Sign Correlations and Parity Nonconservation for Neutron Resonances in ^{232}Th

C. M. Frankle,[(1)] J. D. Bowman,[(2)] J. E. Bush,[(1)] P. P. J. Delheij,[(3)] C. R. Gould,[(1)] D. G. Haase,[(1)] J. N. Knudson,[(2)] G. E. Mitchell,[(1)] S. Penttilä,[(2)] H. Postma,[(4)] N. R. Roberson,[(5)] S. J. Seestrom,[(2)] J. J. Szymanski,[(2),(a)] S. H. Yoo,[(2)] V. W. Yuan,[(2)] and X. Zhu[(5)]

(The TRIPLE Collaboration)

[(1)]*North Carolina State University, Raleigh, North Carolina 27695 and*
Triangle Universities Nuclear Laboratory, Durham, North Carolina 27706
[(2)]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
[(3)]*TRIUMF, Vancouver, British Columbia, Canada V6T 2A3*
[(4)]*University of Technology, Delft, The Netherlands*
[(5)]*Duke University, Durham, North Carolina 27706 and*
Triangle Universities Nuclear Laboratory, Durham, North Carolina 27706

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Parity-nonconserving longitudinal analyzing powers were measured for 23 p-wave neutron resonances in ^{232}Th. Seven resonances show effects of greater than 2σ statistical significance (95% confidence)—the largest sample yet measured in a single nucleus. All seven analyzing powers have positive sign. Strong sign correlations are not a feature of the conventional statistical model of parity mixing between compound nuclear states. The results suggest that the mechanism of parity violation in resonance reactions is more complicated than previously assumed.

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Polarized-neutron transmission experiments show remarkable sensitivity to the presence of small symmetry-violating forces in nuclear interactions. Parity-nonconserving (PNC) analyzing powers of order of a percent or more have been observed [1-3] for p-wave resonances in nuclei ranging from ^{81}Br to ^{238}U. The resonances correspond to highly excited compound nuclear (CN) states—so complicated they can only be described statistically. The number of single-particle components in the wave functions is of order $N \sim (1\text{ MeV})/\Delta E \sim 10^5$-$10^6$, where ΔE is the CN energy level spacing. The large enhancement of the PNC analyzing powers over the typical 10^{-7} size of weak-interaction effects is conventionally explained [4,5] by assuming that the mixing occurs between wave functions of closely spaced CN levels of the same spin J but opposite parity $\pm\pi$. The PNC matrix elements V_{ij} scale as $1/\sqrt{N}$ and the spacings scale as $1/N$, resulting in an enhancement of $\sqrt{N}$ in the wave-function admixture $V_{ij}/\Delta E$. The PNC analyzing power is further enhanced by the favorable ratio of s-wave to p-wave decay amplitudes, γ_{sj}^n and γ_{pi}^n (see below).

For some time it was not considered possible to interpret the analyzing powers in anything but a qualitative fashion due to the complexity of the wave functions involved. But recently, statistical methods [3,6-8] have been developed that relate the root-mean-square PNC matrix element M to symmetry violation in the residual shell-model effective nucleon-nucleon interaction. Thus the complexity of the CN states, which leads to the large magnification of symmetry violation, also leads to a statistical interpretation within which the observed effects can be quantified.

Previous results [1-3] were generally consistent with the conventional CN statistical model. But because only five large effects had been observed, a number of questions about the mechanism of parity mixing remained. The model predicts that all pairs of $J^{\pm\pi}$ resonances should interfere and, at some level, show nonzero PNC analyzing powers. In addition, matrix elements and neutron decay amplitudes are expected to be essentially uncorrelated because of the large number of components in the CN wave functions. Thus V_{ij}, γ_{sj}^n, and γ_{pi}^n are taken to be statistically independent Gaussian random variables [8]. Parity-violating asymmetries are expected to be random in sign.

In the present work we have studied parity-violating asymmetries for 23 p-wave resonances in ^{232}Th and for the first time verify that many p-wave resonances in a single nucleus show large nonzero PNC effects. However, the asymmetries do not have random signs, in contradiction to the conventional CN statistical model.

The measurements were carried out on the 56-m flight path at the Los Alamos Neutron Scattering Center (LANSCE). The experimental techniques were similar to those described in our earlier work [3], except that in the present work the thorium sample was cooled to liquid-nitrogen temperature in order to reduce Doppler broadening of the resonances. The neutron beam was polarized by selective attenuation in a proton spin filter and the neutron spins were reversed frequently by a magnetic spin rotator [9]. The neutrons were detected in a ^{6}Li-glass scintillator array, operated in current mode [10] due to the high instantaneous count rates. The sample consisted of 3.1-cm-thick thorium metal (0.093 atom/b) with trace impurities of gadolinium and tungsten.

