Parity nonconservation for the 0.88-eV neutron resonance in $^{81}$Br

C. M. Frankle,† (1,1) J. D. Bowman,‡ (2) J. E. Bush,§ (1,1) P. P. J. Delheij, (3) C. R. Gould, (4,1) D. G. Haase, (1)
V. W. Yuan, (2) and X. Zhu (5,6)

(The TRIPLE Collaboration)

(1) North Carolina State University, Raleigh, North Carolina 27695-8202 and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308
(2) Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(3) TRIUMF, Vancouver, British Columbia, Canada V6T 2A3
(4) University of Technology, P.O. Box 5046, 2600 GA, Delft, The Netherlands
(5) Duke University, Durham, North Carolina 27708-0305 and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308

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The parity nonconserving longitudinal analyzing power $P$ was measured for the $E_n = 0.88$ eV neutron resonance in $^{81}$Br. The value of $P = +1.77\pm0.33\%$; the sign is determined relative to the 0.73-eV resonance in $^{139}$La.

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Recently our group observed parity violation for a number of resonances in $^{238}$U [1,2] and $^{232}$Th [3,4] by measuring the helicity dependence of the neutron total cross section. The spirit of the approach was to utilize the complexity of the compound nuclear system and to extract a parity nonconserving (PNC) matrix element $M$ from the distribution of the measured asymmetries without requiring detailed knowledge of nuclear properties such as the wave functions. Clearly this analysis requires a number of asymmetries per nuclide, in order that the variance of the distribution of the parity violations be determined. From this view, the measurement of an individual parity violation is interesting but of little quantitative value. However, in the $^{232}$Th data there is evidence that the asymmetries are not randomly distributed in sign. In order to establish the generality of this unexpected effect, it is important to know the relative signs of all of the observed parity violations. The most conservative approach is to remeasure all of the previously measured parity violations with the same experimental system. (Our convention is to compare the signs of all parity violations with the parity violation of the 0.73-eV resonance in $^{139}$La.) Here we report the measurement of parity violation for the 0.88-eV resonance in $^{81}$Br.

Interest in study of parity violation in the neutron-nucleus interaction has greatly increased in recent years. Following a suggestion by Sushkov and Flambaum [5], the Dubna group [6] observed very large PNC effects in the total cross section of epithermal neutrons on heavy nuclei. The limitation of the early measurements was the observation of only a single parity violation in a nuclide. Our group utilized the intense neutron beam at the Los Alamos Neutron Scattering Center (LANSCE) to study parity violation for many resonances. The expectation was that measurements in a chaotic regime [7] would bypass some of the difficulties encountered in parity violation studies in light nuclei [8].

In the $^{238}$U experiment several resonances showed statistically significant parity violations. However, the most striking results were in $^{232}$Th, where seven resonances had parity violations with a relative significance of 2.4$\sigma$ or greater. Two of these $^{232}$Th resonances had asymmetries $\sim 10\%$ (as large as any previously observed). These results strongly suggest that the general model for parity violation (compound nuclear mixing between close-lying states with the same angular momentum but opposite parity) is correct and that parity violation should occur at some level for all $p$-wave neutron resonances. However, for all seven of the resonances in $^{232}$Th with large parity violation the longitudinal asymmetry has the same sign. This contradicts the statistical assumptions employed in determination of the average PNC matrix element, and indicates that our purely statistical approach is too simple.

The background, experimental method, and data reduction procedures are described in [2,4], while the facilities are described by Roberson et al. [9]. The 800-MeV proton beam from the Los Alamos Meson Physics Facility (LAMPF) linac is injected into a proton storage ring (PSR) and the beam compressed to a pulse width of $\sim 250$ ns. The extracted proton beam strikes a tungsten target and neutrons are produced by the spallation process. The neutrons are moderated by water and collimated. Typical proton beam currents for the $^{81}$Br experiment were $\sim 50\,\mu$A.

The neutrons are polarized by selective attenuation through a cell of longitudinally polarized protons [9]. The absolute neutron polarization was determined by

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$^\dagger$Present address: Los Alamos National Laboratory, Los Alamos, NM 87545.
$^\ddagger$Present address: University of Pennsylvania, Philadelphia, PA 19104.
$^\S$Present address: Indiana University, Bloomington, IN 47405.
$^\|$Present address: University of Washington, Seattle, WA 98195.
measuring the transmission through the polarized proton cell as a function of polarization. This measurement was performed immediately following the completion of the bromine runs. (Yuan et al. [10] discuss alternate methods of determining the absolute polarization of the neutron beam.) The relative neutron polarization was measured for each run by determining the proton polarization with NMR [9]. For the $^81$Br experiment the neutron polarization was about 45%.

