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Search for Parity Violation in 93Nb Neutron Resonances

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Search for Parity Violation in 93Nb Neutron Resonances

Abstract

A new search has been performed for parity violation in the compound nuclear states of ^{94}Nb by measuring the helicity dependence of the neutron total cross section. Transmission measurements on a thick niobium target were performed by the time-of-flight method at the Manuel Lujan Neutron Scattering Center with a longitudinally polarized neutron beam in the energy range 32 to 1000 eV. A total of 18 p-wave resonances in ^{93}Nb were studied with none exhibiting a statistically significant parity-violating longitudinal asymmetry. An upper limit of 1.0×10^{-7} eV (95% confidence level) was obtained for the weak spreading widthΓ_w in ^{93}Nb.

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Search for parity violation in ^{93}Nb neutron resonances

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A new search has been performed for parity violation in the compound nuclear states of ^{94}Nb by measuring the helicity dependence of the neutron total cross section. Transmission measurements on a thick niobium target were performed by the time-of-flight method at the Manuel Lujan Neutron Scattering Center with a longitudinally polarized neutron beam in the energy range 32 to 1000 eV. A total of 18 p-wave resonances in ^{93}Nb were studied with none exhibiting a statistically significant parity-violating longitudinal asymmetry. An upper limit of 1.0×10^{-7} eV (95% confidence level) was obtained for the weak spreading width Γ_w in ^{93}Nb. [S0556-2813(99)03202-1]

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After the discovery of large (up to 10%) parity violation (PV) effects in p-wave neutron resonances of lanthanum and other nuclei by Alfimenkov *et al.* [1], a PV study was undertaken in niobium by the same group [2]. At that time niobium seemed a promising candidate for the study of PV effects: there are strong p-wave resonances at low energies that could be studied with the available experimental system. The experiment did not observe any parity violation effect at the level of 0.15% in the 35.8- and 42.2-eV p-wave resonances. The PV effect p is defined from $\sigma_p^{\pm}=\sigma_p(1\pm p)$, where $\sigma_p^{\pm}$ is the resonance cross section for $+$ and $-$ neutron helicities, and σ_p is the resonance part of the p-wave cross section. Assuming the two-level approximation (one s-wave resonance, at 105.8 eV, and one p-wave resonance, either at 35.8 or 42.2 eV), the experimental results from this early measurement led to weak matrix elements V_{sp} of 6.0 ± 8.0 and 1.0 ± 1.8 meV for the 35.8- and 42.2-eV resonances, respectively.

The TRIPLE (Time Reversal Invariance and Parity at Low Energy) Collaboration has an excellent polarized resonance neutron time-of-flight spectrometer, as documented in the latest TRIPLE publications on ^{232}Th [3] and ^{238}U [4], and in references therein. With the sensitivity of this system and extension of the measurement to higher energies, one might expect to observe parity violation in ^{93}Nb. The major focus of the PV experiments in this mass region is to determine the weak spreading width, which is defined as $\Gamma_w=2\pi M_J^2/D_J$, where M_J is the root mean square value for the matrix element of the weak interaction in the compound nucleus and D_J is the level spacing between the s-wave resonances with spin J. The present values for Γ_w for different nuclei measured by TRIPLE are summarized in a forthcoming review [5]; the unweighted average of all experimental weak spreading widths in the mass $A=100$ region is about 4×10^{-7} eV. If one naively assumes that the weak spreading width for ^{93}Nb has this average value, and uses $D_J\simeq195$ eV, then the rms parity violation matrix element in ^{93}Nb should be $\simeq3.5$ meV. Therefore PV effects should be observed for favorable cases (weak p-wave resonance near strong s-wave resonance) in ^{93}Nb.

Our interest in ^{93}Nb also was motivated by our recent PV results for isotopes of silver [6], cadmium [7], tin [8], antimony [9], and iodine [9], which suggest that the spreading width Γ_w may change from nucleus to nucleus. In the pure statistical model approach to symmetry breaking [10], the spreading width for the particular interaction is the same for all nuclei. However, it is well known that the general behavior of the neutron strength function is modified locally by doorway states, by dynamical deformation, and by the spin-

