Parity Nonconservation for Neutron Resonances in ^{238}U

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(Received 28 March 1990)

Parity nonconservation was studied for seventeen states in ^{239}U by measuring the helicity dependence of the total 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 $\Gamma^{PV} = 1.0 \times 10^{-7}$ eV. Under plausible assumptions this gives a value of 4×10^{-7} for $|\alpha_P|$, the ratio of strengths of the P-odd and P-even effective nucleon-nucleon interactions.

PACS numbers: 25.40.Ny, 11.30.Er, 21.30.+y, 27.90.+b

The small ($\sim 10^{-7}$) parity-nonconserving (PNC) force in the nucleon-nucleon (NN) interaction causes the mixing of nuclear levels of the same spin but opposite parity. Here we report determinations of PNC-mixing-matrix elements between compound-nuclear (CN) states in ^{239}U produced as resonances in the scattering of polarized neutrons from ^{238}U. The PNC mixing leads to a helicity dependence of the total cross section (longitudinal asymmetry). Interest in such experiments was stimulated by the observation by the Dubna group[1,2] of large longitudinal asymmetries of order 10^{-2}. A several-percent effect was observed for the ^{139}La 0.734-eV p-wave neutron resonance; this result was confirmed at IAE in Moscow,[3] at KEK,[4] and at Los Alamos.[5] The origins of the large size of longitudinal asymmetries in the CN regime are several: (1) first-order interference between the weak and strong interactions, (2) small CN level spacings (0.1–100 eV), so that a small PNC force can produce a large mixing, and (3) large s-wave scattering amplitudes compared to p-wave scattering amplitudes; a small admixture of an s-wave state into a p-wave state produces a large longitudinal asymmetry.

Previous data on the helicity dependence of neutron-nucleus cross sections were limited in several respects: (i) parity violation was observed for at most one resonance per nucleus, (ii) all observed effects were for resonances below neutron energy $E_n \approx 10$ eV, and (iii) all observed parity violations were for targets with spin $I \neq 0$. The fact that all observed effects were at very low energies could imply that the parity violations occur only near threshold. (Bunakov *et al.*[6] consider this possibility.) For $I \neq 0$, there are two scattering amplitudes corresponding to neutron angular momentum $j = l \pm \frac{1}{2}$; only one of these amplitudes contributes to PNC. In the absence of information on the ratio of these two amplitudes, only limits are determined for the PNC matrix elements. In the present experiment all of these limitations have been removed, and for the first time we can determine the root-mean-squared PNC-mixing-matrix element M between p-wave and s-wave resonances. We also obtain the spreading width corresponding to M and the quantity introduced by French,[7] α_P, the ratio of strengths of the P-odd and P-even effective nucleon-nucleon interactions.

Our measurements take advantage of the intense pulsed epithermal neutron fluxes available at the Los Alamos Neutron Scattering Center (LANSCE). The 800-MeV proton beam from the Los Alamos Meson Physics Facility linac is compressed in a proton storage ring from a pulse width of ~ 800 μs to a width of 270 ns. The extracted protons strike a tungsten target and the resulting spallation neutrons (~ 25 per incident proton) are 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 $(40 \pm 2)\%$. The neutron polarization was reversed every 10 s 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 ^{238}U (36.0 g/cm^2), and are detected in an array of ^6Li glass scintillators, each 1.0 cm thick and 13.3 cm in diameter and viewed by high-current photomultiplier tubes.[9] The neutron energy is determined by time of flight over the 56-m distance from neutron source to the detectors. The instantaneous count rates were high (of order 10^{10}/s) and the neutron flux as a function of time was measured by periodically sampling the phototube current with a transient digitizer during each neutron burst.[10] The sampling frequency was such that the signal was sampled several times over the time width of the narrowest resonance. A data run consisted of a thirty-minute sequence of programmed spin reversals which canceled linear and quadratic time-dependent drifts. A total of about 200 such runs was accumulated.