A run consisted of 20 eight-step spin-reversal sequences, + − − + − + + −, with neutron time-of-flight data stored for 10 s at a time in each ± polarization state. We accumulated a total of 355 runs, interspersed with measurements of the asymmetry of the 0.73-eV resonance in ^{139}La. We have recently measured the analyzing power of this resonance to high absolute precision [11] and use it to calibrate the polarization of the neutron beam. Importantly, this procedure ensures that the signs of the thorium asymmetries are determined unambiguously relative to ^{139}La. Typical beam polarizations were ~25% lower than in our previous work due to radiation damage in the lanthanum magnesium nitrate crystals of the spin filter.

Resonances up to $E_n \sim 400$ eV were studied. The most recent ^{232}Th evaluation [12] identifies 39 p-wave resonances in this energy range. About two-thirds of these were strong enough to be analyzed reliably. Figure 1 shows results for the transmission T and experimental asymmetry ϵ of the 128-eV resonance. We fitted [3] the line shape of each resonance to extract a parity-violating longitudinal analyzing power $P_i=(\sigma_i^+-\sigma_i^-)/(\sigma_i^++\sigma_i^-)$ for each run. Here, $\sigma_i^\pm$ is the resonance cross section of the ith p wave for a neutron of helicity ±. The results are listed in Table I and shown in Fig. 2. The uncertainties were obtained from the distribution of the 355 individual values of P_i. The table also lists the analyzing powers for impurity s-wave resonances with transmission dips comparable to the p-wave resonances in ^{232}Th. As expected these show no parity violation, suggesting that systematic errors in the present P_i data set are small or absent.

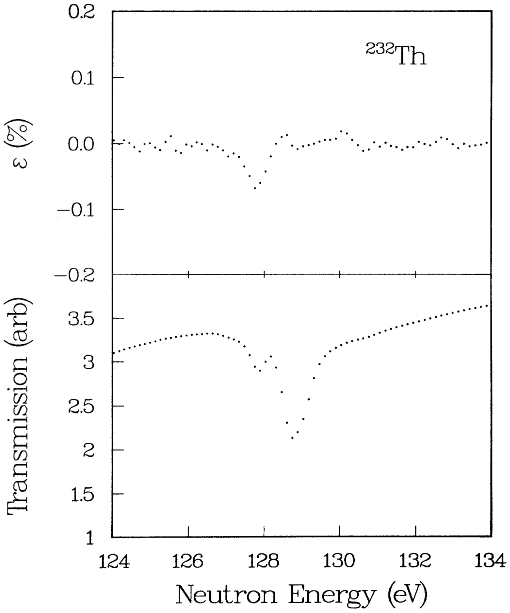

FIG. 1. Asymmetry $\epsilon=(N^+-N^-)/(N^++N^-)$ and transmission yield $T=N^++N^-$ for the 128-eV resonance in ^{232}Th. Here N^+ (N^-) is the count rate when the beam is polarized parallel (antiparallel) to the beam direction.

TABLE I. Longitudinal analyzing powers for neutron resonances in ^{232}Th.

E_n (eV)	P_i (%)	Q_i (meV)
	p-wave resonances	
8.3	1.48 ± 0.25	0.61 ± 0.10
13.1	0.74 ± 0.62	0.20 ± 0.17
37.0	2.5 ± 1.0	1.29 ± 0.52
38.2	10.9 ± 2.3	4.5 ± 0.9
41.0	−2.2 ± 2.1	−0.91 ± 0.87
49.9	−1.1 ± 3.0	−0.30 ± 0.82
64.5	9.8 ± 2.1	0.90 ± 0.19
90.2	−1.05 ± 1.00	−0.97 ± 0.93
98.1	−0.01 ± 1.38	−0.01 ± 1.38
103.7	−0.43 ± 1.04	−0.30 ± 0.73
128.2	1.31 ± 0.18	0.86 ± 0.12
145.9	−0.03 ± 0.22	−0.10 ± 0.73
148.1	−4.9 ± 2.8	−5.4 ± 3.0
167.2	3.5 ± 1.2	0.97 ± 0.33
179.0	−1.47 ± 1.28	−1.25 ± 1.09
196.2	1.10 ± 0.46	0.98 ± 0.41
202.7	2.2 ± 1.4	1.7 ± 1.1
211.0	1.76 ± 1.85	1.58 ± 1.66
242.3	−0.1 ± 1.2	−0.1 ± 1.2
299.8	−1.6 ± 1.7	−1.5 ± 1.6
302.7	−1.8 ± 1.0	−1.7 ± 1.0
380.7	1.1 ± 1.8	2.9 ± 4.7
391.8	−0.7 ± 1.6	−2.4 ± 5.5
	s-wave resonances	
16.7(^{158}Gd)	−0.08 ± 1.27	
18.8(^{187}W)	−0.08 ± 0.69	
33.2(^{157}Gd)	−1.39 ± 2.52	

