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Study of Parity and Time-Reversal Violation in Neutron-Nucleus Interactions

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Abstract. The parity and time-reversal symmetries can be studied in neutron-nucleus interactions. Parity non-conserving asymmetries have been observed for many p-wave resonances in a compound nucleus and measurements were performed on several nuclei in the mass region of $A \sim 100$ and $A \sim 230$. The statistical model of the compound nucleus provides a theoretical basis for extracting mean-squared matrix elements from the experimental asymmetry data, and for interpreting the mean-squared matrix elements. The constraints on the weak meson-exchange couplings calculated from the compound-nucleus asymmetry data agree qualitatively with the results from few-body and light-nuclei experiments. The tests of time-reversal invariance in various experiments using thermal, epithermal and MeV neutrons are being developed.

INTRODUCTION

The weak parity non-conserving (PNC) nucleon-nucleon (N-N) interaction can be described in terms of meson-exchange potentials between strong and weak meson-nucleon couplings. The Desplanques, Donoghue and Holstein (DDH) theory (1) characterizes the PNC interaction with seven weak meson-exchange amplitudes and predicts a range of values of these coupling constants. It is a great experimental and theoretical challenge to determine these weak coupling constants.

Hadronic PNC phenomena have been observed (2) in few body ($A \leq 4$), light nucleus and compound nucleus (CN) systems. In the few-body system all the seven meson couplings are significant. The interpretation of results is direct, but asymmetries are of the order of 10^{-7} and experiments are difficult (2). The only experiments involving $A \leq 4$ that have provided results precise enough to constrain the PNC meson-exchange couplings are measurements of the longitudinal analyzing power (A_L) in $\bar{p} + p$ (3-5) and $\bar{p} + \alpha$ (6) scatterings. Experiments measuring A_L in $\bar{p} + d$, as well as the asymmetry (A_γ) and circular polarization (P_γ) of γ rays from neutron capture on protons or deuterons have been carried out. These measurements still lack sufficient precision (2). Experiments measuring PNC neutron spin-rotation in few-body systems are being pursued (7,8) in order to provide stronger constraints on the PNC meson-exchange couplings.

In light nuclei, the π and ρ (isospin zero) meson-exchange couplings, F_π and F_ρ , respectively, are dominant. The PNC experiments in light nuclei usually deal with special transitions involving closely-spaced parity doublets that have identical spins but opposite parities. Typical observables arise from the interference between a strong parity-conserving transition and a weak PNC transition. The large ratio of the transition strengths and small energy denominators of these nuclei lead to an amplification of 10^2 - 10^4 which brings the N-N PNC effects to a level of 10^{-5} - 10^{-3} . A good example is the measurement of P_γ in ^{18}F (9-11) which is primarily sensitive to the F_π amplitude. The lifetimes and energy-splittings of the nuclear states in ^{18}F are well known. With some nuclear-structure parameters taken from nuclear model calculations, the ^{18}F results indicate a small F_π coupling. Other experiments measuring P_γ in ^{21}Ne and A_γ in ^{19}F have been carried out but the sensitivities are not yet sufficient to provide reliable constraints on F_π and F_ρ couplings. The sensitivity required for the PNC light-nuclei experiments is less stringent than that for the few-body experiments. However, the interpretation of the light-nuclei experimental results requires a detailed knowledge of the nuclear structure, which poses difficulties.

The chaotic nature of the compound nucleus results in a very large enhancement of the PNC asymmetries and allows the data to be interpreted using a statistical model of the compound nucleus. A compound nucleus (CN) is formed when a nucleus, A , captures a neutron to form an excited state of the $A+1$ nucleus. The cross-section for the scattering of low-energy neutrons from medium and heavy nuclei consists of closely spaced (~ 20 eV) extremely narrow (~ 0.1 eV) resonances. The narrowness of these resonances indicates that a long-lived intermediate state is formed, hence the term compound

nucleus. One reason to study fundamental symmetries in the compound nuclear system is to understand how symmetry non-conservation in the effective N-N interaction manifests itself in the complicated many-body systems and to determine the strength of the nuclear weak force.

