Brief Reports

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Limits on *P*- and *P*, *T*-violating absorption of MeV neutrons in ^{165}Ho

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We have searched for enhancements of parity violation and combined parity and time reversal violation in the scattering of MeV neutrons from holmium. *P*-violating analyzing powers, measured by transmission of longitudinally polarized neutrons through unpolarized holmium, were consistent with zero: $\rho_P = (-2.4\pm2.6)\times10^{-4}$ at 7.4 MeV and $(-0.2\pm1.9)\times10^{-4}$ at 12.4 MeV. *P*, *T*-violating analyzing powers, measured by transmission of vertically polarized neutrons through horizontally polarized holmium, were also consistent with zero: $\rho_{P,T} = (-0.9\pm2.0)\times10^{-3}$ at 7.1 MeV and $(-0.4\pm2.9)\times10^{-3}$ at 11.0 MeV.

Results in the study of the interaction of polarized thermal neutrons with heavy targets have shown surprisingly large enhancements in parity-violating observables.[1,2] The enhancement is considered to arise from interference between weak *p*-wave resonances and strong nearby *s*-wave resonances in the compound systems.[3,4] It has been suggested that one can take advantage of these large enhancements to search for time reversal violating observables.[5,6] Since *T*-violation (or equivalently the violation of the combined symmetry of charge conjugation and parity) has not been observed outside the decay of neutral kaons, any experimental evidence in other systems would be of considerable interest.

P- and *T*-violation in neutron transmission have recently been reviewed by Herczeg.[7] The *P*-violating analyzing power, ρ_P, is given by

$$\rho_P = (\sigma'_+ - \sigma'_-)/(\sigma'_+ + \sigma'_-) ,$$

where $\sigma'_+(\sigma'_-)$ is the total cross section for a neutron polarized parallel (antiparallel) to its momentum $\mathbf{k}_n$. A nonzero ρ_P is due to the presence of a $\boldsymbol{\sigma}_n \cdot \mathbf{k}_n$ term, f_P in the neutron-nucleus elastic forward scattering amplitude ($\boldsymbol{\sigma}_n$ = twice the neutron spin). A value of 0.07 has been measured[2] for the 0.734 eV *p*-wave resonance in ^{139}La.

The *P*, *T*-violating analyzing power, $\rho_{P,T}$, is given by

$$\rho_{P,T} = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-) ,$$

where $\sigma_+(\sigma_-)$ is the total cross section for a neutron polarized parallel (antiparallel) to $\mathbf{k}_n \times \mathbf{J}$ ($\mathbf{J}$ = spin of the target nucleus). A nonzero $\rho_{P,T}$ is due to the presence of a $\boldsymbol{\sigma}_n \cdot (\mathbf{k}_n \times \mathbf{J})$ term, $f_{P,T}$ is the neutron-nucleus elastic forward scattering amplitude. Such a term arises only if the interaction simultaneously violates *P*- and *T*-invariance. No measurements of $\rho_{P,T}$ have yet been attempted due to the problem of neutron spin precession in the magnetic and pseudomagnetic fields of the target.[8–10]

Most interest up till now has centered on searching for $\rho_{P,T} \neq 0$ where $\rho_P \neq 0$ since model dependent constraints give $\lambda \equiv \rho_{P,T}/\rho_P$ of magnitude 4×10^{-3} or less.[7] Nevertheless, the amplitudes f_P and $f_{P,T}$ are in general completely independent,[8] and $f_{P,T}$ does not contribute to the scattering of longitudinally polarized neutrons. It is therefore in principle possible for $\rho_{P,T}$ to be nonzero even if $\rho_P = 0$.

In the present work we set first limits on the magnitudes of ρ_P and $\rho_{P,T}$ for 7–12 MeV neutrons, energies at which the precession problems in polarized targets are much reduced. At high excitation in the compound system, we are averaging over many overlapping resonances and enhancement factors as large as seen at eV energies are not expected unless a doorway state imposes a phase coherence on the contributing partial width amplitudes.

Figure 1 shows a schematic of the experimental arrangement for the P,T-violating measurement. Deuterons from the Triangle Universities Nuclear Laboratory (TUNL) polarized ion source and tandem Van de Graaff accelerator are momentum-analyzed by a 59° bending magnet and focussed into a 6 cm long gas cell filled with 8.08×10^5 Pa of deuterium. Steerer feedback circuits center the beam on slits 4.8 mm wide by 6.4 mm high in front of the gas cell and on a beam profile monitor located 2 m upstream. The deuteron energies are such that neutron beams of energy 7.1 and 11.0 MeV are produced from the center of the gas cell.

