Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

LA-UR--90-3193

DE91 000425

TITLE: PARITY AND TIME-REVERSAL SYMMETRY NONCONSERVATION IN
NEUTRON-NUCLEUS INTERACTIONS

AUTHOR(S): *J. David Bowman, C. D. Bowman, J. Knudson, S. Penttilä, S. J. Seestrom,
J. J. Szymanski, V. W. Yuan, J. E. Bush, C. M. Frankle, C. R. Gould,
D. G. Haase, G. E. Mitchell, P. P. J. Delheij, H. Postma, N. R. Roberson,
and X. Zhu*

SUBMITTED TO: The proceedings of the Second International Conference on Medium- and
High-Energy Nuclear Physics, May 14-18, 1990, in Taiwan, R.O.C.

Received by OSTI

OCT 04 1990

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

PARITY AND TIME-REVERSAL SYMMETRY NONCONSERVATION IN NEUTRON-NUCLEUS INTERACTIONS*

J. David Bowman, C.D. Bowman, J. Knudson, S. Penttilä, S.J. Seestrom, J.J. Szymanski and V.W. Yuan
Los Alamos National Laboratory, Los Alamos, NM 87545

J.E. Bush, C.M. Frankle, C.R. Gould, D.G. Haase and G.E. Mitchell
North Carolina State University, Raleigh, NC 27695 and Triangle Universities
Nuclear Laboratory, Durham, NC 27706

P.P.J. Delheij
TRIUMF, Vancouver, British Columbia V6T 2A3

H. Postma
University of Technology, P.O. Box 5046, 2600 GA Delft, The Netherlands

N.R. Roberson and X. Zhu
Duke University, Durham, NC 27706 and Triangle Universities Nuclear Laboratory,
Durham, NC 27706

Parity non-conservation was studied for seventeen states in the compound nucleus ^{239}U by measuring the helicity dependence of the p-wave resonance cross section for epithermal neutrons scattered from ^{238}U . The root-mean-squared parity-violating matrix element for the mixing of p-wave and s-wave states was determined to be $M = 0.58^{+0.50}_{-0.25}$ meV. This corresponds to a parity-violating spreading width of $\Gamma^{\text{PV}} = 1.0 \times 10^{-7}$ eV. This gives a value of 4×10^{-7} for α_p , the ratio of strengths of the P-odd and P-even effective nucleon-nucleon interactions in ^{239}U . The implications of these results for studies of Time Reversal Symmetry in the compound nucleus is discussed.

1. INTRODUCTION

Highly excited nuclear states are so complicated that their description requires a statistical approach. Nevertheless the structure of these states is influenced by weak symmetry-breaking forces. Indeed under certain circumstances complexity can enhance the effect of a weak force and make it easily observable. This talk considers forces that violate the parity and time-reversal-invariance symmetries. The approach of statistical nuclear physics provides a quantitative framework. In this talk we will discuss studies of how the weak parity non-conserving (PNC) nucleon-nucleon (N-N) interaction manifests itself in the compound nucleus (CN) regime. A neutron captured by a nucleus forms highly excited states in the compound system just above the neutron separation energy. The energy

spacing of these complex states is small and the states complex. It is ironic that this complexity amplifies subtle symmetry-breaking forces and makes them observable.

Symmetry violations in the effective (N-N) interaction are greatly enhanced in the many-body nuclear system. For example, remarkably large (PNC) longitudinal asymmetries, $P = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$ where σ_+ and σ_- are the neutron-nucleus cross section for + and - neutron helicity, have been observed in the reaction of polarized neutrons from a number of nuclei. The most spectacular case is the 0.734 eV p-wave resonance in ^{139}La for which the effect is $\sim 10\%$ ^{1,2,3,4,5}. The PNC force in the nucleon-nucleon interaction produces longitudinal asymmetries by mixing nuclear levels of the same total angular momentum but with opposite parity. The large size of this effect is the result of three mechanisms: 1) The effect results from an interference between the weak and strong interactions and hence is first-order in the weak interaction. 2) The level spacing of the (CN) system is small, so that a small PNC force can produce a large mixing of states. 3) s-wave states (neutron orbital momentum 0) have much larger scattering amplitudes than p-wave states (neutron orbital angular momentum 1). Therefore a small admixture of a s-wave state into a p-wave state produces a large longitudinal asymmetry. Here we report determinations of PNC-mixing matrix elements between CN states in ^{239}U by measuring the helicity dependence of the p-wave resonance cross section of neutrons reaction from ^{238}U . From the experimentally determined values of longitudinal asymmetries we determine M , the root mean squared matrix element between s-wave and p-wave compound nuclear states. The techniques used to extract M are discussed. We evaluate the parity violating spreading width Γ^{PV} and α_p , the ratio of the weak to strong force in the nuclear medium. We compare α_p with its free-space value and find qualitative agreement. Not only is the study of PNC of intrinsic interest, it is the first part of our program to study the parity and time-reversal symmetries in the CN system, where enhancement effects are expected to greatly increase the sensitivity of experiments testing both parity and time-reversal symmetries.^{6,7} Time-reversal nonconservation (TNC) has been observed only indirectly in the $K^0-\bar{K}^0$ system, where the observed CP nonconservation is related to T nonconservation by the assumed validity of the CPT theorem. The magnitude of the CP-odd effect provides guidance for the size of P-odd, T-odd effects in the CN system, but no direct evidence of T nonconservation has been observed. On the other hand, PNC effects in the N-N interaction are well established. The study of PNC in the CN system forms the basis of quantitatively understanding how the underlying symmetry nonconservation in the N-N interaction manifests itself in the complicated many-body nuclear system. This understanding will then be applied to the