PNC phenomena of this type were first observed by Abov *et al.* (12). Recent advances in this regime have resulted from the experimental program of the TRIPLE collaboration (13-15). The statistical behavior of the CN observables results from the fact that the CN wave functions are superpositions of a large number ($N \sim 10^4$ - 10^6) of independent particle components. The weak interaction mixes the nearby s-wave (angular momentum $\ell = 0$, positive parity) and p-wave ($\ell = 1$, negative parity) CN states of the same total spin. The mixing matrix elements, $\langle \psi_s | H_w | \psi_p \rangle$, are represented by an ensemble of independent and Gaussian random variables. The useful information is contained in the average quantities, such as the mean-squared matrix element, defined as M^2 :

$$\overline{\langle \psi_s | H_w | \psi_p \rangle^2} = M^2. \quad (1)$$

The statistical model of the CN provides a theoretical basis for extracting mean-squared matrix elements from PNC experimental data and for interpreting the mean-squared matrix elements. In this picture only average properties of the nuclear wave functions need to be calculated.

In this work, we measured PNC asymmetries of numerous p-wave CN resonances and extracted M^2 . This is an advance over the previous PNC studies (12) in the CN where only a single asymmetry per nucleus was measured. A theoretical model has been developed (15) to relate the M^2 to the weak meson-exchange coupling constants. With the M^2 determined from experiment and the theoretical work based on the statistical model, we obtain constraints on F_π and F_ρ . The constraints complement the results of the few-body and light-nuclei experiments. Furthermore, we measure M^2 in two mass regions ($A \sim 100$ and $A \sim 230$) to check the consistency of the constraints.

Parity Non-conserving Asymmetry in the Compound Nucleus

The observable in the TRIPLE experiments is the PNC longitudinal asymmetry. For the i^{th} p-wave resonance, the PNC asymmetry (P_i) is

$$P_i = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \quad (2)$$

where σ_+ and σ_- are the resonance cross sections for positive and negative helicity states of neutrons. The asymmetry is manifestly parity violating. The total cross section (σ_T) is proportional to the forward scattering amplitude $f(0^\circ)$, which is expressed by

$$\sigma_T \propto f(0^\circ) = f_0 + f_1 \vec{\sigma} \cdot \vec{I} + f_2 \vec{\sigma} \cdot (\vec{k}_n \times \vec{I}) + f_3 \vec{\sigma} \cdot \vec{k}_n. \quad (3)$$

Here, $\vec{k}_n$ is the neutron momentum, $\vec{\sigma}$ is the Pauli matrix for neutron spin, and $\vec{I}$ is the target spin. With an unpolarized target and polarized neutron beam, the cross-section contains only one spin-dependent term, $\vec{\sigma} \cdot \vec{k}_n$. The parity symmetry can be tested by measuring the difference in the total cross-section when the sign of the $\vec{\sigma} \cdot \vec{k}_n$ term is changed by flipping the neutron spin direction parallel or anti-parallel to its momentum.

The PNC asymmetries in the CN are remarkably large because of a huge amplification arising from the high degree of level mixing in the CN. For two-state PNC mixing, the asymmetry (P_i) is a function of the mixing matrix element, the energy level splitting ($E_{s_j} - E_{p_i}$), and the ratio of the neutron width amplitudes of s-wave and p-wave resonances, $\sqrt{\Gamma_{s_i}^n}$ and $\sqrt{\Gamma_{p_i}^n}$, respectively,

$$P_i = 2 \frac{\langle \psi_{s_j} | H_w | \psi_{p_i} \rangle}{E_{s_j} - E_{p_i}} \sqrt{\frac{\Gamma_{s_j}^n(k_n)}{\Gamma_{p_i}^n(k_n)}}. \quad (4)$$

The high level density and a large ratio of the widths can give an overall enhancement of $\sim 10^6$. This makes the observable asymmetry as large as 10% in the CN system. Indeed, we have observed a PV asymmetry as large as 10% in ^{139}La and ^{232}Th .

