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EXPERIMENTS ON PARITY VIOLATION IN THE COMPOUND NUCLEUS

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Results from experiments that measure parity-violating longitudinal asymmetries in the scattering of epithermal neutrons from compound-nuclear resonances at the Manuel Lujan Neutron Scattering Center at Los Alamos are discussed. Parity non-conserving asymmetries have been observed for many p-wave resonances in a single target. 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. For all nuclei but ^{232}Th measured asymmetries have random signs. For ^{232}Th eight of eight measured asymmetries are positive. This phenomenon is discussed in terms of doorway models.

1 Introduction

The weak parity non-conserving (PNC) nucleon-nucleon (N-N) interaction can be described in terms of meson-exchange potentials between nucleons. The Desplanques, Donoghue, and Holstein (DDH) theory¹ characterizes the PNC interaction with seven weak meson-exchange amplitudes and predicts a reasonable range of values for these coupling constants. It is a great experimental and theoretical challenge to determine these weak coupling constants.

Hadronic PNC phenomena have been observed² 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 difficult². 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 scattering. 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, but these measurements still lack sufficient precision to constrain the couplings². 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 isospin-one π and isospin zero ρ 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 $^{18}\text{F}^{9-11}$, which is sensitive to the F_π . The lifetimes and energy-splittings of the nuclear states in ^{18}F are well known. With some nuclear-structure parameters taken from experiment, 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 interpretation of these experiments involves shell-model calculations of the wave functions of the states involved. The experimental 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 in which the energy of the incident neutron is shared among all the nucleons in the daughter nucleus; 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. A second reason is extract quantitative information about the strengths of the weak hadronic couplings, F_π and F_ρ .

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, V_{sp} , 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 :

$$\overline{|V_{sp}|^2} = M^2 . \quad (1)$$

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.

PNC phenomena of this type were first observed by Abov *et al.*¹². Recent advances have resulted from the experimental program of the TRIPLE collaboration¹³⁻¹⁵ working at the Manuel Lujan Neutron Scattering Center. Before the work of the TRIPLE collaboration, a number of asymmetries had been measured in individual nuclei¹⁶. The TRIPLE collaboration developed experimental techniques to measure many asymmetries in individual nuclei. The availability of many asymmetries in individual led Bowman *et al.*¹⁷ to develop statistical methods to extract average matrix elements of the PV interaction, M^2 , from the measured PV asymmetries.

A theoretical model has been developed¹⁵ 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.

1.1 Parity Non-Conserving Asymmetry in the Compound Nucleus

The PNC longitudinal asymmetry, P_i , for the i^{th} p-wave resonance is defined as

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

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 can be expressed by

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

Here, $\vec{k}_n$ is the neutron momentum, $\vec{\sigma}$ are the Pauli matrices, 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, $\sqrt{\Gamma_{s_j}^n}$ and $\sqrt{\Gamma_{p_i}^n}$, respectively,

$$P_i = 2 \frac{V_{ij}}{E_{s_j} - E_{p_i}} \sqrt{\frac{\Gamma_{s_j}^n}{\Gamma_{p_i}^n}} . \quad (4)$$

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 .

2 Recent Results

The TRIPLE collaboration at Los Alamos has developed apparatus and techniques to take advantage of the very high neutron flux available at the Manuel Lujan 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

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

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.

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.

The apparatus¹⁸ 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 monitor¹⁹ 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 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 polarizer²⁰. The protons in a sample of irradiated NH_3 are dynamically polarized by microwave pumping at a temperature of 1 K and 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,"²¹ 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. Calculations²¹ 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 aerial density) are placed in the downstream part of the spin-flipper.

The neutron detector²², 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 by ^{10}B 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.

2.1 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 order¹⁸. 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.

2.2 Recent 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

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.

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 scintillators²³. 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. Because $p_{3/2}$ resonances cannot exhibit PNC only statistically significant results are shown.

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.

2.3 Interpretation of Data

The PNC asymmetry for the i^{th} level, P_i , may be written as a perturbation series^{24,25}

Figure 4: The preliminary result of PNC asymmetries multiplied by $\sqrt{E}$.