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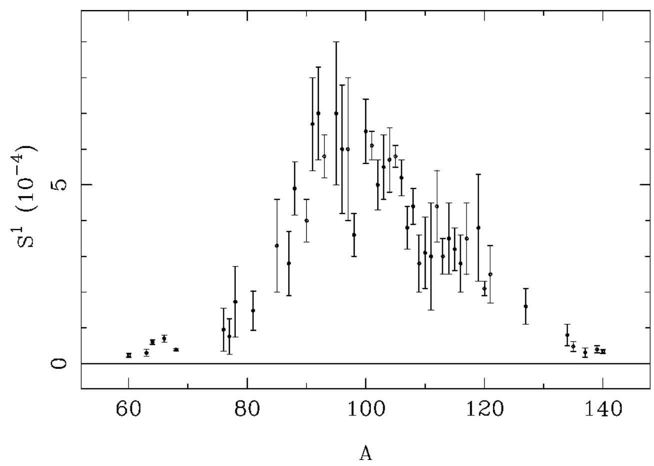

FIG. 1. The p-wave neutron strength function S^1 versus mass number A in the region of the $3p$ maximum.

orbit interaction. The p-wave neutron strength functions in the region of the $3p$ maximum (near $A=100$) are shown in Fig. 1, where data from Ref. [11] are supplemented with results from the TRIPLE spectroscopic studies of neutron p-wave resonances in several nuclides. According to calculations by Camarda [12], the spin-orbit interaction cannot strongly modify the total strength function $S^1=(S^1_{j=1/2}+2S^1_{j=3/2})/3$, but does shift the location of the maxima of the two components — the $j=3/2$ component to lower A and the $j=1/2$ component to higher A. The relative magnitude of the two components also changes significantly, with the $j=3/2$ component larger at lower A and the $j=1/2$ component larger at higher A. Locations for the maxima for the two components were determined [13] from an experimental study of neutron angular distributions: the $S^1_{j=3/2}$ component has a maximum at $A\simeq 95$, while the $S^1_{j=1/2}$ component has a maximum near $A\simeq 105$. Our other PV measurements near the $3p$ strength function maximum [6–9] were in the region where the $j=1/2$ component dominates. The ^{93}Nb nuclide is suitable for a study of the role of the spin-orbit interaction in parity violation, because the $S^1_{j=3/2}$ component should be larger than $S^1_{j=1/2}$ for nuclei around $A\simeq 90$.

We use the level spacing D_J observed in this experiment as the spacing between s-wave resonances with spin J and determine the rms matrix element M_J from the measured longitudinal PV asymmetries p with a statistical analysis. The statistical ansatz is that the individual PV matrix elements are statistically distributed: the matrix elements are Gaussian random variables with mean zero and variance M_J^2. The rms PV matrix element is determined from the experimental longitudinal asymmetries with a likelihood analysis [14].

For a ^{93}Nb target (target spin $I=9/2$), p-wave neutrons (orbital angular momentum $\ell=1$) excite compound states with spins $J=3$, 4, 5, or 6, while s-wave neutrons (orbital angular momentum $\ell=0$) excite only states with spins $J=4$ or 5. Since s-wave states with two different spins can contribute to the parity mixing, this complicates the statistical analysis, introducing the j-spin ($j=1/2$ and 3/2) partial neutron amplitudes $g_{p_{1/2}}$ and $g_{p_{3/2}}$ of the p-wave levels. The longitudinal asymmetry p is

$$p=\sum_{s:J_s=J_p}\frac{2V_{sp}}{(E_s-E_p)}\frac{g_s}{g_p}\frac{g_{p_{1/2}}}{\sqrt{g^2_{p_{1/2}}+g^2_{p_{3/2}}}}, \quad (1)$$

where V_{sp} is the matrix element of the parity-violating interaction between levels p and s, E_p and E_s are the corresponding resonance energies, and g_s and g_p are the neutron amplitudes defined through the corresponding neutron widths as $g^2_{s,p}=\Gamma_{n_{s,p}}$. The sum is over all s-wave states that have the same total angular momentum as the p-wave state. The value of the matrix elements V_{sp} and the quantity $2g_s/[g_p(E_s-E_p)]\equiv A_{sp}$ essentially determine the size of the experimental PV effects. The combination $A^2_J=\Sigma_s A^2_{sp}$ is used in the likelihood analysis for each p-wave resonance. The presence of unknown partial amplitudes in the last fraction in Eq. (1) is accounted for statistically by using the appropriate distribution functions for these amplitudes and the value of the ratio $a^2=S^1_{j=3/2}/S^1_{j=1/2}$. Details of the likelihood analysis are given by Bowman *et al.* [15].