time-reversal symmetry tests to extract information on the TNC N-N interaction. For this reason the fact that PNC effects can be understood in terms of conventional nuclear physics ideas is encouraging. The same types of analysis can then be applied to the interpretation of experiments that study the breaking of time reversal invariance symmetry.

2. EXPERIMENTAL TECHNIQUE

The experiment was performed at the Los Alamos Neutron Scattering Center (LANSCE). The 800-MeV proton beam from the Los Alamos Meson Physics Facility linac is accumulated in a proton storage ring and extracted as pulses having a width of 270 nsec. The extracted protons strike a tungsten target and the resulting spallation neutrons (~25 per incident proton) are partially moderated by water and collimated to produce a beam. The neutrons are polarized by selective attenuation in a spin filter consisting of a cell of longitudinally polarized protons.⁸ The proton polarization is monitored by nuclear magnetic resonance techniques and calibrated by measurements of the neutron transmission through the spin filter. The neutron polarization was about 40% and was known with a fractional error of 5%. The neutron polarization was reversed every ten seconds by a system of magnetic fields and every day by changing the spin-filter pumping frequency. This latter method left all magnetic guide fields unchanged. The neutrons pass through a metallic sample of ²³⁸U (18.0 gm/cm²), and are detected in an array of seven ⁶Li glass scintillators, each 1.0 cm thick and 13.3 cm in diameter and viewed by high-current photomultiplier tubes.^{9,10} The neutron energy is determined by time of flight over the 56 m distance from neutron source to the detectors. The current from the phototubes was encoded by a transient digitizer every 10⁻⁷ seconds and stored. In this way the transmission for every resonance was measured for every neutron burst. A data run consisted of a thirty-minute sequence of programmed spin reversals, which cancelled linear and quadratic time-dependent drifts. A total of about 200 such runs were accumulated. Seventeen resonances up to E_n ≈ 300 eV were analyzed. The experimental asymmetry ϵ , is defined as $\epsilon = (N^+ - N^-)/(N^+ + N^-)$, where N⁺ and N⁻ are the counts for the two helicity states. A value of the longitudinal asymmetry $P = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$ was determined for each resonance for each of the 200 data runs. Figure 1 shows the neutron transmission and ϵ as functions of neutron energy. There is a clear peak in ϵ at the position of the small transmission dip produced by the 63.5 eV p-wave resonance. We report the mean value $\bar{P}$ for each of the seventeen resonances. The error in each mean, σ , was determined from the fluctuations in the individual values of P for that resonance. The results are listed in Table 1. Five of the seventeen resonances show greater than two-

standard-deviation effects (only 0.7 such effects are expected from random fluctuations). The 63.5-eV resonance has a 6.6 standard-deviation effect. We are confident that systematic errors are very small or absent because results for s-wave resonances of comparable size to the p-wave resonances in ^{238}U show no parity violation; these are also listed in Table 1. Contaminant s-wave resonances were used for this test because s-wave resonances have zero PV asymmetries and transmissions comparable to p-wave resonances in ^{238}U .

Figure 1. Neutron transmission and PNC asymmetry ϵ plotted as functions of neutron energy.