Vertically polarized neutrons from the $^2H(d,n)^3He$ reaction are collimated by a polyethylene shield with a 0.95 cm diameter aperture. The polarized target is a cube of single-crystal ^{165}Ho, 1.8 cm on a side, located 1.2 m from the gas cell. Transmitted neutrons are detected in a 13 cm (diameter) by 13 cm (long) NE213 liquid scintillator 2.3 m from the sample. The flux of neutrons varies with the intensity and tensor polarization of the incoming deuteron beam, and is monitored with a 1.3 cm diameter by 1.9 cm long NE213 liquid scintillator located 53 cm from the gas cell.

The sample is cooled by the TUNL Cryogenic Polarized Target Facility[11] to 140 mK in a 1 T magnetic field. The nuclear polarization of 69% was calculated from the temperature and magnetic field, taking into consideration incomplete magnetic saturation due to shape effects.[12] The c axis of the sample is vertical, while the magnetic field is horizontal (along the b axis) and transverse to the beam momentum. The target polarization is therefore transverse to both the spin and momentum of the incident neutrons. Calculations indicate that at 11.0 MeV the neutron spin will precess about the magnetic field by an angle of 16.7° in approaching the center of the target, so the incident deuteron spin was oriented at an angle of −16.7° with respect to the vertical. The precession of the neutron spin in traversing the target was 4.3° at this energy.

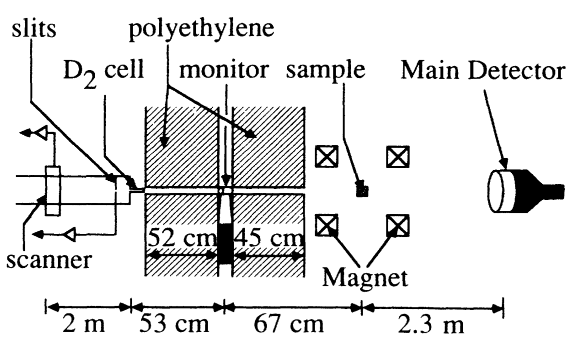

FIG. 1. Experimental arrangement for the P,T-violation measurements.

With 100 nA of deuterons on the gas cell, typical count rates for neutrons were 2 kHz in the monitor detector and 1 kHz in the main detector. Typical deuteron polarizations were 52–63 %, resulting in neutron polarizations of 46–57 %.

At each energy, 50 runs were taken with the target cold, and 50 runs with the target warm ($T=9$ K, $P_t=0.04$). Each run consisted of four pairs of measurements with the spin oriented first parallel and then antiparallel to $\mathbf{k}\times\mathbf{J}$, the neutron spin being reversed by flipping the deuteron spin every 200 s. The analyzing power is given by

$$\rho_{P,T}=-\frac{\langle\epsilon\rangle_{\text{cold}}-\langle\epsilon\rangle_{\text{warm}}}{x\sigma_0\langle p_n\rangle(P_{\text{t,cold}}-P_{\text{t,warm}})},$$

where $\langle\epsilon\rangle$ is the average asymmetry in the yield of transmitted neutrons:

$$\epsilon=(N\uparrow-N\downarrow)/(N\uparrow+N\downarrow).$$

The normalized neutron counts for spin parallel (antiparallel) to $\mathbf{k}\times\mathbf{J}$ are $\mathbf{N}\uparrow$ ($N\downarrow$); $\langle p_n\rangle$ is the average neutron polarization calculated from the measured deuteron polarization and the known $^2H(d,n)^3He$ polarization transfer coefficients; P_t is the target polarization; σ_0 is the total cross section; and x is the sample thickness, 0.058 atoms/b. The error weighted averages of the measurements are given in Table I. The errors are determined from the standard deviations, s of the runs in each data set (or the statistical errors, whichever is larger). The standard deviations are comparable to the statistical errors, σ indicating no large nonstatistical errors. Typical values of $\chi\equiv s/\sigma$ are 0.9 to 1.2. At both energies, the asymmetries are consistent with zero to the level of our counting statistics.

A number of measurements were made to investigate sources of nonstatistical error. The neutron detectors were gain-stabilized with precision light-emitting diode (LED) pulser systems, and for the time intervals corresponding to our measurements, false analyzing powers due to gain drifts were less than a few parts $\times10^{-5}$. A more serious problem was that due to coherent changes in the position and direction of the deuteron beam. The feedback system that centered the beam on the gas cell was calibrated via balance signals that were proportional to the differences in the currents on the left-right and up-down slits. The calibration was performed by introducing offset currents on the slits with a frequency of 200 s. False analyzing powers as large as 10^{-3} were observed for offset currents representing large (mm) beam displace-

TABLE I. Asymmetries and threefold correlation analyzing powers [due to the $\boldsymbol{\sigma}_n\cdot(\mathbf{k}_n\times\mathbf{J})$ term] measured for vertically polarized neutrons incident on a horizontally polarized ^{165}Ho target. The energy spreads are based on kinematics and deuteron energy loss in the gas cell.