The experiment was performed by the time-of-flight method at the pulsed neutron source [16] of the Manuel Lujan Neutron Scattering Center at the Los Alamos Neutron Science Center. Transmission data were measured with a longitudinally polarized neutron beam. An early description of the experimental apparatus was given by Roberson *et al.* [17]. A more up-to-date description is provided by Crawford *et al.* [4]. The neutron beam was 70% polarized by transmission through a polarized proton target. The protons in frozen ammonia were polarized by the dynamic polarization process at 1-K temperature in the 5-T field of a split-coil superconducting magnet. The proton polarization direction relative to the polarizing magnetic field (positive and negative proton polarization) were reversed every few days. The neutron spin direction parallel or antiparallel to the neutron beam momentum (positive or negative helicity state) was rapidly reversed by an adiabatic spin flipper in an eight-step sequence with each spin state lasting 10 s. This sequence was designed to reduce the effects of gain drifts and residual transverse magnetic fields. The neutron beam intensity was monitored by a pair of helium ionization chambers and the neutron polarization was monitored by NMR measurement of the proton polarization. The absolute value of the neutron beam polarization was obtained from PV measurements with a lanthanum sample by normalizing to the well known longitudinal asymmetry [18] for the 0.73-eV resonance in ^{139}La.

The 99.999% chemically pure niobium target was a cylinder of length 9.16 cm and diameter 9.84 cm. The target mass was 5988 g, which corresponds to an areal density of 5.10×10^{23} niobium atoms/cm^2. Neutrons were detected at 56.74 m by a large ^{10}B-loaded liquid scintillation detector segmented into 55 cells. The 55 separately discriminated signals were linearly summed. An ADC transient recorder was used to sample the summed signal in 8192 time-of-flight channels of 100-ns width. After 20 eight-step sequences, the data from this approximately 30-minute period were stored as a ''run'' on a disk. In the final data analysis 90 runs were used. A sample neutron time-of-flight spectrum for ^{93}Nb is shown in Fig. 2.

The longitudinal asymmetry for each p-wave resonance was determined with the use of a Reich-Moore multilevel,

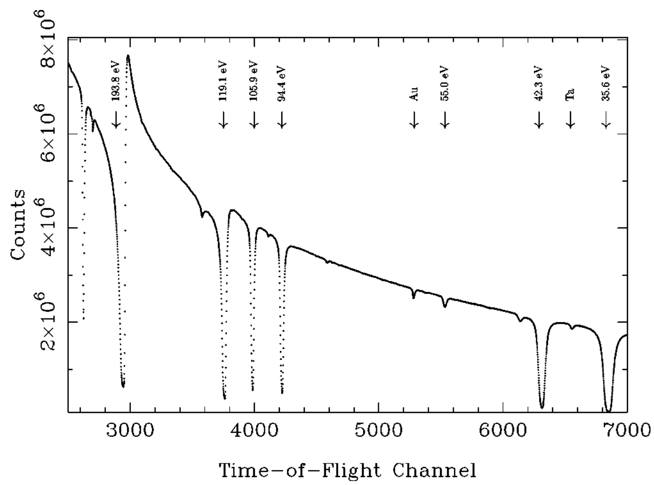

FIG. 2. A sample neutron time-of-flight spectrum for ^{93}Nb. The channel width is 100 ns and the counts are for one helicity state and are summed over 48 runs.

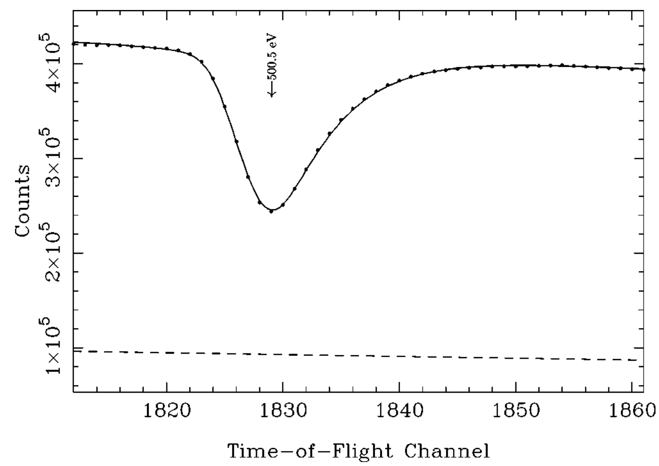

FIG. 3. Sample fit to time-of-flight (TOF) spectrum for the resonance at 500.5 eV. The counts are for one run and are summed over the two helicity states. The dashed line is the background.