$$P_i = \sum_j \frac{2}{E_j - E_i} \sqrt{\frac{\Gamma_j}{\Gamma_i}} V_{ij} \equiv \sum_j A_{ij} V_{ij} , \quad (6)$$

where E_i and E_j are the energies of the p-wave resonance and the admixed s-wave resonances, V_{ij} is the matrix element of the PNC interaction between states i and j , and Γ_j and Γ_i are their neutron widths of the p and s-wave resonances. The parameter $A_{ij} = \sqrt{\Gamma_j/\Gamma_i} (2/E_j - E_i)$ is a function of resonance energies and neutron widths. These quantities are known experimentally. According to the statistical model of the CN, the neutron-decay amplitudes and the mixing matrix elements are independent mean-zero Gaussian random variables. These assumptions imply that the measured asymmetries deviled by $A_i^2 = \sum_j A_{ij}^2$ are also mean-zero Gaussian random variables with variance

$$\left\langle \frac{P_i^2}{A_i^2} \right\rangle = M^2 . \quad (7)$$

Here M^2 is the mean squared matrix element of the PV interaction. (The assumption that the decay amplitudes and matrix elements are independent is necessary.) Equation (7) shows that M^2 could be determined as the average of the reduced asymmetries squared. The experimental asymmetries are shown in Fig. 4. We have done a likelihood analysis to determine the value of M^2 by including the experimental uncertainties and the unknown spin assignments. The nucleus ^{232}Th is different than the other targets because the measured asymmetries are all positive. A two-dimensional likelihood analysis that separates the fluctuations in P_i , associated with the first term in Eq. (9) (below), and the average value of $P_i/\sqrt{E_i}$, associated with B , has been done for the ^{232}Th data in order to extract M and B values. In order to reduce the A dependence of M^2 we introduce the spreading width of the PV interaction $\Gamma_{\text{PNC}} = 2\pi M^2/d_J$, where d_J is the level spacing. One can understand why the spreading width has a smaller A dependence than the mean squared matrix element as follows. The p-wave resonance level spacing, d_J (~ 10 eV), is roughly $1/N$ (N is the number of components in the CN wave function) of the shell-model level spacing (a few MeV). The mean-squared matrix element is proportional to $1/N$ of the matrix element squared of the effective N-N interaction between single particle states. Therefore, the N dependencies of the numerator and denominator in Eq. (7) are the same, and one expects that Γ_{PNC} is independent of the atomic mass of the compound nucleus in a mass region $\Delta A \ll A$. We can combine data in the same mass region to obtain better statistics (Fig. 5 bottom). The A dependence of the PV spreading width is shown in Fig. 5.

Figure 5: The preliminary result of the PNC weak spreading widths for mass A~100 and A~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.

A theoretical model¹⁵ has been developed to relate the M^2 to the π -meson and ρ -meson exchange couplings, F_π and F_ρ , respectively,

$$M^2 = \alpha(A)F_\pi^2 + \beta(A)F_\pi F_\rho + F_\rho^2 \gamma(A) . \quad (8)$$

The coefficients $\alpha(A)$, $\beta(A)$, and $\gamma(A)$ are determined using the statistical model of the CN. Johnson, Bowman, and Yoo,¹⁵ and Johnson and Bowman²⁶ have discussed the problem of calculating the coefficients. This subject will be discussed in talks by Mikkel Johnson, Steve Tomsovic, and Anna Hayes at this workshop. I will make a few remarks about some important features of the theory of the coefficients that enter into the expression for M^2 .

The theory of M^2 is very different from the theory of parity mixing between states in light nuclei in two ways. First, for light nuclei, measurements provide a value of the matrix element of the PV interaction between a pair of states. In order to obtain a constraint on the values of the weak meson couplings, the expansion

coefficients of the wave functions must be known. It is necessary to calculate the phases of the expansion coefficients as well as their magnitudes. In heavy nuclei the value of the mean-squared matrix element is determined from experiment. The coefficients $\alpha(A)$, $\beta(A)$, and $\gamma(A)$ depend on the mean squared values of the expansion coefficients of the CN wave functions in an energy interval near neutron threshold, but not on the phases of the expansion coefficients. In order to extract information about the values of the weak meson couplings from experimental data it is not necessary to calculate the wave functions of particular CN states. This situation is fortunate because while such a calculation is difficult in light nuclei, it is impossible in heavy nuclei. Second, in light nuclei the one-body part of the weak nucleon-nucleon interaction is more important than the two-body part, while in heavy nuclei the relative importance is opposite. The contribution of the two-body interaction is small compared to that of the one-body interaction because the semi-diagonal nature of the one-body matrix elements. The importance of the one-body operator enhancement by a factor $\sim A$ relative to the importance of the two-body matrix elements. This enhancement applies to both light and heavy nuclei. In light nuclei the spins of shell-model states are small and the spin orbit force does not mix major shells. Energy denominators for one-body and two-body matrix elements are both of order $\hbar\omega$. In heavy nuclei, the spins of shell-model states can be large and the spin-orbit interaction reduces the energies the orbitals of the highest spin (intruder states) by $\sim \hbar\omega$. The meson-exchange potential can not change the orbital angular momentum by more than 1, so the matrix elements between configurations that differ by the state of more than one nucleon vanish. The two-body weak meson exchange potential can connect configurations that differ by the configurations of two nucleons. The energy denominators of these configurations can be small because of the presence of intruder states. Johnson and Bowman²⁶ estimated the relative importance of one and two-body contributions in heavy nuclei and found that the two-body contributions are several times larger than one-body contributions.