Seventeen p-wave resonances up to $E_n \approx 300$ eV were analyzed. The transmitted neutron yield in the neighborhood of these p-wave resonances was fitted by the form

$$Y_{\pm} = N_{\pm} C(E_n) \exp[-n\sigma_p^{\max}\phi(1 \pm f_n P)],$$

where $N_{\pm}$ is the normalization for + and − helicities, $C(E_n)$ describes the energy dependence of the neutron flux, the detector efficiency, and the absorption due to the nonresonant cross section, n is the target thickness, $\sigma_p^{\max}$ is the maximum value of the p-wave resonance cross section, ϕ is the Doppler-broadened p-wave line shape, f_n is the neutron polarization, and $P = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$ is the parity-violating longitudinal asymmetry of the resonance cross section. Sample results for the 63.5-eV resonance are shown in Fig. 1. A value of the longitudinal asymmetry P was determined for each resonance for each of the 200 data runs. 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 I. Five of the seventeen resonances show greater than 2-standard-deviation effects (only 0.7 such effects are expected from random fluctuations). The 63.5-eV resonance has a 6.6σ 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 listed in Table I. (We used contaminant resonances for this test in order that the s- and p-wave resonances have comparable transmissions.)

We now consider how to extract the root-mean-

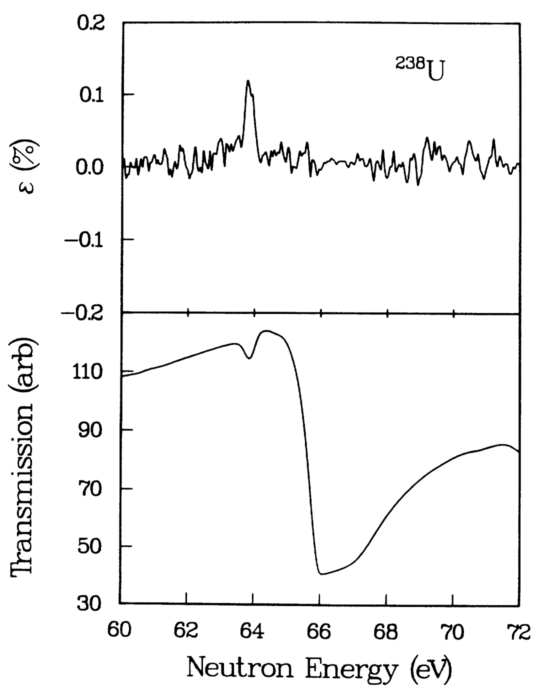

FIG. 1. In the lower part of the figure the neutron transmission is shown in the vicinity of the 63.5-eV p-wave resonance. In the upper half the experimental asymmetry $\epsilon = (N^+ - N^-)/(N^+ + N^-)$ is shown, where N^+ and N^- are the counts for the two helicity states.

TABLE I. Helicity differences for neutron resonances.

E_n (eV)	$10^3\bar{P}_i$	Q_i (meV)
	p-wave resonances in ^{238}U [a]	
10.2	-1.7 ± 0.9	-0.06 ± 0.03
11.3	7.2 ± 4.0	0.13 ± 0.07
45.2	-13 ± 21	-0.4 ± 0.6
57.9	56 ± 28	0.8 ± 0.4
63.5	25 ± 4	0.7 ± 0.1
83.7	19 ± 8	1.4 ± 0.6
89.2	-2.4 ± 1.1	-0.5 ± 0.2
93.1	-0.3 ± 23	-0.01 ± 1.0
98.0	-22 ± 13	-0.4 ± 0.2
125.0	11 ± 9	1.1 ± 0.9
152.4	-1.5 ± 6.1	-0.4 ± 1.4
158.9	-3.8 ± 15	-0.4 ± 1.7
173.1	11 ± 8	1.4 ± 1.0
242.7	-6.1 ± 6.2	-1.3 ± 1.3
253.9	-1.6 ± 6.4	-0.5 ± 2.0
263.9	-0.1 ± 4.1	-0.05 ± 1.7
282.4	3.8 ± 13	0.8 ± 2.7
	s-wave resonances in ^{235}U, ^{139}La, and ^{65}Cu [b]	
8.9 ^{235}U	0.5 ± 1.7	...
11.7 ^{235}U	-1.9 ± 3.6	...
12.4 ^{235}U	-2.3 ± 1.7	...
72.2 ^{139}La	-0.2 ± 0.5	...
229.1 ^{65}Cu	$+0.1 \pm 3.5$	...

