to within 5.1×10^{-3} (80% confidence).

In this Letter, we present results from an improved search for PC TRNI, using polarized neutron transmission through a rotating, cryogenically aligned, ^{165}Ho target [3]. The measurement tests reciprocity, or more colloquially, "running the movie backwards." If reciprocity holds, the total cross sections will be equal for vertically polarized spin-up and spin-down neutrons transmitted through a tensor polarized target whose alignment axis lies in the horizontal plane at 45° with respect to the beam direction [4]. We find the relative cross sections for 5.9 MeV neutrons to be equal to within 1.2×10^{-5} (80%), which, compared to detailed balance studies, is a factor of 400 improvement in a measurement of PC TRNI relative cross sections.

A more fundamental comparison of results of different experiments at low energies is made in terms of a meson-exchange model. Simonius has shown that parity-conserving, time-reversal violation arises only through charged meson exchanges, with the major contribution arising from the ρ meson [5]. We take advantage of a recently developed model incorporating T-violating ρ meson exchange [6] to interpret our result.

The present measurement consists of a search for the fivefold correlation (FC) term $\vec{s} \cdot (\vec{I} \times \vec{k})(\vec{I} \cdot \vec{k})$ in the neutron-nucleus forward scattering amplitude. Here, $\vec{s}$ is the spin of the neutron, $\vec{k}$ is the momentum of the neutron, and $\vec{I}$ is the spin of the holmium target. The total cross section for neutrons polarized parallel (antiparallel) + (−) to the direction $\vec{I} \times \vec{k}$ is [7]

$$\sigma_T^{\pm}(\theta) = \sigma_0[1 + \tilde{t}_{20}(I)\sigma_2 P_2(\cos\theta) \pm \tilde{t}_{10}(s)\tilde{t}_{20}(I)A_5 \sin 2\theta], \qquad (1)$$

where $\tilde{t}_{10}(s)$ is the polarization of the neutron beam, $\tilde{t}_{20}(I)$ is the tensor alignment of the holmium target with respect to its crystal symmetry axis, σ_0 is the unpolarized cross section, σ_2 is the deformation effect cross section, A_5 is the PC TRNI spin-correlation coefficient, and θ is the angle between the alignment axis of the holmium crystal and the beam direction.

The FC term is isolated by reversing the spin of the neutron beam, and simultaneously rotating the holmium alignment axis. A sequence of measurements of the transmission asymmetry

$$\epsilon_5(\theta) = \frac{N^+(\theta) - N^-(\theta)}{N^+(\theta) + N^-(\theta)} \qquad (2)$$

$[N^{\pm}(\theta) = N_0 e^{-n\sigma_T^{\pm}(\theta)}$, where n is the target thickness and N_0 is the incident flux] is fit by the form $a_0 + a_2 \sin 2\theta$ (a_0, a_2 constants) to extract the spin-correlation coefficient

$$A_5 = \frac{a_2(1 + \phi)}{\tilde{t}_{10}(s)\tilde{t}_{20}(I)n\sigma_0}, \qquad (3)$$

where $n = 0.065$ atom/b, and σ_0 is the unpolarized cross section (5.1 b at $E = 5.9$ MeV). The factor ϕ accounts for the small number of gamma rays detected and counted as neutrons (see later).

Systematic effects associated with time drifts, spin and beam misalignments, and finite geometry effects are analyzed in detail elsewhere [8]. In general, none lead to a $\sin 2\theta$ modulation at the level investigated here. In particular, sequential interactions which mimic the FC signal exactly are second order in the weak interaction, and are negligible to the accuracy of the present experiment.

A schematic of the experimental arrangement is shown in Fig. 1. The count rate and accuracy improvement compared to our previous work [3] result from (a) using the $^2\mathrm{H}(\vec{d},\vec{n})^3\mathrm{He}$ reaction instead of the $^3\mathrm{H}(\vec{p},\vec{n})^3\mathrm{He}$ reaction, (b) using a cryogenically cooled deuterium gas cell, (c) moving source and detectors into a close, unshielded geometry, and (d) longer run times.