Fast spin reversal was accomplished with a magnetic spin rotator or "spin flipper" [11], in which the neutron spin is reversed by a transverse field which has two possible directions. In one configuration there is a fixed longitudinal field which reverses sign at the midpoint of the spin flipper. To flip the neutron spin a transverse field is added to the longitudinal field. The transverse field sequence $\{0, +, -0, +0, 0, -\}$ produces a spin sequence [parallel, antiparallel, $A, P, A, P, A$]. This eight-step sequence eliminates in first order the effect of transverse stray fields on the system and linear and quadratic time drifts in the detectors.

The target was located just past the exit of the spin flipper. The target was natural liquid bromine contained in a 7.2-cm OD reagent bottle, which in turn was inside a thin aluminum canister. The neutrons were detected with a system of $^6$Li-loaded glass detectors located at 56 m from the neutron source. Due to the very high count rates involved, the detectors were operated in current mode [12]. The neutron beam flux was monitored with a thin $^6$Li glass paddle detector placed directly in front of the neutron-spin polarizer. After each eight-step sequence the average neutron flux is determined and the data are accepted only if all data are within a predetermined range (normally ±8%). Each step in the eight-step sequence lasted 200 neutron bursts (10 s). The sequence was then repeated 20 times and this collection of data (20 eight-step sequences) combined into a "run."

The parity violating asymmetry $P$ for a $p$-wave resonance is defined from

$$\sigma^\pm = \sigma_p (1 \pm f_n P), \quad (1)$$

where $\sigma^\pm$ is the resonance cross section for $+$ and $-$ helicity neutrons, $\sigma_p$ the resonance part of the $p$-wave cross section, and $f_n$ the neutron polarization. The neutron transmission yield at the detector is given by

$$N^\pm = F(E_n) \exp \left\{ -nt[\sigma_{\text{pot}}^\pm + \sigma_p (1 \pm f_n P)] \right\}$$

$$= C(E_n) \exp \left\{ -nt\sigma_p (1 \pm f_n P) \right\}, \quad (2)$$

where $F(E_n)$ is the neutron flux, $E_n$ the neutron energy, $\sigma_{\text{pot}}$ is the potential scattering cross section, $C(E_n) = F(E_n) \exp \left\{ -nt\sigma_{\text{pot}} \right\}$, $n$ the number density of the $^81$Br target nuclei, and $t$ the thickness of the target. The final form for the transmission yield, after including Doppler broadening, expressing parameters directly in terms of time-of-flight (TOF) channel numbers, and allowing for a slow energy dependence of the effective background, is

$$N^\pm = C^\pm \exp \left\{ -n\sigma_{\max}^\pm (1 \pm f_n P) \right\}$$

$$= \frac{N'(1 \pm \alpha)}{K - K_t} \left[ 1 + \sum_{i=1}^{5} \alpha_i \right] \left[ \frac{K - \frac{K_b + K_e}{2}}{1000} \right]^i \exp \left\{ -n\sigma_{\max}^\pm (1 \pm f_n P) \right\}, \quad (3)$$

where $C^\pm$ is the flux, $(\sigma_{\max}^\pm)$ the Doppler broadened p-wave resonance line shape, $N'$ the normalization factor, $K$ the TOF channel number, $K_t$ the effective zero-TOF channel determined from the energy calibration, $\alpha$ the beam intensity asymmetry in the two helicity states, and $[K_b, K_e]$ the range of channels under consideration. In our earlier analyses the polynomial expression in the square brackets proved adequate even for background effects which change rapidly with energy, and should simulate very well the s-wave background for the present data. The summed spectra were fit first to determine the general resonance parameters, and then each run fit following the procedure described by Zhu et al. [12]. Since this is a phenomenological fitting procedure, some of the fit parameters cannot be interpreted literally.

The $^81$Br production data were taken as 8192 channel spectra, with each channel having a TOF bin width of 1 μs. The effective energy window was 0.2–50 eV. The neutron yields are sorted by helicity states and accepted or rejected depending on the range of fluctuations in the monitor counts. Each production run was inspected before being accepted for final analysis. The final data set consisted of 89 runs.

After fitting the summed spectrum to determine the line shape parameters which were assumed constant from run to run, each run $k$ was fit to determine the product of the parity violation $P$ and the neutron polarization $f_n$—($f_n P_k$). For each run $k$ the polarization $f_n$ is measured, and a value for $P_k$ determined. The average parity violating asymmetry is the weighted average of the individual $P_k$ values. The weighting factors are the errors assigned to each value of $f_n P_k$ by the fitting program. As discussed by Zhu et al. [2], these errors are reliable measures of the uncertainties in the individual $P_k$ values, but are not appropriate for the overall error in $P$. We determined the overall error from the distribution of $P_k$ values. The $P_k$ values are histogrammed and the overall error $\delta$ determined from $\delta = \sigma / \sqrt{N}$, where $N$ is the number of runs and $\sigma^2$ is the variance of the $P_k$ data set.