TRIPLE EXPERIMENTS AND RECENT RESULTS

The TRIPLE collaborators have developed an apparatus to take advantage of the very high neutron flux available at the Los Alamos Neutron Scattering Center. The 500- μs -wide 800-MeV proton pulses from the Los Alamos Meson Physics Facility linac are injected into the Proton Storage Ring at the rate of 20 Hz and time compressed into triangular pulses 250-ns wide at the base. These pulses impinge on a tungsten target surrounded by a water moderator. The intensity of the epithermal neutron beam at neutron energy E is approximately given by

$$\frac{d^2n}{dE dt} = \frac{0.01}{E} \frac{I}{e} f \Omega \sim \frac{6.6 \times 10^7}{E} (1/\text{eV}/\text{s}), \quad (5)$$

where I is the average proton current ($\sim 70 \mu\text{A}$), e is the quantum of charge, $f \sim 0.63$ is the fraction of the 13-cm by 13-cm moderator viewed by the collimator system, and $\Omega \sim 4 \times 10^{-5} \text{sr}$ is the solid angle. It is the large neutron intensity that makes the measurements described here possible.

The apparatus (16) is designed to make simultaneous measurements of the longitudinal asymmetries of multiple p-wave resonances. The apparatus is shown schematically in Fig. 1. First, neutrons pass through a flux monitor (17) consisting of a pair of ionization chambers. The first chamber contains ^3He and the second ^4He at atmospheric pressure. The ^3He ion chamber responds to both neutrons and photons, while the ^4He ion chamber responds only to photons. The signals from each of these ion chambers are amplified by operational amplifiers and digitized by voltage-to-frequency

FIGURE 1. Schematic view of the apparatus in the PV experiment. Neutrons from the pulsed source pass through a polarizer, a cell of longitudinally polarized protons, where one helicity state is filtered out leaving a beam of longitudinally polarized neutrons. The neutron spin can be reversed by the spin flipper, a system of magnetic fields. After passing through the target, the neutrons are detected by a neutron detector. The neutron energy is measured by the time-of-flight between the pulsed source and the detector.

converters. The neutron flux is measured for each burst (with 0.1% accuracy) by subtracting the digitized ^4He signal from the digitized ^3He signal.

The neutrons next pass through a polarized-proton polarizer (18). The protons in a sample of irradiated NH_3 are dynamically polarized by microwave pumping at a temperature of 1 K while in a longitudinal magnetic field of 5 T. The cross section for neutrons with spin parallel to the proton spin is much smaller than for neutrons with spin anti-parallel. The neutrons with anti-parallel spin are filtered out, producing a 70% polarized neutron beam for neutron energies up to ~ 50 keV.

It is necessary to reverse the neutron polarization over a wide range of neutron energies in order to study many resonances simultaneously. This is accomplished by a "spin flipper," (19) a system of magnetic fields located after the polarizer. The spin flipper has a solenoidal field along the beam direction that blends into the stray field of the polarizer. This 0.01-T longitudinal field smoothly decreases, changes direction at the spin-flipper midpoint, and increases to a value opposite in sign and equal in magnitude to the initial field. A longitudinally polarized neutron near the spin-flipper cylindrical axis experiences no torque and passes through the spin flipper with its spin direction unchanged. In order to reverse the neutron spin direction, a transverse field is applied. This field smoothly builds up and decreases over a one-meter transition length where the longitudinal field reverses direction. The moving neutron experiences a field that is initially parallel to its velocity and then rotates slowly to be anti-parallel over a distance

of one meter. Since the Larmor frequency of the neutron spin is large compared to the rate at which the field direction rotates, the neutron spin follows the field direction adiabatically and is reversed. The neutron spin direction is controlled by turning the transverse field on or off. Calculations (19) show that the neutron spin is efficiently (better than 88%) reversed for neutron energies between 0.1 and 1000 eV. Thick target samples, $n\sigma_T \sim 3$ (n is the areal density) are placed in the downstream part of the spin-flipper.

The neutron detector (20), which is located 56 m from the spallation source, consists of an array of 55 ^{10}B -loaded liquid scintillator cells arranged in a hexagonal pattern. A neutron is captured in the reaction $n + ^{10}\text{B} \rightarrow ^7\text{Li} + ^4\text{He} + 2.79 \text{ MeV}$ which produces scintillation light detected by the photomultipliers. The neutron-boron capture cross-section is inversely proportional to the neutron velocity. The neutrons are first slowed down by elastic collisions with the hydrogen in the mineral oil base of the scintillator. When the neutron energy decreases, the chance for neutron-boron capture reaction increases. The hydrogen serves to confine the neutrons within the volume of the scintillator and increase the probability of the neutron-boron capture. An efficiency better than 90% was observed for neutron energies up to 1 keV. The measured efficiency is consistent with a Monte Carlo prediction.