Two-thirds of the ^{232}Th p-wave resonances are expected to have $J=\frac{3}{2}$, and cannot exhibit s-p parity mixing. The $p_{3/2}$ resonances will be somewhat weaker than the $p_{1/2}$ resonances on average, but if we assume one-third of our data set is $p_{1/2}$, then we expect to see about eight PNC effects. In fact, we see seven results at $>2\sigma$ statistical significance (95% confidence). These correspond to the resonances at 8, 37, 38, 64, 128, 167, and 196 eV. Two of the effects (38 and 64 eV) are of order 10%, as large as any effect seen previously. The data thus show convincingly that parity violation is a general feature of all $p_{1/2}$ resonances in ^{232}Th.

In the conventional statistical model, the longitudinal analyzing power P_i of the p-wave resonance at energy E_{pi} arises from admixtures of s-wave resonances at energies E_{sj}:

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

The partial neutron width amplitudes of the resonances γ^n_{pi} and γ^n_{sj} and the PNC mixing matrix elements V_{ij} are expected to be independent Gaussianly distributed random variables with mean zero. In addition, the sign of

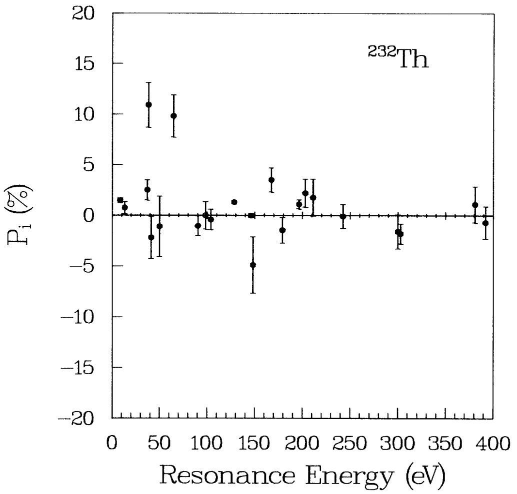

FIG. 2. Longitudinal analyzing powers for p-wave resonances in ^{232}Th.

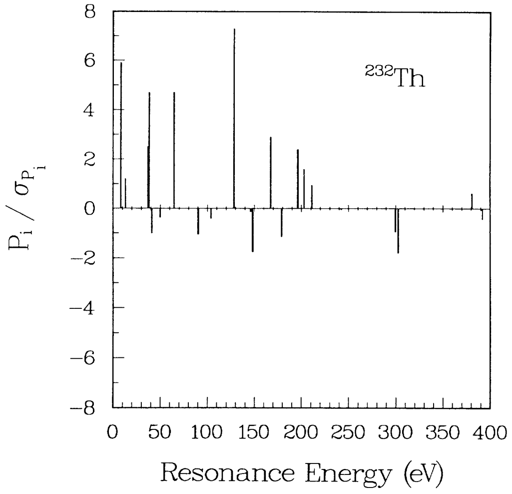

FIG. 3. Statistical significance P_i/σ_{P_i} of longitudinal analyzing powers for the p-wave resonances in ^{232}Th. Note that all of the parity violations with statistical significance greater than 2σ have positive signs.

the energy difference $E_{sj}-E_{pi}$ is expected to vary randomly since close-lying s-wave resonances are as likely to be above in energy as below compared to the p-wave resonance.

Following Ref. [3], we define a new variable $Q_i \equiv P_i/(\sum A_{ij}^2)^{1/2}$ which has the same distribution as V_{ij}, namely, mean zero and variance M^2. The values of Q_i are listed in Table I and a likelihood analysis yields a value of $M=1.39^{+0.55}_{-0.38}$ meV.