The cooled deuterium gas cell is a 0.851 cm diameter by 3.18 cm long cylinder filled with 8 atm of deuterium gas. The vector and tensor polarized deuteron beam from the TUNL tandem accelerator enters the cell through a 15.2 μm thick Havar window and is stopped in a 0.051 cm sleeve of gold surrounding the cell walls. The cell is cooled to 168 K through a 2.54 cm diameter copper cold finger extending into a liquid nitrogen bath. The cell temperature is stabilized by a feedback heater to ± 0.5 K to minimize gas density fluctuations due to beam heating. A 2.0 μA beam of 4.9 MeV deuterons produced $\sim 10^5$ neutrons/cm^2 s at the front surface of the 0° detector array with a mean energy of 5.9 MeV and a spread of 2.6 MeV. A pair of liquid scintillator detectors are located at ±36° with respect to the beam direction to monitor the neutron polarization via the left-right analyzing power of the neutron production reaction.

Holmium is chosen as a target material because it is monoisotopic and can be cryogenically aligned in the absence of an external magnetic field. The target consists of a cylindrical single-crystal sample (2.3 cm diameter, 2.8 cm in height) with its c axis (or alignment axis) oriented perpendicular to the cylinder axis. The crystal is mounted with its cylinder axis along $\hat{y}$, placing its alignment axis in the x-z plane. The target is rotated about the cylinder axis thereby defining the angle θ between the alignment axis and the beam direction. The sample is cooled to $\sim$150 mK using a $^3\mathrm{He}$-$^4\mathrm{He}$ dilution refrigerator, causing spontaneous nuclear alignment (90%) due to the interaction of the magnetic dipole and electric quadrupole moments with the unpaired electrons through the large internal hyperfine field. The vector polarization of the sample due to the Earth's magnetic field is 10^{-4}, and is negligible for the present measurement. The alignment of the holmium was measured using thermometry and verified with independent measurements of the deformation effect cross section [9]. These measurements were performed at 9.5 MeV where the deformation effect cross section is large (~ -500 mb). The time-reversal measurements were carried out at 5.9 MeV where the deformation effect is small (<5 mb), but sensitivity to TRNI is a maximum [6].

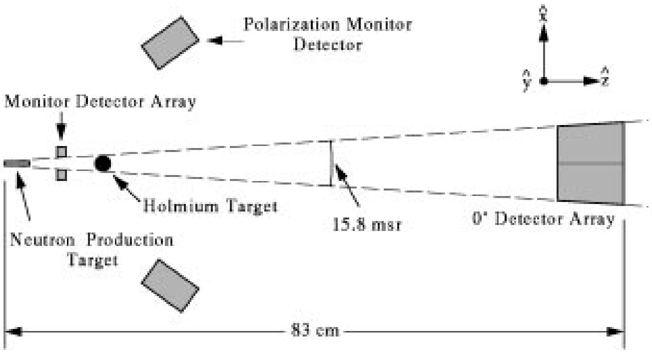

FIG. 1. The experimental setup for the time-reversal measurement. A vertically ($\hat{y}$) polarized neutron beam with momentum $\hat{k}$, directed along $\hat{z}$, is produced via the $^2\mathrm{H}(\vec{d},\vec{n})^3\mathrm{He}$ reaction, transmitted through the aligned holmium target, and detected at 0°. The dashed lines depict the solid angle subtended by the neutron detectors. All components and distances are drawn to scale.

The intense neutron fluxes at both the monitor and 0° detectors required the development of two four-detector arrays of plastic scintillator neutron detectors. The monitor detector array is 1.27 cm thick and detects neutrons in a "halo" surrounding the solid angle subtended by the 0° detector array. The 0° array is $12.7 \times 12.7 \times 10.2$ cm thick and divided into four equal segments. Detectors are operated in pulse mode. Since plastic scintillators are used, pulse shape discrimination between neutrons and gamma rays is not possible. Thus, the ratio of gamma rays to neutrons is determined independently using time-of-flight techniques, and is measured to be $\phi = 0.064 \pm 0.001$.