Using the experimental value of M and estimates of $\alpha(A)$, $\beta(A)$, and $\gamma(A)$ ¹⁵, 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 ²³⁸U and ²³²Th 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 theory¹ covers everything on the plot. The straight lines are the constraints given by PNC experiments in the few-body ($\bar{p} + \alpha$) and light-

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}.

nuclei (^{18}F , ^{19}F , and ^{21}Ne) systems. Among those experiments, the ^{18}F system has the least dependence on nuclear theory because the matrix-element of the weak meson-exchange potential can be determined from β decay rates of analog transitions. The constraint from ^{18}F indicates that F_π is small. F_ρ does not enter into the ^{18}F result. The uncertainty of the constraints given by the ^{21}Ne experiment has not been 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 ²⁷, 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 and may provide constraints on the weak meson-exchange couplings from different experiments and different theoretical perspectives.

As expected, the measured asymmetries (in Fig. 4) have large fluctuations; both positive and negative asymmetries are observed for all target nuclei, *except* for ^{232}Th . For ^{232}Th out of eight asymmetries have a positive sign. All other nuclei studied, including the neighboring nucleus ^{238}U , have random signs. If the distribution of asymmetries were symmetric about zero, the probability of all eight asymmetries having the same sign would be $2^{-7} = 1/128$. Theoretical models²⁸⁻³⁵ have been developed to explain the non-zero average. A common feature of all models developed to describe the non-zero average asymmetry is that the asymmetries in ^{232}Th can be expressed as the sum of two terms²⁸,

$$P_i = \sum_j \frac{2V_{ij}}{E_j - E_i} \sqrt{\frac{\Gamma_j}{\Gamma_i}} + B \sqrt{\frac{1\text{eV}}{E_i}} \quad (9)$$

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 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 . Early models that attempted to explain the non-zero average asymmetry had a serious problem: they require a very large matrix element of the parity-violating matrix element between the doorway states responsible for the correlations and they predict that all nuclei should exhibit non-random behavior. This problem arose from the fact that the probability of finding any particular doorway configuration in the CN wave function is of order d_j/Γ_s , where d_j is the CN level spacing and Γ_s is the spreading width of the strong interaction, ~ 2 MeV.

Several authors have proposed explanations of the non-zero average asymmetry based on local doorways for which the spreading width is much less than 2 MeV. Auerbach, Bowman, and Spevak²⁹ proposed a mechanism based on the idea that excited states of ^{233}Th , the daughter of the $n + ^{232}\text{Th}$ reaction, exhibit parity doublets³⁶ based on pear-shaped deformations. These doublets have spacings of 1-40 KeV and are connected by strong E1 γ transitions. The properties of these parity doublets have been explained by interpreting the parity doublets as arising from large octupole deformations³⁷. Hussein, Kerman, and Lin proposed³⁵ that the two-particle-one-hole configurations that act as doorways for neutron decay and

are expected to have spreading widths considerably smaller than 2 MeV are responsible for the average non-zero asymmetry. Desplanques and Noguera³² have suggested that the local doorways are states in the second well. These authors give a critical comparison of different explanations of the non-zero average asymmetry. These theories offer plausible explanations of the non-zero average asymmetry. A challenge for theory and experiment is to develop tests of these competing explanations and determine which, if any, is correct.

3 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 nucleus ^{232}Th exhibits non-statistical behavior. Eight of eight measured PV asymmetries were positive. The probability of this happening by chance is 1/128. The most likely explanation for this phenomenon is the existence of some sort of local doorways that have spreading widths of much less than the spreading width of the strong interaction, 2 MeV.

References

1. B. Desplanques, J. F. Donoghue, and B. R. Holstein, *Ann. Phys.* **124**, 449 (1980).
2. E. G. Adelberger and W. C. Haxton, *Ann. Rev. Nucl. Part. Sci.* **35**, 501 (1985).
3. D. E. Nagle *et al.*, *Proc. 3rd Int. Symp. on High Energy Physics with Polarized Beams and Polarized Targets*, Argonne, 1978, *AIP Conf. Proc.* **51**, 24 (1979).