However, it is clear that the present data are not consistent with the assumption of independent variables randomly distributed in sign. Figure 3 shows the statistical significance P_i/σ_{P_i} and the signs of the analyzing powers. All seven $>2\sigma$ results are positive in sign. The chance of obtaining the same sign for seven out of seven randomly distributed quantities is 1.6% (given by 2 times the binomial distribution factor $P(x,n,p)=[n!/x!(n-x)!]p^x(1-p)^{n-x}$). These values almost certainly correspond to $p_{1/2}$ resonances. We can therefore calculate a weighted mean $Q_{\rm av}$ for these seven Q_i's from the fact that they are drawn from Gaussians of width $M^2+\sigma_{Q_i}^2$. We find $Q_{\rm av}=1.31\pm0.55$, 2.4σ different from zero.

Six of eight $>2\sigma$ analyzing powers known for other nuclei are also positive in sign. These are results from Alfimenkov *et al.* [1] for ^{81}Br (0.88 eV), ^{111}Cd (4.53 eV), ^{117}Sn (1.33 eV), and ^{139}La (0.73 eV), and from our previous work [3] for ^{238}U (57.9, 63.5, 83.7, and 89.2 eV). The sign of the ^{139}La (0.73 eV) effect has been confirmed by Masuda *et al.* [2] and by us [11]. We have also confirmed the sign of the ^{81}Br and ^{117}Sn effects. The only known negative values are a 7σ effect for the 4.53-eV resonance in ^{111}Cd and a $\sim 2\sigma$ effect for the 89.2-eV resonance in ^{238}U. The chance of obtaining the same sign for thirteen of fifteen randomly distributed quantities is 0.6%. We conclude therefore that the present data for ^{232}Th and the data in the literature for other nuclei suggest an unexpected correlation in the signs of PNC analyzing powers for CN resonances.

Within the conventional statistical model, this can occur only if there is a correlation between three (nominally) randomly distributed quantities: The PNC matrix elements V_{ij}, the neutron decay amplitudes γ_{pi}^n and γ_{sj}^n, and the energy denominators $E_{sj}-E_{pi}$. Assuming a nonzero mean for the V_{ij} will not lead to sign correlations because of the random signs of the other factors contributing to P_i.

Amplitude and sign correlations are expected in CN processes whenever a common doorway or special state mixes with background states [13]. The best known example is the asymmetric enhancement of the fine structure near an isobaric-analog state [14]. The Coulomb mixing matrix element is correlated with the proton decay amplitudes of the background state and analog state, and an asymmetry arises because the interference term changes sign depending on whether the background state is above or below the energy of the analog state. While superficially similar to the present experiment, the model is not directly applicable because no special state can be identified; the s-wave levels interfering with the p-wave level are as likely to be above as below in energy, and the sign of the PNC effect again becomes random.

Sign correlations also arise in valence models, or, equivalently, if direct reactions contribute [15]. In the valence model of parity violation, PNC mixing occurs between the single-particle components of the entrance-channel neutron wave functions rather than between the CN wave functions themselves [16,17]. The matrix element is then correlated with the neutron decay amplitudes, just as in the analog-state case. Zaretskii and Sirotkin [16] and Noguera and Desplanques [17] both find that the presence of close-lying resonances leads to enhancement of PNC observables. However, they disagree as to whether the mechanism can quantitatively explain the data of Alfimenkov *et al.* [1]. A recent measurement by Abov *et al.* [18] in $^{207}\mathrm{Pb}(n,\gamma)$ failed to detect any PNC effect in a situation where the valence mechanism was clearly expected to give a nonzero asymmetry. The valence model also cannot explain the correlation with the energy denominator unless one invokes a dominant contribution due to many far away s-wave resonances above the energy of the p-wave resonance. We conclude therefore that none of the models of parity violation that have been discussed in the literature is quantitatively able to predict the signs and magnitudes of the PNC effects observed for $^{232}\mathrm{Th}$.

To summarize, we have shown that parity violation in compound nuclear resonances is a universal phenomenon. Essentially all the $p_{1/2}$ resonances we can observe in $^{232}\mathrm{Th}$ show statistically significant PNC analyzing powers. Two of the effects are as large as any previously observed. Remarkably, the signs of the effects are all positive. This result is inconsistent with the conventional model of CN mixing of independent random variables, indicating a more complicated reaction mechanism, or unexpected correlations between CN observables. More experimental data and further study of the theory of PNC effects in heavy nuclei appear necessary.

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[a] Present address: Indiana University, Bloomington, IN 47405.

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