The data for the time-reversal measurements are collected using a double modulation technique, where the neutron spin direction is reversed every 100 ms in the eight-step sequence $+--+-++-$. After 256 eight-step sequences, the target alignment axis is rotated to a new angle in the sequence $-180°$ to $+180°$ and back to $-180°$ in 22.5° steps. Both the spin-flip and target rotation sequences are chosen to minimize time-dependent drifts that can arise in the transmission asymmetry.

The neutron transmission data are corrected for deadtime and cross talk between detector pairs before normalizing to the counts in the monitor detector array. An asymmetry is formed [Eq. (2)] for each eight-step sequence and averaged over the entire set of 256 eight-step sequences. A constant background ($\sim 5 \times 10^{-4}$) term arises, due to the difference in tensor polarizations of the deuteron beam between the two polarization states, which results in different neutron fluxes. The T-violating FC term, if it exists, appears in the data as a $\sin 2\theta$ oscillation on top of this constant background. It is this angle modulation, in combination with the rapid neutron spin flip, that makes possible the high precision achieved in this experiment.

The data were accumulated over a period of one week, and correspond to a total of $\sim 10^{12}$ neutrons detected. The

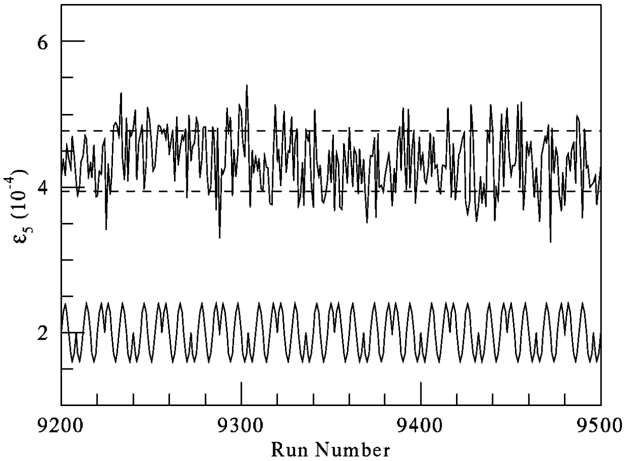

FIG. 2. Monitor normalized detector asymmetry ϵ_5 as a function of run number for a 300 run subset of data. Each run corresponds to 4 min of data at a given angle, taken in the sequence $-180° \rightarrow +180° \rightarrow -180°$ in 22.5° steps. The dashed lines indicate the $\pm 1\sigma$ errors on the data. The $\sin 2\theta$ angle dependence associated with time-reversal violation is shown below the data with an arbitrary amplitude and a known phase. Based on fits to these and the other data, we find the amplitude of the time-reversal violating $\sin 2\theta$ term to be $(1.1 \pm 1.0) \times 10^{-6}$.

monitor normalized asymmetry $\epsilon_5(\theta)$ for a sequence of 300 runs is shown in Fig. 2. Each run corresponds to 256 eight-step sequences at a given angle and the subset shown represents 25% of the data. The asymmetry is fit to the form $a_0 + a_2 \sin 2\theta$ using least squares. A value of $a_2 = (1.1 \pm 1.0) \times 10^{-6}$ is extracted from the data. The chi square per degree of freedom is 0.9994, indicating no significant random errors other than those associated with counting statistics. Using the measured polarizations $[\tilde{t}_{10}(s) = 0.67 \pm 0.05, \tilde{t}_{20}(I) = 0.62 \pm 0.05]$ and the measured ratio of gamma rays to neutrons ($\phi = 0.064 \pm 0.001$), the asymmetry is converted to the spin-correlation coefficient A_5 [Eq. (3)], yielding

$$A_5 = (8.6 \pm 7.7) \times 10^{-6}, \tag{4}$$

consistent with time-reversal invariance. At 45°, the relative spin-up versus spin-down cross section difference is less than 1.2×10^{-5} (80% confidence).