[a]The spins of the resonances are not well determined; approximately $\frac{2}{3}$ of these should have $J = \frac{3}{2}$ and show no parity violation, while $\frac{1}{3}$ should have $J = \frac{1}{2}$ and may show parity violation.
[b]These "contaminant" s-wave resonances are comparable in size to the p-wave resonances in ^{238}U, and should display no parity violation.

squared PNC-mixing-matrix element M from the experimental values of $\bar{P}$. The analysis treats individual matrix elements as independent random variables having a common Gaussian distribution with mean zero and variance M^2. The mean of the matrix element is zero and matrix elements between different levels are independent because in the CN regime many thousands of 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]

$$P=[2V/(E_s-E_p)](\Gamma_s^n/\Gamma_p^n)^{1/2}.$$

The neutron widths Γ_s^n and Γ_p^n are evaluated at the p-wave resonance energy. 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 ith 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 the relative weight A_{ij}. That is,

$$P_i=\sum_j A_{ij}V_{ij}, \quad \text{with } A_{ij}=2\frac{(\Gamma_{sj}^n/\Gamma_{pi}^n)^{1/2}}{E_{sj}-E_{pi}}.$$

The A_{ij} coefficients are known since they are functions of known resonance parameters Γ_p^n, Γ_s^n, E_p, and E_s. Values are taken from the ENDF/B-VI evaluation.[13] Subthreshold resonances are included. Our sample of p-wave resonances is biased in the sense that we observe only large p-wave resonances. It is reasonable to assume that the Γ_p^n are independent of each V_{ij}, just as the V_{ij} are independent. Then the selection of stronger p-wave states does not affect the value of M. In practice, only the closest few s-wave resonances have large A_{ij}. Consider the new quantity $Q_i\equiv P_i/(\sum A_{ij}^2)^{1/2}$. The sum of independently Gaussianly 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. (The latter 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_i. In the present experiment detailed analysis could be performed for seventeen p-wave resonances. The total angular momentum of p-wave resonances can be either $\frac{1}{2}$ or $\frac{3}{2}$, but only the spin-$\frac{1}{2}$ resonances can mix with spin-$\frac{1}{2}$ s-wave resonances and exhibit parity violation. The angular momenta of p-wave resonances in ^{238}U are not definitively established. We expect twice as many $p_{3/2}$ levels as $p_{1/2}$ levels. Deviations from this ratio are expected to be small for ^{238}U (see von Egidy, Schmidt, and Behkami[15]). The likelihood function for M, $L(M)$, is then

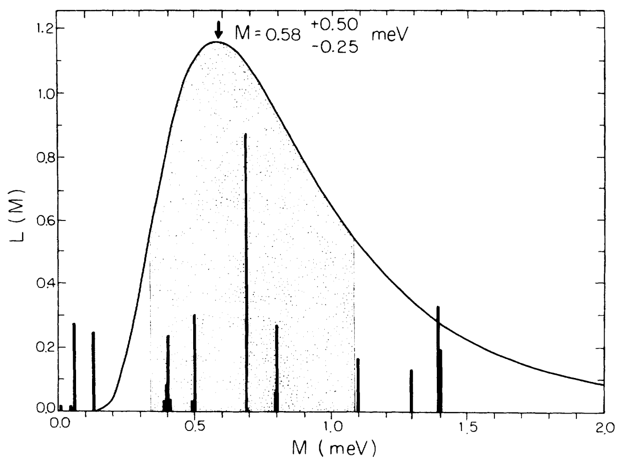

FIG. 2. Likelihood function of the root-mean-squared mixing-matrix element M. The location of the vertical bars is the absolute value of the Q's (see text) and the heights are proportional to the statistical significance. The shaded region is the 68%-confidence interval.

$$L(M)=\prod_{i=1}^{17}\left[\frac{1}{3[2\pi(\sigma_{Q_i}^2+M^2)]^{1/2}}\exp\left(-\frac{Q_i^2}{2(\sigma_{Q_i}^2+M^2)}\right)+\frac{2}{3(2\pi\sigma_{Q_i}^2)^{1/2}}\exp\left(-\frac{Q_i^2}{2\sigma_{Q_i}^2}\right)\right].$$

A plot of $L(M)$ vs M is shown in Fig. 2. The most probable value of M and the most compact 68%-confidence interval are $M=0.58^{+0.50}_{-0.25}$ meV. We find that the value of M is insensitive to the ratio of $\frac{1}{2}$ to $\frac{3}{2}$ level densities. Note that the null values of Q are important in establishing the upper limit on M and the nonzero values establish the lower limit.