The data acquisition system is operated in a hybrid digital-current mode. The 55 signals from the photomultiplier tubes viewing the scintillator cells are discriminated and the digital pulses sent to the data acquisition system located 150 m away. The digital signals are shaped and added together, and the analog sum is reconverted to digital signals by a transient digitizer. This unit periodically samples the combined analog signals and encodes the digitized signal into a 12-bit word. The resulting sequences of digitized signals are added into a 8192-channel summation memory located in CAMAC. The memory is read out by the data acquisition computer after every 200 beam pulses have been accumulated. The combined instantaneous rate of the 55 detectors is as large as 500 MHz.

Systematic Errors

Several techniques are used to reduce noise and systematic errors. One sixtieth of a second after the data from each beam pulse are encoded by the transient digitizer, the data from a beam-off time interval are encoded and then subtracted from the data in the summation memory. This procedure reduces the size of the 60-Hz noise by two orders of magnitude.

The neutron spin is reversed every ten seconds in the eight-step spin-flipper sequence NRRNRNNR, which eliminates drifts up to second order (16). For no reversal, N, the spin-flipper transverse field is off. For reversal, R, the transverse field direction is alternated so that, on the average, the stray transverse field is zero. This alternation of the transverse field direction eliminates the effects of the stray transverse field in first order. The spin direction is reversed independent of the spin flipper by reversal of the

polarization direction of the protons in the polarizer. This is done by tuning the microwave pumping frequency to a different transition. The combination of spin-flipper and polarizer reversal eliminates any systematic errors from either reversal method on the detector in first order. The leading systematic effect from the combined reversal method is the product of the first-order effects in both. The first-order effect from the spin-flipper reversal is estimated to be less than 10^{-10} and the systematic effect from changing the microwave pumping frequency is thought to be zero.

Systematic errors were shown to be less than a few times 10^{-5} from *in situ* measurements on s-wave impurity resonances, while measured longitudinal asymmetries of p-wave resonances were typically 10^{-3} to 10^{-1} . Thus, we believe that the systematic errors are negligible compared to other errors or the size of non-zero asymmetries in the results reported below.

Recent TRIPLE Experimental Results

In 1993, the TRIPLE collaboration measured PNC longitudinal asymmetries in the following targets, ^{238}U , ^{232}Th , ^{127}I , ^{115}In , ^{113}Cd , and natural Ag (^{107}Ag and ^{109}Ag). The data are still under analysis, but many new PNC asymmetries have been observed. The time-of-flight spectrum of ^{238}U near the neutron energy of 65 eV is shown in Fig. 2. The CN resonances appear as dips in the spectrum because we measure neutron transmission. At 63.5 eV, there exists a small $p_{1/2}$ resonance which is nearly degenerate with a large $s_{1/2}$ resonance at 65.5 eV. A large PV asymmetry is observed. The yield asymmetry shown in Fig. 2 near the $p_{1/2}$ resonance at 63.5 eV has a statistical accuracy better than 1%. Near the $s_{1/2}$ resonance region, the asymmetry has a large fluctuation due to a lack of neutron counts caused by the large cross-section. The yield and asymmetry spectra of ^{232}Th are presented in Fig. 3. Multiple non-zero asymmetries were observed in an individual nucleus. The asymmetries change sign (between the middle and bottom plots of Fig. 3) when the polarization direction of the polarizer is reversed. The signal-to-noise ratios of the PNC asymmetries are large and the PNC asymmetries are apparent in the data.

The preliminary PNC asymmetries from the 1993 data are presented in Fig. 4. For all of the target nuclei, except for ^{113}Cd , asymmetries were obtained by measuring the neutron transmission. The ^{113}Cd data were obtained by measuring the capture- γ rays using BaF_2 scintillators (21). This detector system measures the total cross-section because the p-wave resonances decay almost completely through the (n, γ) channel. The data are plotted as the asymmetry multiplied by $\sqrt{E}$ in order to correct for the energy dependence of the angular momentum barrier. The error bars represent the quadratic sum of the statistical error and the fitting error. The crosses are the statistically significant ($P/\Delta P(\text{statistical}) > 3$) non-zero asymmetries. It is clear that significant non-zero asymmetries are observed in all of the nuclei. Parity non-conservation appears to be a universal phenomenon in the compound nucleus.