4. R. Balzer *et al.*, *Phys. Rev. C* **30**, 1409 (1984).
5. V. W. Yuan *et al.*, *Phys. Rev. Lett.* **57**, 1680 (1986).
6. J. Lang *et al.*, *Phys. Rev. Lett.* **54**, 170 (1985).
7. B. R. Heckel, University of Washington, private communication (1994).
8. L. Lowie, North Carolina State university, private communication (1994).
9. C. A. Barnes *et al.*, *Phys. Rev. Lett.* **40**, 840 (1978).
10. P. G. Bizetti *et al.*, *Lett. Nuovo Cimento* **29**, 167 (1980).
11. G. Ahrens *et al.*, *Nucl. Phys. A* **390**, 486 (1982).
12. Yu. G. Abov, P. A. Krupchitsky, and Yu. A. Oratovsky, *Phys. Lett.* **12**, 25 (1964).
13. J. D. Bowman, G. T. Garvey, M. B. Johnson, and G. E. Mitchell, *Annu. Rev. Nucl. Part. Sci.* **43**, 829 (1993).
14. J. D. Bowman *et al.*, in *Proceedings of the Second International Workshop on Time Reversal Invariance and Parity Violation in Neutron Reactions*, ed. C. R. Gould, J. D. Bowman, and Yu. P. Popov (World Scientific, Singapore, 1993), pp. 8–29.
15. M. B. Johnson, J. D. Bowman, and S. H. Yoo, *Phys. Rev. Lett.* **67**, 310 (1991).
16. V. P. Alfimenkov *et al.*, *Nucl. Phys. A* **398**, 93 (1983), S. A. Biryukov *et al.*, *Yad. Fiz.* **45**, 1511 (1987), Y. Masuda *et al.* *Nucl. Phys. A* **504**, 269 (1989), V. W. Yuan *et al.* *Phys. Rev. C* **44**, 2187 (1991), V. P. Alfimenkov *et al.*, *Yad. Fiz.* **54**, 1489, (1991).
17. J. D. Bowman *et al.*, *Phys. Rev. Lett.* **65**, 1192 (1990).
18. N. R. Roberson *et al.*, *Nucl. Instrum. Methods A* **326**, 549 (1993).
19. J. J. Szymanski *et al.*, to be published in *Nucl. Instrum. Methods* (1994).
20. S. I. Penttilä *et al.*, in *Proceedings of the Ninth International Symposium on High-Energy Spin Physics*, Bloomington 1994.
21. J. D. Bowman, S. I. Penttilä, and W. B. Tipples, *Nucl. Instrum. Methods A* **369**, 195, (1996).
22. Yi-Fen Yen *et al.*, in *Proceedings of the Second International Workshop on Time Reversal Invariance and Parity Violation in Neutron Reactions*, ed. C. R. Gould, J. D. Bowman and Yu. P. Popov (World Scientific, Singapore, 1993), pp. 210–219.
23. P. E. Koehler, Oak Ridge National Laboratory, private communication (1993).
24. V. P. Alfimenkov *et al.*, *Nucl. Phys. A* **398**, 93 (1983).
25. J. R. Vanhoy *et al.*, *Z. Phys. A* **333**, 229 (1988).

26. M. B. Johnson and J. D. Bowman, *Phys. Rev.* **C51**, 999 (1995).
27. M. B. Johnson, Los Alamos National Laboratory, private communication (1994).
28. J. D. Bowman *et al.*, *Phys. Rev. Lett.* **68**, 780 (1992).
29. N. Auerbach, J. D. Bowman, and V. Spevak, *Phys. Rev. Lett.* **74**, 2638 (1994).
30. S. E. Koonin, C. W. Johnson, and P. Vogel, *Phys. Rev. Lett.* **69**, 1163 (1992).
31. C. H. Lewenkopf and H. A. Weidenmüller, *Phys. Rev.* **C46**, 2601 (1992).
32. B. Desplanques and S. Noguera, *Nucl. Phys.* **A561**, 189 (1993); B. Desplanques and S. Noguera, *Nucl. Phys.* **A598**, 139, (1996).
33. D. F. Zaretskii and V. K. Sirotkin, *Phys. At. Nucl.* **57**, 35 (1994).
34. N. Auerbach and J. D. Bowman, *Phys. Rev.* **C46**, 2582 (1992).
35. M. Hussein, A. Kerman, and C. Lin, Preprint, submitted to *Z. Phys.*
36. J. Blons *et al.*, *Nucl. Phys.* **A414**, 1 (1984); **A502**, 121c (1989).
37. S. Cwiok *et al.*, *Phys. Lett.* **B322**, 304 (1994).