Energy (MeV)	7.1±0.9	11.0±0.5
$\langle\epsilon\rangle_{\text{cold}}$ ($\times10^{-4}$)	−10.6±1.8	1.1±2.1
$\langle\epsilon\rangle_{\text{warm}}$ ($\times10^{-4}$)	−11.5±1.2	0.7±1.6
$\rho_{P,T}$ ($\times10^{-3}$)	−0.9±2.0	−0.4±2.9

ments. A similar calibration was made for the beam profile monitor. During the experiment, the shape of the beam at the profile monitor was digitized at 10 Hz and stored in the data acquisition computer. Typically the centroids for the two spin states in a run differed by less than 30 μm and the balance signals indicated shifts of less than 40 μm. A run with differences in the balance signals or centroids that implied a possible false analyzing power greater than 5×10^{-5} was rejected. Fewer than 1% of the runs were in this category. Remaining systematic errors due to uncontrolled changes in the polarized ion source were assumed to be compensated for by the monitor detector.

The experimental arrangement for the *P*-violation measurements is the same as that for the *P*, *T*-violation measurements, except that the sample is replaced by a rod of polycrystalline ^{165}Ho 0.95 cm in diameter by 15.2 cm. The rod is placed just after the neutron flux monitor and further collimation of the transmitted neutrons is achieved by replacing the cryostat magnet with a water collimator.

With 100 nA of deuterons on the gas cell, typical count rates for neutrons were 1.5 kHz in the monitor detector, 2 kHz in the main detector with no sample in place, and 0.2 kHz with the sample in place. Typical deuteron polarizations were 56–66 %, resulting in neutron polarizations of 44–53 %.

At each energy, 100 runs were taken with the sample in place, and 50 runs with no sample ("blank"). The blank measurements provide a check on the relative responses of the main and monitor detectors to coherent changes in the polarization and intensity of the deuteron beam. Each run consisted of four pairs of measurements with the spin oriented first parallel and then antiparallel to the beam momentum, the neutron spin being reversed every 200 s. The analyzing power is given by

$$\rho_P = -\frac{\langle\epsilon\rangle_{\text{sample}} - \langle\epsilon\rangle_{\text{blank}}}{\sigma_0 \times \langle p_n\rangle} ,$$

where $\langle\epsilon\rangle$ is the average symmetry in the yield of transmitted neutrons:

TABLE II. Asymmetries and longitudinal analyzing powers (due to the $\boldsymbol{\sigma}_n\cdot\mathbf{k}_n$ term) measured for longitudinally polarized neutrons incident on an unpolarized ^{165}Ho target.

Energy (MeV)	7.4 ± 0.7	12.4 ± 0.4
$\langle\epsilon\rangle_{\text{blank}}$ ($\times10^{-4}$)	1.5 ± 2.0	0.1 ± 1.1
$\langle\epsilon\rangle_{\text{Ho}}$ ($\times10^{-4}$)	4.0 ± 1.8	-0.1 ± 2.4
ρ_P ($\times10^{-4}$)	-2.4 ± 2.6	0.2 ± 1.9

$$\epsilon = (N_+ - N_-)/(N_+ + N_-) .$$

The normalized neutron counts for spin parallel (antiparallel) to the beam momentum are N_+ (N_-); $\langle p_n\rangle$ is the average neutron polarization; σ_0 is the total cross section; and x is the sample thickness 0.488 atoms/b.

The measurements were taken at two energies: 7.4 and 12.4 MeV. The weighted averages of the measurements are given in Table II and are consistent with zero. The errors are determined from the standard deviations, s of the asymmetries in each data set, and are again comparable to the statistical errors, σ ($\chi = 1.0$ to 1.1).

In summary, we have performed measurements on a polarized sample of single-crystal ^{165}Ho in an attempt to find *P*, *T*-violation due to the threefold correlation $\boldsymbol{\sigma}_n\cdot(\mathbf{k}_n\times\mathbf{J})$. We have determined that this observable is consistent with zero at the 5×10^{-3} (2σ) level. We have also performed measurements on an unpolarized sample of ^{165}Ho in an attempt to find enhancements in *P*-violation due to the term $\boldsymbol{\sigma}_n\cdot\mathbf{k}_n$. We have determined that this observable is consistent with zero in ^{165}Ho at the 5×10^{-4} (2σ) level. Further improvements in accuracy will be possible when higher fluxes of polarized neutrons become available, but at present it seems more appropriate to focus efforts on the low-energy regime where nuclear structure effects are providing the largest enhancements.

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