FIGURE 2. The yield and yield-asymmetry spectra of ^{238}U near the 65-eV region. A non-zero PNC asymmetry appears near the $p_{1/2}$ resonance at 63.5 eV while the asymmetry elsewhere is consistent with zero. The large fluctuation of the asymmetry near the $s_{1/2}$ resonance region is due to a lack of neutron counts caused by the large cross-section.

FIGURE 3. Multiple non-zero PNC asymmetries in ^{232}Th p-wave resonances (indicated by arrows). The yield spectrum is on the top. Yield asymmetries for opposite polarization directions of the polarizer are in the middle and bottom plots.

FIGURE 4. The preliminary result of PNC asymmetries multiplied by $\sqrt{E}$. The statistically significant ($P/dP(\text{statistical}) > 3$) non-zero asymmetries are labeled by crosses and the other data points by circles.

Interpretation of Data

The PNC asymmetry for the i^{th} level, P_i , may be written as a perturbation series (22,23)

$$P_i = \sum_j \left[\frac{2}{E_{s_j} - E_{p_i}} \sqrt{\frac{\Gamma_{s_j}^n(E_{p_i})}{\Gamma_{p_i}^n(E_{p_i})}} \right] \langle \psi_{s_j} | H_w | \psi_{p_i} \rangle \quad (6)$$

$$\equiv \sum_j A_{ij} \cdot V_{ij},$$

where E_i and E_j are the energies of the p-wave resonance and the admixed s-wave resonances, $V_{ij} \equiv \langle \psi_{s_j} | H_w | \psi_{p_i} \rangle$ is the matrix element of the PNC interaction between states i and j , and $\Gamma_{p_i}^n$ and $\Gamma_{s_j}^n$ are their neutron widths. The parameter $A_{ij} \equiv 2\sqrt{\Gamma_{s_j}^n/\Gamma_{p_i}^n}/(E_{s_j} - E_{p_i})$ is a function of resonance energies and neutron widths, known experimentally. According to the statistical model of the CN, the neutron-decay amplitudes and the mixing matrix elements are mean-zero Gaussian random variables. This implies that the measured asymmetries are also mean-zero with variance

$$\langle P_i^2 \rangle = A_i^2 M^2. \quad (7)$$

Here $M^2 = \langle V_{ij}^2 \rangle = \langle \psi_{s_j} | H_w | \psi_{p_i} \rangle^2$ and $A_i^2 = \sum A_{ij}^2$. We have done a likelihood analysis to determine the value of M^2 by including the experimental uncertainties and the unknown spin assignments.

As expected, the measured asymmetries (in Fig. 4) have large fluctuations and both positive and negative asymmetries are observed for all target nuclei, except for ^{232}Th . There is strong evidence that the asymmetries for ^{232}Th are not random and have a non-zero average. Theoretical models (24,25) are being developed to explain the non-zero average. Basically, the asymmetries in ^{232}Th can be expressed as two terms (24),

$$P_i = \sum_j \left[\frac{2 \langle \psi_{s_j} | H_w | \psi_{p_i} \rangle}{E_{s_j} - E_{p_i}} \sqrt{\frac{\Gamma_{s_j}^n(E_{p_i})}{\Gamma_{p_i}^n(E_{p_i})}} \right] + B \sqrt{\frac{\text{leV}}{E_i}}. \quad (8)$$

The first term fluctuates about zero with random signs. The second term is the non-zero average arising from correlations between the mixing matrix element, $E_{s_j} - E_{p_i}$, neutron width amplitudes of the p-wave resonance and far away s-wave resonances. A non-zero average of the PNC asymmetries is observed only in the ^{232}Th data (Fig. 4) presumably due to some particular nuclear structure in ^{232}Th (25). A two-dimensional likelihood analysis has been done for the ^{232}Th data in order to extract M and B values. The M value of the ^{232}Th data presented below is deduced from the two-dimensional likelihood analysis.