TABLE 1 Helicity differences for neutron resonances

E_n (eV)	$\bar{P}_i \times 10^{-3}$	E_n (eV)	$\bar{P}_i \times 10^{-3}$
p-wave resonances in ^{238}U			
10.2	-1.7 ± 0.9	125.0	11 ± 9
11.3	7.2 ± 4.0	152.4	-1.5 ± 6.1
45.2	-13 ± 21	158.9	-3.8 ± 15
57.9	56 ± 28	173.1	11 ± 8
63.5	25 ± 4	242.7	-6.1 ± 6.2
83.7	19 ± 8	253.9	-1.6 ± 6.4
89.2	-2.4 ± 1.1	263.9	-0.1 ± 4.1
93.1	-0.3 ± 23	282.4	3.8 ± 13
98.0	-22 ± 13		
s-wave resonances in ^{235}U , ^{139}La , and ^{65}Cu			
8.9	0.5 ± 1.7	^{235}U	
11.7	-1.9 ± 3.6	^{235}U	
12.4	-2.3 ± 1.7	^{235}U	
72.2	-0.2 ± 0.5	^{139}La	
229.1	0.1 ± 3.5	^{65}Cu	

3. THE EXTRACTION OF THE ROOT MEAN-SQUARED MATRIX ELEMENT, M

The analysis treats individual matrix elements as random variables having a common Gaussian distribution with mean zero and variance M^2 . The quantity M^2 is the mean-squared PNC matrix element of the weak Hamiltonian connecting s-wave and p-wave states. The mean of the matrix element is zero because in the CN regime many shell-model amplitudes having random phases are needed to describe the wave function of a state. For the mixing of one s-wave state into one p-wave state the relationship between the longitudinal asymmetry P and the mixing matrix element V is simple. The expression for P is^{1,11,12}:

$$P = \frac{2V}{E_s - E_p} \sqrt{\Gamma_s^n / \Gamma_p^n}.$$

In general there may be large contributions from several s-wave states; in this case the individual matrix elements cannot be determined. We adopt the following notation: the

longitudinal asymmetry for the i^{th} p-wave resonance is P_i and is due to the sum of contributions from the s-wave resonances j , each with matrix element V_{ij} and with relative weight A_{ij} . That is,

$$P_i = \sum_j A_{ij} V_{ij}, \text{ with } A_{ij} = 2 \frac{\sqrt{\Gamma_{sj}^n / \Gamma_{pi}^n}}{(E_{sj} - E_{pi})}$$

The A_{ij} coefficients are known since they are functions of known resonance parameters Γ_p^n , Γ_s^n , E_p , E_s . (Values are taken from the ENDF/B-VI evaluation¹³.) Consider the new quantity $Q_i \equiv P_i / (\sum A_{ij}^2)^{1/2}$. The sum of independently Gaussian-distributed random variables with mean zero is a Gaussian random variable with mean zero.¹⁴ Therefore Q has the same distribution as each of the V_{ij} , a Gaussian distribution of mean zero and variance M^2 . This follows from our choice of normalization and the fact that the V_{ij} are independent. Therefore, M^2 can be determined directly from the set of experimental values of P_i *without determining the individual V_{ij} for each p-wave resonance*. In the present experiment detailed analysis could be performed for 17 p-wave resonances. The total angular momentum of p-wave resonances can be either 1/2 or 3/2, but only the spin-1/2 resonances can mix with spin-1/2 s-wave resonances and exhibit parity violation. Because deviations from $2J+1$ weighting should be small for ^{238}U , we expect twice as many spin-3/2 resonances as spin-1/2 resonances.¹⁵ A maximum likelihood analysis gives the most probable value of M and the most compact 68% confidence interval as $M = 0.58^{+0.50}_{-0.25}$ meV.

4. DISCUSSION

The spreading width for the PNC interaction is $\Gamma^{\text{PV}} = 2\pi M^2/D$, where D is the level spacing. Using the methods of statistical nuclear spectroscopy, French et al.^{16,17} have related the TNC spreading width, Γ^{TV} , to the ratio of the strengths of the T-nonconserving to T-conserving interactions, α_T , such that $\Gamma^{\text{TV}} \sim 2\pi(10^5 \text{ eV})(\alpha_T)^2$. Assuming this relationship applies to parity, we can also find the ratio of the strengths of the P-nonconserving to P-conserving interactions, α_p . Our result, $\alpha_p \sim 4 \times 10^{-7}$, is in qualitative agreement with the ratio of the weak- to strong-coupling constants, $G_{\text{Fermi}} Q^2 / G_{\text{Strong}} \sim 10^{-5} (\text{GeV}/c)^{-2} Q^2 \sim 2 \times 10^{-7}$, where Q is taken as a typical value of the Fermi momentum in the nucleus of $0.15 \text{ GeV}/c$. We find the qualitative agreement between α_p and the strength of the weak force very encouraging.

