Experimental limit on parity violation in nonresonant neutron-nucleus scattering

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The parity-nonconserving longitudinal asymmetry P has been measured in nonresonant regions in ^{232}Th for neutron energies in the range 6–86 eV. The measured value of $P_{\rm nonres}=(9.8\pm21.7)\times10^{-6}$ is consistent with statistical descriptions of parity violation.

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Recently, several groups have observed parity violation for compound-nuclear resonances by measuring the helicity dependence of the neutron total cross section [1–6]. The parity-nonconserving (PNC) longitudinal asymmetry, P, is the fractional difference in the resonance-cross section for positive and negative helicity neutrons: $P=(\sigma_+-\sigma_-)/(\sigma_++\sigma_-)$. Parity violation appears to be a general feature of p-wave resonances. Asymmetries as large as 10% have been measured, and several resonances with nonzero asymmetries have been observed in individual nuclei [5,6]. The large size of these asymmetries has been explained in terms of two enhancement mechanisms: the level density in the compound nucleus is so large that a small parity-violating interaction produces a large parity admixture in the wave function, and the neutron decay amplitudes of the admixed s-wave states are very large compared to those of the p-wave resonances under study.

In contrast to the work on parity violation in light nuclei (see Adelberger and Haxton [7] for a comprehensive review), a new approach to symmetry violation treats the compound nuclear system as chaotic and assumes that the symmetry-breaking matrix elements are random variables [8–11]. With this statistical ansatz one obtains root-mean-square values for the PNC matrix elements in ^{238}U and ^{232}Th, which, under plausible assumptions, lead to reasonable values for the ratio of strengths of the P-odd and P-even effective nucleon-nucleon interaction. More experimental data are expected to lead to a more precise determination of the PNC matrix element, while improved theoretical treatment should provide a better understanding of the connection between the PNC matrix element and the nucleon-nucleon effective interaction.

However, there was an unexpected experimental observation: all seven asymmetries measured for p-wave resonances in ^{232}Th with statistical significance $>2.4\sigma$ had the same sign. This sign correlation is inconsistent with a purely statistical description. The data were then fitted with two terms: a constant term and a fluctuating term. A number of authors have proposed explanations of this experimental observation [12–18]. All of the proposed explanations seem flawed, since taken at face value these explanations require implausibly large, weak matrix elements between nuclear states. Some of these theoretical papers suggest that there might be a nonzero asymmetry for the nonresonant scattering. In this article we report an experimental upper limit for the PNC longitudinal asymmetry measured for energies between resonances in ^{232}Th.

We analyzed the off-resonance data in ^{232}Th following closely the spirit of the analysis of the resonance data [5,6]. In these parity-violation experiments [19] the 800-MeV beam from the Los Alamos Meson Physics Facility (LAMPF) is injected into a proton storage ring, the extracted proton beam strikes a tungsten target, and neutrons are produced by the spallation process. At the Los Alamos Neutron Scattering Center (LANSCE) the neutrons are moderated and collimated to produce a beam. The neutron beam is polarized by selective attenuation through a cell of longitudinally polarized protons. Adiabatic neutron-spin reversal was accomplished by a system

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of magnetic fields [20]. The polarized neutrons then passed through a 3.1-cm-thick target and were detected at 56 m by ^{6}Li-loaded glass detectors. The neutron spin-reversal sequence was chosen to produce a particular eight-state spin sequence which minimized effects of stray fields and time drifts. Twenty of these eight-step sequences were combined into a "run" and these runs were treated as the basic unit of data. For ^{232}Th the data consisted of 355 runs. Each run was analyzed and the results from all of the runs were then combined.