The M values determined by the likelihood analyses for ^{238}U , ^{232}Th , ^{115}In and ^{113}Cd are shown in Fig. 5. In order to relate M to the properties of the N-N interaction, the results are presented by the square-root of the PNC weak spreading width, $\sqrt{\Gamma^{\text{PNC}}} = \sqrt{2\pi M^2/d_J}$. The p-wave resonance level spacing, d_J (~ 10 eV), is roughly $1/N$

FIGURE 5. The preliminary result of the PNC weak spreading widths for mass $A \sim 100$ and $A \sim 230$ regions. The weak spreading width is expected to have a smooth mass dependence. The data near the same mass region are combined and shown at the bottom.

of the typical shell model level spacing (MeV). The mean-squared matrix element is proportional to $1/N$ of the matrix element squared of the effective N-N interaction. Therefore one expects that Γ^{PNC} is independent of the atomic mass of the compound nucleus. We can combine the data in the same mass region to obtain better statistics (Fig. 5 bottom).

A theoretical model (15) has been developed to relate the M^2 to the π -meson and ρ -meson exchange couplings, F_π and F_ρ , respectively,

$$M^2 = \alpha F_\pi^2 + \beta F_\pi F_\rho + \gamma F_\rho^2. \quad (9)$$

The coefficients α , β and γ are determined using the statistical model of the CN. Using the experimental value of M and the above relation, our results give constraints on F_π and F_ρ . From the M values at $A \sim 100$ and $A \sim 230$ regions, we can learn about the mass-dependence of the constraints and check the theory. Figure 6 shows an example of the constraints (the "donut" shape) calculated from the previous ^{238}U and ^{232}Th data, which have 20-fold worse statistical accuracy than the recent data. The range of values of the F_π and F_ρ predicted by the DDH theory (1) covers everything on the plot. The straight lines are the constraints given by PNC experiments in the few-body ($\bar{p} + \alpha$) and light-nuclei (^{18}F , ^{19}F and ^{21}Ne) systems. Among those experiments, the ^{18}F system has the most complete information. It indicates that F_π is small but the experiment is insensitive to F_ρ . The uncertainty of the constraints given by the ^{21}Ne experiment has not been

FIGURE 6. Constraints on the isovector π and isoscalar ρ weak meson-nucleon coupling constants, F_π and F_ρ , respectively, imposed by various experiments. (2,15)

included in this plot since it is believed to be larger than the uncertainties of the other light-nuclei experiments. With the new PNC data from this work and newly developed theory (26), we expect a larger donut that possibly covers the overlap region of the $\bar{p} + \alpha$ and ^{19}F predictions. The most exciting discovery of this work is that the very different theoretical frameworks for understanding the light-nuclei and compound nucleus PNC experiments agree qualitatively.

TEST OF TIME-REVERSAL INVARIANCE IN NEUTRON-NUCLEUS INTERACTION

A sensitive test of time-reversal invariance (TRI) can be carried out by observing the dependence of the total cross section at a p-wave resonance on the scalar triple product $\vec{\sigma} \cdot (\vec{k}_n \times \vec{I})$, which is the P-odd T-odd term in the neutron forward scattering amplitude (Eq. (3)). Bunakov and Gudkov (27) have argued that the enhancement factor for the triple correlation asymmetry should be of the same order of magnitude as for the PNC longitudinal asymmetry. Their studies indicated that for certain models the size of the triple correlation asymmetry may be as large as 10^{-3} of the PNC longitudinal asymmetry. Herczeg (28) has estimated that a sensitivity of 10^{-3} in the $\vec{\sigma} \cdot (\vec{k}_n \times \vec{I})$

correlation is comparable to the TRI test provided by the neutron electric dipole moment (EDM) of $10^{-25} \text{ e} \cdot \text{cm}$.

To test the $\vec{\sigma} \cdot (\vec{k}_n \times \vec{I})$ term, we need to orient the neutron spin, neutron momentum and target spin perpendicular to each other. The sign of the triple term can be changed by flipping the spins. The experimental apparatus (Fig. 7) includes a polarizer, upstream spin-rotator, polarized target, downstream spin-rotator, analyzer, and neutron detector. The addition of the analyzer eliminates a false asymmetry resulting from the final state interactions and therefore makes the experiment manifestly time-reversal symmetric. The target is polarized perpendicular to the reaction plane. The polarizer and analyzer have the same polarization directions which are perpendicular to both the neutron momentum and target polarization. The time-reversal condition can be accomplished by simultaneously flipping the spin-directions of the polarizer and analyzer. The TRI asymmetry will be measured at the 0.734-eV p-wave resonance in ^{139}La , where a large PNC asymmetry of 0.0955 ± 0.0035 has been observed (29).