multichannel fitting code FITXS [19], which includes line broadening due to beam, target, and detector. The resonance parameters were determined by fitting the time-of-flight spectra summed for both of the helicity states. The resonance parameters were then held fixed while the longitudinal asymmetries p^+ and p^- [which we redefine from $\sigma_p^{\pm}=\sigma_p(1+p^{\pm})$] were determined separately for the + and − helicity states. Finally, the longitudinal asymmetry p were determined from $p=(p^+-p^-)/(2+p^++p^-)$. Details on the application of the FITXS code to PV data are given by Crawford *et al.* [4]. A sample fit for the 500-eV resonance in niobium is shown in Fig. 3.

For each p-wave resonance studied the PV longitudinal asymmetries from separate runs were histogrammed to obtain a mean value of the asymmetry p and its uncertainty. The results are listed in Table I together with the resonance parameters. The resonance energy, neutron width, orbital angular momentum ℓ, and total angular momentum J are given for all resonances, while the quantity A_J is listed for those p-wave resonances for which the longitudinal asymmetry was measured. There are one or two entries for A_J depending on whether the spins are known or not. The A_J values are zero for spins $J=3$ and $J=6$ because such p-wave resonances cannot exhibit parity violation. Since the initial time-of-flight spectra were taken with unknown detector efficiency and neutron flux, a normalization procedure was performed using known resonance parameters [11] for several low-energy niobium resonances. This procedure was the main source of the systematic uncertainty of $\approx 8\%$ in our $g\Gamma_n$ values. Most of the resonance parameters are consistent with the assignments of Mughabghab *et al.* [11].

Following Bollinger and Thomas [20], we used a probabilistic method to assign parity to three resonances whose ℓ values were previously unreported: 364.8 eV (95%), 617.2 eV (93%), and 1127 eV (86%). The numbers in parentheses represent the Bayesian probability that the resonance is a p-wave resonance. Two new p-wave resonances were observed at 55.0 eV (98%) and 808.6 eV (93%). From our resonance data up to 1127 eV we determined the p-wave

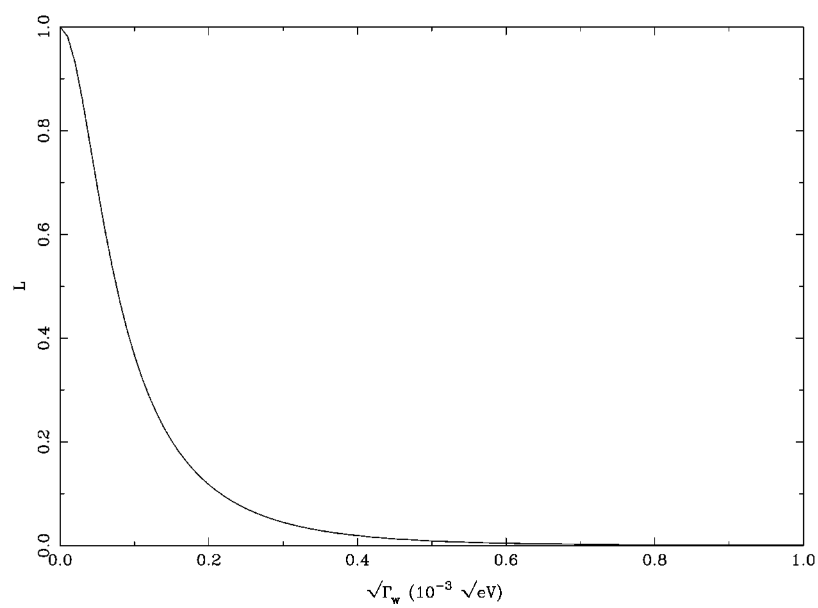

FIG. 4. Likelihood function L versus the square root of the weak spreading width Γ_w for p-wave resonances in ^{93}Nb.

TABLE I. Neutron resonance parameters and longitudinal PV asymmetries p for ^{93}Nb.