The most natural parameter for describing PC TRNI is $\bar{g}_\rho$, the ratio of T-violating to T-conserving coupling constants for ρ exchange. Using a recent theoretical analysis by Engel, Gould, and Hnizdo, A_5 can be directly converted into $\bar{g}_\rho$ [6]. In this analysis, the Simonius potential is used in a folding model calculation to generate an optical potential for ^{165}Ho. This optical potential is then used in a coupled-channels calculation to extract A_5 as a function of $\bar{g}_\rho$. Using our value of A_5, we obtain $\bar{g}_\rho = (2.3 \pm 2.1) \times 10^{-2}$. The FC term arises only from the valence proton in holmium, and therefore the aligned target PC TRNI experiments suffer from a $1/A$ suppression compared to one body nuclear effects such as parity violation. Nevertheless, we see that an experiment with MeV neutrons is able to probe TRNI in the ρ-exchange part of the N-N potential at the level of a few percent.

Recent theoretical analyses [6,10–12] now allow comparison between TRI tests in various systems. While the parameter $\bar{g}_\rho$ is the most natural point of comparison, an alternative quantity α_T, the ratio of T-violating to T-conserving nuclear matrix elements has also been widely used in the past. The quantity α_T was introduced by the Rochester group, and bounds of order 10^{-3} were deduced by them from level spacing data in heavy nuclei [13]. It was considered initially that α_T was also an approximate measure of the relative strength of the PC TRNI in the N-N system. But more recent work has shown that α_T and $\bar{g}_\rho$ are numerically quite different, and typically $\alpha_T = 0.012\bar{g}_\rho$ [11,12].

Previously, the detailed balance measurement of Blanke *et al.* [2] had provided the most stringent dynamical test of parity-conserving, time-reversal noninvariance. In their experiment the cross sections for the reactions $^{24}\text{Mg}(\alpha, p)^{27}\text{Al}$ and its inverse were found to be equal to an accuracy of $\Delta = 5.1 \times 10^{-3}$ (80% confidence). The experimental observable is not as simply related to the underlying nucleon-nucleon TRNI as in the FC experiment, and numerous statistical analyses [10,14–16] have been performed over the years to extract more fundamental TRNI parameters from the data, such as α_T. The analyses of Refs. [10,14] give similar bounds, $\alpha_T \lesssim 3.5 \times 10^{-3}$ (95%). Comparing to our results for $\bar{g}_\rho$ at the same confidence limit, we find the FC experiment therefore represents a factor of 5 improvement in a bound on $\bar{g}_\rho$.

While the present measurement represents the most precise test of PC TRNI to date in a dynamical system, other tests can in some cases provide more restrictive bounds indirectly. The most important of these other bounds comes from measurement of the atomic electric dipole moment of ^{199}Hg ($d \lesssim 1.3 \times 10^{-27} e\,\text{cm}$ [17]). The observable in that case is both P and T violating, but sets constraints on the assumed PC TRNI interaction via weak corrections. In a recent work, Haxton, Höring, and Musolf [11] obtained a limit $\bar{g}_\rho \lesssim 1 \times 10^{-2}$ at the 95% confidence level from the ^{199}Hg result.

Direct tests of PC TRNI continue to be discussed, both at high energies (0.5 GeV/c) in few-nucleon systems, and at low energies in resonance reactions in medium mass and heavy nuclei. Measurements of the FC in $\vec{p}$-$\vec{d}$ scattering have been proposed for the new storage ring facility COSY at Julich [18]. Few-nucleon systems allow for a clean theoretical interpretation, and first estimates indicate potentially an order of magnitude improvement in a direct test of PC TRNI [19]. Resonance tests hold the most promise for large enhancements, but are also theoretically the hardest to interpret. Both neutron and charged particle tests have been discussed [20]. An important consideration in such tests is the need to obtain data on more than just one resonance. This is a realistic goal for the FC test in holmium, and for traditional detailed balance tests in charged particle reactions. It continues to be an issue for P-violating TRNI neutron transmission tests, where to date only single isolated resonances have been identified in polarizable nuclei (for example, in ^{139}La).