A transmission spectrum for a typical run is shown for the 0.88-eV resonance in the upper part of Fig. 1. The histogram for the 89 bromine runs is shown in the lower part of Fig. 1. The observed error $\sigma$ should be determined by the statistics of a single run. Since $\delta$ is determined directly from the distribution, this method should be a reliable way to determine the overall error. (See Zhu et al. [2] and Roberson et al. [9] for a detailed discussion of errors in these PNC experiments.) The uranium and thorium data are consistent with very small systematic errors.

One additional correction is for the spin flipper [11]. The spin-preserving efficiency $s$ (same) is essentially
Bromine Transmission Spectrum

![Graph showing neutron energy and number of runs](image)

**FIG. 1.** (top) A sample fit to the 0.88-eV resonance in $^{81}$Br. The data are for one spin state of a single run. The top curve is the background portion of the fitting function and the bottom curve is the fit to the resonance plus the background. Note the zero offset on the vertical scale. (bottom) Histogram of the 89 values of $P$.

100%, while the spin-flipping efficiency $r$ (reverse) is less than 100% and is energy dependent. The value of $P$ obtained with our program is $P_{\text{true}}F_{\text{eff}}$, where the average spin-flipper efficiency is defined as $F_{\text{eff}}=\frac{r+s}{2}$. For $E_n=0.88$ eV with the target at the exit of the spin flipper, $F_{\text{eff}}=96\%$. In our measurement the bromine target was located 3.3 cm from the end of the spin flipper, which led to an additional 5% depolarization. The final value for $P$ is 1.77$\pm0.33$ %.

In the two-level approximation the PNC longitudinal asymmetry $P$ is

$$P = \frac{2V}{(E_n-E_p)}\left[\Gamma_+^n/\Gamma_p^n\right]^{1/2},$$

where the neutron widths $\Gamma_+^n$ and $\Gamma_p^n$ are evaluated at the resonance energy $E_p$, and $V$ is the PNC matrix element between the two states in question. Since the required spectroscopic information is not available for $^{81}$Br, a value for $V$ cannot be determined from the present data.

All seven asymmetries in $^{232}$Th with statistical significance $>2.4\sigma$ have positive sign. The probability of 7 of 7 randomly distributed quantities having the same sign is 1.6%. The signs of all measured PNC asymmetries are known relative to the sign of the 0.73-eV resonance in $^{139}$La. The sign of the $^{139}$La resonance has been confirmed by Masuda et al. [13] and by our group [10]. Five of the seven $>2\sigma$ effects (other than in $^{232}$Th) are also positive: from Alfimenkov et al. [6] for $^{81}$Br (0.88 eV), $^{117}$Sn (1.33 eV), and $^{139}$La (0.73 eV) and from our previous work [1,2] for $^{238}$U (63.5 and 83.7 eV). We confirmed the sign of the effect in $^{117}$Sn [14]. The only negative values are a 7$\sigma$ effect in $^{111}$Cd (4.53 eV) [6] and a 2$\sigma$ effect in $^{238}$U (89.2 eV) [2]. The probability of 12 of 14 randomly distributed quantities having the same sign is 1.1%. There is a preliminary report of a negative effect for $^{113}$Cd (7.0 eV) [15].

Alfimenkov et al. [6] obtained $+2.4\pm0.4$ % for the $^{81}$Br $E_n=0.88$-eV resonance, compared with the present value of $+1.77\pm0.33$ %. The present (positive) sign for the 0.88-eV resonance in $^{81}$Br confirms the sign obtained earlier at JINR, and therefore leaves unchanged the statistical evidence for sign correlations: 12 of 14 statistically significant parity violations have positive signs.

More data are extremely important to definitively establish the sign correlations. There are now several approaches which attempt to explain the effect: Bowman et al. [16], Flambaum [17], Auerbach [18], Weidenmüller [19], and Koonin et al. [20]. Since the observed asymmetries appear to have a nonzero average value, but also show appreciable fluctuations, analysis requires both a constant term and a fluctuating term.

Our general experimental goal is to determine more precisely the magnitudes of the constant term and of the PNC matrix element $M$. With a well-determined value of $M$, the connection between the observed PNC matrix element and the effective nucleon-nucleon interaction should yield interesting results [21]. To determine $M$ precisely requires that the mechanism for parity violation be well understood. More experimental data are required to determine the relative magnitude of the constant and fluctuating terms. Improved experimental results should help resolve the present questions concerning the reaction mechanism, and provide a more precise value for the PNC matrix element $M$.

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