We also analyzed the off-resonance data run by run. Since the time of flight is proportional to $E_n^{-1/2}$, the number of channels included in the analysis of on-resonance parity violation varied for each resonance. As natural units we chose channel-bin sizes determined from the widths of the resonances in a local region. We took the full width at 0.1 maximum as the local channel-bin size. Another issue was which regions to define as off-resonance, and therefore to include in the present analysis. We excluded regions around all resonances (whether p- or s-wave resonances in ^{232}Th or contaminant resonances); a region of five natural channel-bin units (as defined above) was excluded above and below each resonance.

The transmission spectrum for ^{232}Th is shown in Fig. 1, with the regions included in the analysis indicated. The prescription described above yielded 61 subregions suitable for analysis; these are listed in Table I. Although the energy range for these intervals changes by a factor of 7—$\Delta E = 0.09$ eV (0.62 eV) at $E_n = 6$ eV (86 eV)—the statistical uncertainties in each region are comparable. For each of the 61 subregions i, and for each of the 355

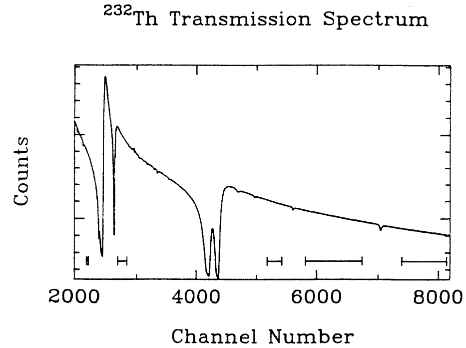

FIG. 1. ^{232}Th transmission spectrum. The PNC longitudinal asymmetry was studied for nonresonant scattering in the regions indicated. The criteria for selecting these regions are described in the text.

TABLE I. Longitudinal asymmetries P for nonresonant regions in ^{232}Th.

Region	Channel range		Energy range (eV)		ΔE (eV)	$10^4 P$	$10^4 \Delta P$
1	2195	2203	85.25	85.87	0.62	0.45	1.61
2	2204	2212	84.56	85.17	0.61	1.64	1.59
3	2213	2221	83.88	84.48	0.60	−1.06	1.44
4	2222	2230	83.20	83.80	0.60	−2.69	1.73
5	2694	2702	56.69	57.03	0.34	2.90	2.58
6	2703	2711	56.32	56.65	0.33	0.53	2.37
7	2712	2720	55.95	56.28	0.33	−0.14	2.49
8	2721	2729	55.58	55.91	0.33	3.35	2.24
9	2730	2738	55.21	55.54	0.33	0.16	2.22
10	2739	2747	54.85	55.17	0.32	2.04	2.30
11	2748	2756	54.50	54.81	0.31	−5.44	2.29
12	2757	2765	54.14	54.45	0.31	−0.93	2.21
13	2766	2774	53.79	54.10	0.31	−3.77	2.45
14	2775	2783	53.44	53.75	0.31	−3.78	2.25
15	2784	2792	53.10	53.41	0.31	−1.22	2.52
16	2793	2801	52.76	53.06	0.30	−0.07	2.32
17	2802	2810	52.42	52.72	0.30	−1.21	2.25
18	2811	2819	52.09	52.39	0.30	3.43	2.43
19	2820	2828	51.76	52.05	0.29	−2.56	2.25
20	2829	2837	51.43	51.72	0.29	0.47	2.42
21	2838	2846	51.11	51.40	0.29	−0.77	2.23
22	5175	5210	15.26	15.47	0.21	1.79	1.54
23	5211	5246	15.05	15.26	0.21	−4.88	1.55
24	5247	5282	14.85	15.05	0.20	0.01	1.68
25	5283	5318	14.65	14.84	0.19	−3.35	1.65
26	5319	5354	14.45	14.64	0.19	1.18	1.58
27	5355	5390	14.26	14.45	0.19	0.95	1.65
28	5391	5427	14.07	14.26	0.19	−0.11	1.80
29	5819	5864	12.05	12.24	0.19	0.14	1.47
30	5865	5910	11.86	12.04	0.18	1.55	1.57
31	5911	5956	11.68	11.86	0.18	−0.38	1.55

TABLE I. (Continued).