The issue of symmetry breaking in chaotic nuclear systems is of considerable current interest[16-18] and has been studied by French *et al.* by the techniques of random-matrix theory.[7,19] It is convenient to define a parity-violating spreading width $\Gamma^{PV}=2\pi M^2/D$, where D is a level spacing. Spreading widths are expected to show much less sensitivity than matrix elements to the excitation energy and nuclear mass. Taking D to be the s-wave level spacing 21.0 eV gives $\Gamma^{PV}=1.0\times10^{-7}$ eV. Near the ground states of light nuclei, D is a few MeV, and typical[20] measured mixing-matrix elements M are in the range 0.03–3 eV, which gives a crude estimate for the spreading width in light nuclei of $\Gamma^{PV}\sim10^{-7}$ eV.

Using the methods of statistical nuclear spectroscopy, French has established for time-reversal invariance the connection between symmetry breaking in the CN system and symmetry breaking for the effective NN interaction. Assuming this relation to be general, the strength

α_P of the P-odd effective NN interaction relative to the P-even part is given by $\alpha_P^2 = \Gamma^{PV}/(2\pi \times 10^5 \text{ eV})$. The present results lead to a value of $|\alpha_P| \sim 4 \times 10^{-7}$. This value can be compared with an order-of-magnitude estimate $\alpha_P \sim G_F m_\pi^2 / G_s \sim 10^{-7}$, where G_F is the Fermi constant and $G_s = 1$ is the strong-coupling constant. The fact that the values for M and α_P are in qualitative agreement with expectations is very encouraging. The proposed use of enhancements in the study of time-reversal-symmetry violation in CN systems thus appears to be on firm experimental ground.

In summary, we have obtained for the first time values of CN parity-violating matrix elements free of detailed assumptions about nuclear spectroscopy. Results for seventeen resonances provide the first determination of the variance of the parity-violation matrix element. The value of $M = 0.58^{+0.50}_{-0.25}$ meV corresponds to a spreading width of $\Gamma^{PV} = 1.0 \times 10^{-7}$ eV. It would be of interest to determine the variance M^2 for other nuclei, in particular, to study the possible dependence of Γ^{PV} on mass number and excitation energy. An estimate for the symmetry breaking in the effective NN interaction, $|\alpha_P| \sim 4 \times 10^{-7}$, is obtained from the measured variance M^2.

The authors express their appreciation for valuable discussions with V. E. Bunakov, E. D. Davis, G. T. Garvey, and H. A. Weidenmüller. We thank R. Mortensen for his technical assistance and dedication to this experiment. We also appreciate valuable contributions from C. Espinoza and the technical staff at LAMPF and LANSCE. This work was supported in part by the U.S. Department of Energy, Office of High Energy and Nuclear Physics, under Contracts No. DE-AC05-76ER01067 and No. DE-FG05-88ER40441.

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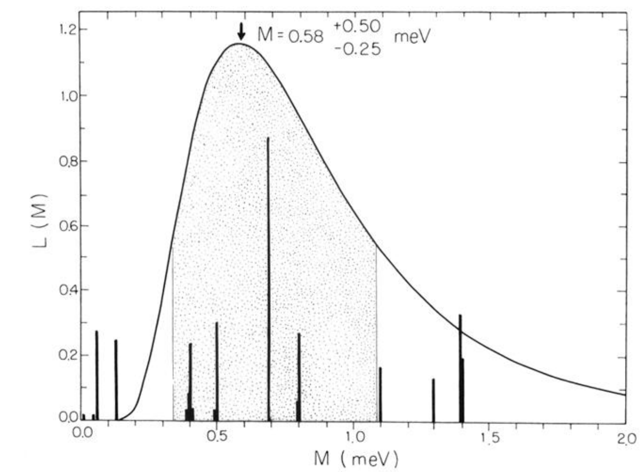

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