E (eV)	ℓ [a]	J [a]	$g\Gamma_n$ (meV)	p (%)	A_4(eV^{-1})	A_5(eV^{-1})
35.9	1	5	0.055±0.005	-0.007±0.022		0.21
42.3	1	4	0.044±0.004	0.01±0.02	0.68	
55.0 [b]	1[c]		0.0016±0.0002	0.04±0.16	3.5	1.52
94.4	1	3	0.16±0.02	-0.01±0.03	0.0	0.0
105.9	0	4	0.22±0.02			
119.1	0	5	2.30±0.18			
193.8	0	5	23.0±2.5			
243.9	1	4	1.02±0.08	-0.02±0.04	0.12	
318.9	1	5	0.87±0.08	-0.07±0.07		0.27
335.5	0	4	7.04±0.56			
362.7	1		0.15±0.01	0.07±0.10	2.3	0.56
364.8	1[c]		0.30±0.03	0.02±0.07	0.39	1.95
378.4	0	5	53.0±4.0			
392.4	1		1.05±0.08	0.10±0.09	0.14	1.03
460.3	0	5	3.91±0.31			
500.5	1	5	2.54±0.20	0.22±0.11		0.09
598.8	1	4	0.57±0.05	-0.03±0.12	0.22	
603.7	1	6	1.57±0.13	0.01±0.10	0.0	0.0
617.2	1[c]		0.68±0.05	0.18±0.11	0.22	0.14
640.9	0	4	2.65±0.22			
671.9	1	6	4.22±0.34	-0.05±0.10	0.0	0.0
678.2	1		1.07±0.09	0.12±0.13	0.30	0.12
720.9	1	4	6.08±0.49	0.001±0.09	0.36	
741.0	0	4	81.0±6.5			
757.0	1		1.11±0.09	-0.13±0.18	1.08	0.16
808.6 [b]	1[c]		0.29±0.03	0.07±0.23	0.69	0.49
910.1	0	4	2.50±0.02			
933.3	0	5	210.0±17			
952.9	1	6	6.50±0.50			
1011.0	0	4	290.0±24.0			
1127.0	1[c]		8.00±0.64			

[a]Values from Mughabghab [11] *et al.*

[b]New resonances.

[c]Orbital angular momentum assigned in this work.

strength function value $S^1=(5.1\pm1.6)\times10^{-4}$. The errors were calculated from $\sqrt{2/N}$, where N is the number of levels analyzed. This value agrees with the previously reported value of $S^1=(6.0\pm0.6)\times10^{-4}$ [12] obtained from the energy average neutron-transmission measurements above 1 keV. However, for s-wave levels our estimate $D_0=(95\pm8)$ eV disagrees strongly with the previously reported value of 44 ± 4 eV. There appears to be typographical error in Ref. [11], since the quoted value for the level density does not agree with the level spacing calculated directly from the resonance energies listed.

Finally, we constructed the Bayesian likelihood function L versus $\sqrt{\Gamma_w}$ using the asymmetries from Table I and Eq. (28) from Ref. [15] for L. This expression holds for our particular case: s-wave spins known, most p-wave spins not known, and neutron-spin amplitudes not known. These uncertainties were accounted for in a statistical manner as described by Bowman *et al.* [19]; the value of the parameter a was taken to be 0.67 ± 0.1 [13]. The likelihood function is shown in Fig. 4. The upper limits obtained for Γ_w and rms M_J (assuming the latter independent of J) are presented in Table II for 68 and 95% confidence levels.

Our sensitivity of 0.02% for the asymmetry p in the resonances at 35.9 and 42.3 eV is seven times better than in the previous PV study on ^{93}Nb [1]. However, for most of the resonances at higher energy our sensitivity is $\simeq0.15\%$. This is the only nuclide that our group has studied that does not show any parity violation for p-wave resonances. It seems worth considering whether ^{93}Nb has any special characteristics. The amplification factors A are very small for ^{93}Nb—the average value of A is a factor of ten smaller for ^{93}Nb than the average value of A for the neighboring nuclide ^{107}Ag. Therefore for the same rms parity violating matrix element, the longitudinal asymmetries should be reduced by an order

TABLE II. Upper limits for Γ_w and M_J in ^{93}Nb.

Confidence	$\Gamma_w(10^{-7})$ (eV)	M_J (meV)
68%	0.11	0.6
95%	1.05	1.8

of magnitude. However, one expects the matrix elements to fluctuate strongly and the weak spreading width to be approximately constant. Therefore an anomalous value for the weak spreading width in ^{93}Nb is of greater interest. From the results for 16 resonances the upper limit on the rms M_J value in ^{93}Nb is 0.6 meV at the 1σ confidence level. The corresponding 68% upper limit for Γ_w is very low as compared with nuclei on the higher mass side of the $3p$ maximum of the neutron strength function. However, the conclusion assuming the more conservative 95% confidence level is not as strong, and its significance will depend on the final results for other nuclei in this region.

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