We plan to continue our measurements of PNC in several nuclei, both to continue our studies of weak spreading widths. It is to be expected that Γ^{PV} will not depend strongly on excitation energy or the particular isotope being studied. By measuring Γ^{PV} in many nuclei we can establish to what extent this expectation is fulfilled. Furthermore a survey of PNC asymmetries will serve to identify candidates for time-reversal studies. For our first TNC experiment we will install a low-temperature nuclear-aligned ^{165}Ho target. This target is suitable for tests of P-conserving TNC interactions using the correlation $(\vec{J} \cdot \vec{K})(\vec{\sigma}_n \cdot \vec{J} \times \vec{K})$, where $\vec{J}$ is the nuclear spin, $\vec{\sigma}_n$ is the neutron spin and $\vec{K}$ is the momentum vector of the neutron (Figure 2). With a recently designed spin-filter neutron-beam polarizer, a TNC experiment in ^{165}Ho will set a bound on α_T of $\sim 10^{-6}$ in a 10^7 second run. This is a factor of $\sim 10^3$ better than the current limit.

Figure 2. Experimental arrangement for the P-conserving TNC interaction test.

The correlation $(\vec{\sigma}_n \cdot \vec{J} \times \vec{K})$ is both P-nonconserving and T-nonconserving. Thus, this correlation can be caused by the same interaction that results in the CP violation in K decay. This experiment requires a polarized target and polarized beam, with the polarizations arranged so that the three vectors $\vec{\sigma}_n$, $\vec{J}$ and $\vec{K}$ are orthogonal. The systematic errors are more difficult to deal with in this experiment, compared to the P-conserving TNC interaction test. We are continuing to investigate the feasibility of this experiment as we gain experience with experimental techniques and systematic errors.

*This work was supported in part by the U.S. Department of Energy, Office of High Energy and Nuclear Physics, Contracts No. DE-AC05-76ER01067 and DE-FG05-88ER40441.

REFERENCES

- 1) V. P. Alfimenkov *et al.*, Nucl. Phys. **A398** (1983) 93.
- 2) V. P. Alfimenkov, Sov. Phys. Usp. **27** (1984) 797.
- 3) S. A. Biryukov *et al.*, Sov. J. Nucl. Phys. **45** (1987) 937.
- 4) Y. Masuda *et al.*, Nucl. Phys. **A504** (1989) 269.
- 5) C. D. Bowman, J. D. Bowman and V. W. Yuan, Phys. Rev. **C39** (1989) 1721.
- 6) Tests of Time Reversal Invariance in Neutron Physics, ed. N.R. Roberson, C.R. Gould and J.D. Bowman (World Scientific, 1987), J.D. Bowman in The Third Conference on the Intersections between Particle and Nuclear Physics, AIP Conference Proceedings Series **176** (1988) 1112 and C.D. Bowman *et al.*, Proceedings of the Symposium on Spin and Symmetries, ed. W.D. Ramsey and W.T.H. van Oers (TRIUMF Vancouver, 1989) p. 113.
- 7) J.D. Bowman *et al.*, to be published, Phys. Rev. Lett. Sept. (1990)
- 8) G. A. Keyworth *et al.*, Phys. Rev. **C8** (1973) 2352.
- 9) C. D. Bowman *et al.*, Hyperfine Interactions **43** (1988) 119.
- 10) J. D. Bowman *et al.*, submitted to Nuclear Instruments and Methods in Physics Research.
- 11) V. E. Bunakov and V. P. Gudkov, Nucl. Phys. **A401** (1983) 93.
- 12) J. R. Vanhoy *et al.*, Z. Phys. **A333** (1988) 229.
- 13) ENDF/B - VI preliminary data file for ^{238}U (National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY, July 1989), resonance evaluation by M. Moxon.
- 14) W. T. Eadie *et al.*, *Statistical Methods in Experimental Physics* (North-Holland, Amsterdam, 1971) p. 59.
- 15) T. von Egidy, H.H. Schmidt and A.N. Behkami, Nucl. Phys. **A481** (1988) 189.
- 16) J. B. French *et al.*, Ann. Phys. (NY) **181** (1988) 198.
- 17) J. B. French *et al.*, Ann. Phys. (NY) **181** (1988) 235.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

END

DATE FILMED

10 / 25 / 90