Region	Channel range		Energy range (eV)		ΔE (eV)	10^4P	$10^4\Delta P$
32	5957	6002	11.50	11.68	0.18	1.16	1.47
33	6003	6048	11.33	11.50	0.17	−1.70	1.51
34	6049	6094	11.16	11.32	0.16	1.71	1.51
35	6095	6140	10.99	11.15	0.16	2.14	1.60
36	6141	6186	10.83	10.99	0.16	0.87	1.42
37	6187	6232	10.67	10.82	0.15	1.48	1.51
38	6233	6278	10.51	10.66	0.15	3.07	1.46
39	6279	6324	10.36	10.51	0.15	−1.13	1.43
40	6325	6370	10.21	10.36	0.15	1.38	1.55
41	6371	6416	10.07	10.21	0.14	2.25	1.53
42	6417	6462	9.92	10.06	0.14	0.49	1.64
43	6463	6508	9.78	9.92	0.14	0.28	1.49
44	6509	6554	9.65	9.78	0.13	2.21	1.62
45	6555	6600	9.51	9.64	0.13	0.88	1.58
46	6601	6646	9.38	9.51	0.13	0.32	1.58
47	6647	6992	9.25	9.38	0.13	−1.44	1.59
48	6693	6738	9.13	9.25	0.12	0.94	1.64
49	7398	7454	7.46	7.57	0.11	1.82	1.52
50	7455	7511	7.35	7.46	0.11	1.09	1.61
51	7512	7568	7.23	7.34	0.11	−2.11	1.57
52	7569	7625	7.13	7.23	0.10	−0.21	1.47
53	7626	7682	7.02	7.12	0.10	0.47	1.58
54	7683	7739	6.92	7.02	0.10	−1.77	1.52
55	7740	7796	6.82	6.92	0.10	0.72	1.67
56	7797	7853	6.72	6.82	0.10	0.24	1.53
57	7854	7910	6.62	6.72	0.10	−1.55	1.63
58	7911	7967	6.53	6.62	0.09	1.70	1.57
59	7968	8024	6.44	6.53	0.09	0.89	1.54
60	8025	8081	6.35	6.44	0.09	−1.35	1.47
61	8082	8138	6.26	6.35	0.09	−0.22	1.59

data runs j, the transmission asymmetry $\varepsilon_{ij}=(N^+-N^-)/(N^++N^-)$ was determined. For each interval i, an average value for ε_i was determined and the statistical error was obtained from the distribution of the 355 ε_{ij} values. (See Ref. [5] for a detailed discussion of the error determination from the asymmetry distribution.) The transmission asymmetry $\varepsilon=-\tanh(n\sigma t f_n P)$, where n is the number density of the target, t the thickness of the target, σ the cross section, f_n the neutron polarization, and P the PNC longitudinal asymmetry. If the argument is small, then $\varepsilon\sim -n\sigma t f_n P$. This simple expression is adequate for the present purposes, although it is not completely valid for the resonance analysis [5,6]. The quantities n, t, and σ are known, and the relative neutron polarization f_n was measured for each run. (The relative error in f_n is very small compared to the error in ε and was neglected.) Therefore P can be obtained from the measured value of ε. It is important to note that in the resonance analysis the relevant cross section is σ_p, the p-wave resonance cross section, while in this off-resonance analysis the appropriate cross section is the total cross section, which is at least an order of magnitude larger than the p-wave resonance cross section.