In summary, we have tested reciprocity in nuclear reactions by measuring a T-violating spin-correlation coefficient A_5 of $(8.6 \pm 7.7) \times 10^{-6}$ in polarized neutron transmission through nuclear spin aligned holmium. The measurement corresponds to a bound on a T-violating meson coupling of $\bar{g}_\rho \leq 5.8 \times 10^{-2}$ (95%). This represents the most precise test of parity-conserving, time-reversal noninvariance in a dynamical process.

This work was supported in part by the U.S. Department of Energy, Office of High Energy and Nuclear Physics, under Contracts No. DE-FG09-88-ER40411 and No. DE-FG05-91-ER40619.

---

*Present address: Department of Physics, Harvard University, Cambridge, MA 02138.

†Present address: IUCF, 2401 Milo B. Sampson Lane, Bloomington, IN 47405.

[1] P. Herczeg, Hyperfine Interact. **43**, 77 (1988).
[2] E. Blanke, H. Driller, W. Glöckle, H. Genz, A. Richter, and G. Schrieder, Phys. Rev. Lett. **51**, 355 (1983).
[3] J. E. Koster, E. D. Davis, C. R. Gould, D. G. Haase, N. R. Roberson, L. W. Seagondollar, W. S. Wilburn, and X. Zhu, Phys. Lett. B **267**, 23 (1991).
[4] P. K. Kabir, Phys. Rev. Lett. **60**, 686 (1988).
[5] M. Simonius, Phys. Lett. **58B**, 147 (1975).
[6] J. Engel, C. R. Gould, and V. Hnizdo, Phys. Rev. Lett. **73**, 3508 (1994).
[7] V. Hnizdo and C. R. Gould, Phys. Rev. C **49**, R612 (1994).
[8] P. R. Huffman, Ph.D. thesis, Duke University, 1995 (unpublished).
[9] J. E. Koster, C. R. Gould, D. G. Haase, and N. R. Roberson, Phys. Rev. C **49**, 710 (1994).
[10] J. B. French, A. Pandey, and J. Smith, in *Tests of Time Reversal Invariance in Neutron Physics*, edited by N. R. Roberson, C. R. Gould, and J. D. Bowman (World Scientific Publishing Co., Inc., Teaneck, NJ, 1987), p. 80.
[11] W. C. Haxton, A. Höring, and M. J. Musolf, Phys. Rev. D **50**, 3422 (1994).
[12] M. Beyer, Phys. Rev. C **48**, 906 (1993).
[13] J. B. French, V. K. B. Kota, A. Pandey, and S. Tomsovic, Phys. Rev. Lett. **58**, 2400 (1987).
[14] D. Boosé, H. L. Harney, and H. A. Weidenmüller, Phys. Rev. Lett. **56**, 2012 (1986).
[15] H. L. Harney, A. Hüpper, and A. Richter, Nucl. Phys. **A518**, 35 (1990).
[16] V. E. Bunakov, H. L. Harney, and A. Richter, Nucl. Phys. **A560**, 71 (1993).
[17] J. P. Jacobs, W. M. Klipstein, S. K. Lamoreaux, B. R. Heckel, and E. N. Fortson, Phys. Rev. Lett. **71**, 3782 (1993).
[18] P. D. Eversheim *et al.*, in *Polarization Phenomena in Nuclear Physics*, edited by E. J. Stephenson and S. E. Vigdor (AIP Press, Woodbury, NY, 1995), p. 191.
[19] M. Beyer, Nucl. Phys. **A560**, 895 (1993).
[20] *Time Reversal Invariance and Parity Violation in Neutron Reactions*, edited by C. R. Gould, J. D. Bowman, and Yu. P. Popov (World Scientific Publishing Co., Inc., Teaneck, NJ, 1994).