Polarized ^{139}La targets have been developed by our collaborators at Kyoto University and KEK (30,31). A ^{139}La polarization of 20% has been achieved with a $5\text{-cm}^3 \text{ LaAlO}_3$ crystal polarized by the dynamic nuclear polarization technique in a magnetic field of 2.3 T and temperature of 1.5 K. The ^{139}La polarization as large as 70% may be obtained by using a dilution refrigerator for cooling. Two polarized ^3He systems will be built for the polarizer and analyzer. The ^3He polarization of 70% has been achieved recently at Los Alamos by optical pumping with high-power diode laser arrays (32). The time-reversal modulation can be done with the upstream and downstream spin-rotators (in seconds), with the polarizer and analyzer adiabatic-fast-passage (in hours) or with the ^{139}La polarization direction (in days). Based on the sensitivity of the PNC asymmetry measurements, it is estimated that in $2 \times 10^6 \text{ s}$, a statistical sensitivity of about 10^{-3} in the ratio of $\langle \vec{\sigma} \cdot (\vec{k}_n \times \vec{I}) \rangle / \langle \vec{\sigma} \cdot \vec{k}_n \rangle$ can be achieved. This sensitivity level is comparable to the sensitivity of the neutron electric dipole moment measurements (28,33).

FIGURE 7. An experimental apparatus for the time-reversal invariance (TRI) test. The TRI asymmetry is measured by changing the sign of the triple correlation term, $\vec{\sigma} \cdot (\vec{k}_n \times \vec{I})$.

The triple correlation term can also be tested by measuring the asymmetry of neutron spin rotation through a polarized target. An experimental apparatus has been developed (34) to do such a measurement on a polarized LaAlO_3 target. The sensitivity in the ratio of $\langle \vec{\sigma} \cdot (\vec{k}_n \times \vec{I}) \rangle / \langle \vec{\sigma} \cdot \vec{k}_n \rangle$ from this experiment is expected (35) to be 3×10^{-4} , which is about one order of magnitude better than the neutron EDM measurement.

A test of the P-even and T-odd five-fold correlation term, $\vec{\sigma} \cdot (\vec{k}_n \times \vec{I})(\vec{k}_n \cdot \vec{I})$, has been carried out (36) using fast (6.7 MeV) neutrons. The TRI asymmetry is measured by polarized neutron transmission through a rotating, cryogenically aligned ^{165}Ho target. The P-even T-odd spin correlation coefficient, $A_5 = (1.1 \pm 2.3) \times 10^{-5}$, obtained in this measurement is consistent with time-reversal invariance. This sets a bound of 3.8×10^{-3} (99% confidence) on α_T , the ratio of T-odd to T-even couplings in the effective nucleon-nucleon interaction.

SUMMARY

Parity non-conservation (PNC) phenomena have been studied in compound nuclei in mass regions of $A \sim 100$ and $A \sim 230$. The chaotic nature of the compound nucleus results in a very large enhancement of the PNC asymmetries and allows the data to be interpreted using the statistical model of the compound nucleus. The mean-squared PNC mixing matrix element (M^2) was extracted from a set of PNC longitudinal asymmetry data of many p-wave resonances using the likelihood technique. Applying the statistical model of the compound nucleus, the M^2 can be related to the π and ρ meson-exchange couplings (F_π and F_ρ , respectively). With the PNC longitudinal asymmetry data in compound nuclei, constraints on F_π and F_ρ are calculated. The results agree qualitatively with the constraints given by PNC studies in the few-body and light-nuclei systems.

The time-reversal observables in the compound nucleus can have the same large enhancement as the PNC observables. Experiments to test the time-reversal invariance (TRI) in neutron-nucleus interactions are being developed. The triple correlation P-odd T-odd term can be tested by measuring the asymmetry of the compound nucleus cross-sections when the sign of the triple term is changed by flipping neutron or target spins. The triple term can also be tested by measuring the asymmetry of the neutron spin rotation through a polarized target. For these experiments, a polarized ^{139}La target was chosen because a large PNC asymmetry has been observed at the 0.734 eV p-wave resonance. With high energy (MeV) neutrons, the five-fold correlation P-even T-odd term has been tested by measuring the neutron transmission through a rotating aligned ^{165}Ho target. This experiment sets a bound of 3.8×10^{-3} on the ratio of T-odd to T-even couplings in the effective nucleon-nucleon interaction.

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