The 61 experimental values for the longitudinal asymmetries and their errors (P_i and ΔP_i) are listed in Table I. The weighted average value $\langle P_{\rm nonres}\rangle=(9.8\pm21.7)\times10^{-6}$, where the weighting is standard. Note that the quoted error is purely statistical. The ^{232}Th data are consistent with very small systematic errors; this conclusion agrees with all other previous evidence for these experiments [6]. The analysis was performed two additional times, with the previous channel-bin sizes halved and doubled. There was no significant difference in the values for $\langle P_{\rm nonres}\rangle$ and its error for the three cases. Possible energy dependence was examined by fitting the 61 values for the longitudinal asymmetry to the form $P=mE+b$. The best-fit values for the constants m and b are consistent with zero. Of course, previously unobserved p-wave resonances could lead to (local) parity violation in presumably resonance-free regions. There is no strong evidence for a new $p_{1/2}$ resonance in the regions we have studied.

The contributions of the tails of the parity-violating resonances and of potential scattering to off-resonance parity violation is estimated below the framework of the statistical approach. Although the distinction between potential scattering and effects of distant resonances is sometimes blurred, the precise separation will not matter for these qualitative arguments.

Since the enhancement mechanisms that greatly increase the parity-violation effect for p-wave resonances do not apply to potential scattering, the potential-scattering longitudinal asymmetry is expected to be of the same order as that for parity violation in nucleon-nucleon scattering. The scattered neutron interacts with target nucleons with momentum transfers of order of the Fermi momentum. The ratio of the weak and strong forces acting on a neutron in a nuclear potential is expected to be of the same order as the corresponding ratio for the nucleon-nucleon interaction, $P \sim G_F m_\pi^2 / G_S \sim 10^{-7}$.

The tails of parity-violating resonances that extend into the regions analyzed will make a very small contribution to P_{nonres}. The transmission asymmetry ε for a fairly large parity violation in ^{232}Th is of order 10^{-3}, which translates into a large PNC longitudinal asymmetry P because one divides by the relatively small p-wave cross section. For the off-resonance region the divisor is the total- (mainly s-wave) cross section σ_{total}, which is at least an order of magnitude larger than σ_p. In addition, the energy dependence of the resonance part of the PNC cross section (far from resonance) is given approximately by

$$\sigma_+ - \sigma_- = 2P\sigma_p = 2P\pi \lambda\!\!\!^{-2} g \Gamma_n \Gamma / [(E - E_p)^2 + \Gamma^2/4] , \quad (1)$$

where $\lambda\!\!\!^-$ is the neutron wavelength divided by 2π, g the statistical weight factor, Γ_n the neutron width, Γ the total width, and E_p the energy of the p-wave resonance. Relative to the value of the parity violation on resonance, the parity violation $\Delta\sigma$ in the tails of these resonances is reduced by several orders of magnitude. As a result of these effects the contribution from the p-wave resonances to the off-resonance PNC longitudinal asymmetry is small relative to the experimental upper limit. Although s-wave resonances should show a $\Delta\sigma$ equal to that for the p-wave resonances, the resonance transmission asymmetry is very small because the s-wave resonance cross section is several orders of magnitude larger than the p-wave resonance cross section. The energy dependence [see Eq. (1)] of the s-wave parity violation is the same as that for the p-wave resonances. Therefore both s- and p-wave neighboring resonances should contribute very little to the off-resonance PNC longitudinal asymmetry.

The only remaining contributions are from distant states. Since these resonances are even further away and are expected to contribute with random signs, the distant states also are expected to contribute very little to the off-resonance parity violation. Of course, if there is a sign correlation, then the effects of many distant states can contribute coherently. It would be very interesting to have explicit predictions for the off-resonance PNC longitudinal asymmetry in the models that attempt to explain the sign correlation.

We conclude that within the framework of the statistical approach one expects an extremely small off-resonance PNC longitudinal asymmetry. Our data are consistent with this prediction, but are not sufficiently precise to provide a sensitive test. With improved experimental conditions we hope to reduce the present upper limit of about 2×10^{-5} by an order of magnitude. At present, the empirical upper limit for the off-resonance PNC longitudinal asymmetry of $\sim 2\times10^{-5}$ does not appear to distinguish between the various models of parity violation.

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