ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
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Parity violation in p-wave neutron resonances has been studied by measuring the cross section longitudinal asymmetries at neutron energies up to 300–2000 eV, depending on the target. The measurements were performed by the TRIPLE collaboration using the polarization set-up at the pulsed spallation neutron source of the Los Alamos Neutron Science Centre. Parity violations were observed in 75 resonances of Br, Rh, Pd, Ag, Sn, In, Sb, I, Cs, Xe, La, Th, and U. Statistical methods were developed to determine the weak interaction r.m.s. matrix elements and the corresponding spreading widths Γ_w. The average value of Γ_w is about $1.8 \cdot 10^{-7}$ eV. The individual weak spreading widths are consistent with a constant or slowly varying mass dependence, but there is evidence for local fluctuations.

Нарушение четности в p-волновых резонансах исследовано посредством измерений продольной асимметрии эффективных сечений ядер для нейтронов с энергией до $300 \div 2000$ эВ (различной для разных ядер). Измерения выполнены коллаборацией TRIPLE с применением поляризационной установки на импульсном нейтронном источнике в Лос-Аламосе. Нарушение четности обнаружено в 75 резонансах ядер Br, Rh, Pd, Ag, Sn, In, Sb, I, Cs, Xe, La, Th, U. Развиты статистические методы извлечения среднеквадратичных матричных элементов слабого взаимодействия и соответствующих ширин Γ_w. Получена средняя по всем ядрам величина $\Gamma_w = 1,8 \cdot 10^{-7}$ эВ. Значения Γ_w для конкретных ядер соответствуют константе или слабой зависимости от массового числа при наличии локальных флуктуаций.

INTRODUCTION

Following the discovery of large parity violating effects for neutron resonances made at the Joint Institute for Nuclear Research [1], the Time Reversal Invariance and Parity at Low Energies (TRIPLE) Collaboration was formed to study parity violation (PV) in compound nuclei. The high neutron flux and good time-of-flight resolution available at the Manuel Lujan, Jr. Neutron Scattering Centre (MLNSC) at LANL were well suited for PV measurements in many resonances with the use of longitudinally polarized neutrons. A statistical ansatz was adopted: the compound nucleus is considered to be a chaotic system and the symmetry-breaking matrix elements are random variables. With this ansatz, the final result of a PV experiment is the root-mean-square symmetry-breaking matrix element M_J, which is obtained from a set of measured longitudinal asymmetries $\{p\}$ for individual resonances. The r.m.s. weak matrix element allows for theoretical interpretation without detailed information about the wave functions of compound states.

The longitudinal cross section asymmetry p is defined by

$$p = (\sigma_p^+ - \sigma_p^-)/(\sigma_p^+ + \sigma_p^-), \tag{1}$$

where $\sigma_p^\pm$ is the p-wave resonance cross section for $+$ and $-$ helicities. The cross sections are functions of the neutron energy E while the asymmetry p is a constant quantity around the resonance. Due to the weakness of p-wave resonances at low energies, the PV measurements are feasible only near the $3p$ and $4p$ maxima of the p-wave neutron strength function. Parity nonconserving (PNC) effects were observed for all but one of the many studied targets. For targets with nonzero spin the analysis is complicated and requires the knowledge of additional spectroscopic information for resonances besides their energies and neutron widths. When such information was absent averaging was performed over the various possibilities.

Results from the early measurements are discussed in reviews by Bowman et al. [2], and Frankle et al. [3]. After the initial measurements we improved the experimental system, repeated and improved the early measurements, and carried out experiments with many targets. The most recent reviews are by Mitchell, Bowman, and Weidenmüller [4] and by Mitchell, Bowman, Penttilä and Sharapov [5].

1. EXPERIMENTAL METHOD

Measurements of the longitudinal asymmetries were performed at the MLNSC pulsed neutron source [6]. The apparatus developed by the TRIPLE Collaboration for these measurements is described in a number of papers, including the original experimental layout [7], the neutron monitor [8], the polarizer [9], the spin flipper [14], and the detectors [11, 12]. The layout of the polarized neutron beam line for the latest PNC experiments is given in Ref. 13. The measurements were performed on flight path 2, which views a gadolinium-poisoned water moderator. After the moderator the neutrons are collimated to a 10-cm diameter beam inside a 4-m thick biological shield. The neutrons then pass through a flux monitor and through a polarizer — a dynamically polarized proton target. Here neutrons with one of the two helicity states are preferentially scattered out of the beam, leaving a beam of longitudinally-polarized neutrons with polarization $f_n \simeq 70$ %. Fast neutron spin reversal (every 10 s) was accomplished by passing the neutron beam through a spin flipper consisting of a system of magnetic fields. The neutron spin direction was also changed by reversing the polarization direction of the proton spin filter approximately every two days.

For most of the targets the PNC effects were measured by transmitting the neutron beam through samples located at the downstream part of the spin flipper. A large area ^{10}B-loaded liquid scintillation neuton detector [11] was located 56.7 m from the neutron source. For small targets of separated isotopes the samples were placed at the end of the flight path, the neutron spin transport system was extended to 60 m and the measurements were performed with a 4π CsI gamma-ray detector [12]. The data acquisition process is initiated with each proton burst. The detector signals are linearly summed and filtered. An ADC transient recorder digitally samples the summed detector signal 8192 times in intervals determined by the dwell time. The $+$, $-$ helicities data are stored separately in a 30-minute «run» for the subsequent analysis.

2. ANALYSIS

The shape analysis of time-of-flight spectra was performed with the code FITXS, which was written by Bowman, Crawford, Matsuda and Yen to analyze the TRIPLE Collaboration data. The multilevel, multichannel formalism of Reich and Moore was used for the neutron cross sections, which were convoluted with the TOF resolution function as described by Crawford et al. [13]. The neutron resonance parameters were obtained by fitting the unpolarized cross section $\sigma_p = (\sigma_p^+ + \sigma_p^-)/2$ and then held fixed while fitting separate helicity data for the longitudinal asymmetry p.

The observed PNC effect in the μth p-wave resonance is due to contributions from a number of neighboring s-wave resonance ν:

$$p_\mu = 2\sum_\nu \frac{V_{\nu\mu}^J}{E_\nu - E_\mu}\frac{g_\nu g_{\mu_{1/2}}}{\Gamma_{\mu_n}}, \tag{2}$$

where $g_{\mu_{1/2}}$ and g_ν are the neutron decay amplitudes of levels μ and ν ($g_\mu^2 = g_{\mu_{1/2}}^2 + g_{\mu_{3/2}}^2 \equiv \Gamma_{\mu_n}$ and $g_\nu^2 \equiv \Gamma_{\nu_n}$), E_μ and E_ν are the corresponding resonance energies, and $V_{\nu\mu}^J$ is the matrix element of the PNC interaction between levels μ and ν with spin J. Since, for each p-wave resonance, there are several mixing matrix elements $V_{\nu\mu}^J$ and one measured asymmetry, one cannot obtain the individual matrix elements. However, if the weak matrix elements are random variables, then the asymmetry p is also a random variable. We assume that asymmetries p have mean zero and are statistically independent. For targets with $I^\pi = 0$, the s-wave resonances have spins $J = 1/2^+$; and the p-wave resonances, spins $1/2^-$ or $3/2^-$. Only the spin $J = 1/2$ resonances can mix and show parity violation. From the $\{p\}$ set of data one can infer the variance M_J^2 of the individual matrix elements $V_{\nu\mu}^J$ — the mean square matrix element of the PNC interaction. We are using the Bayesian likelihood analysis to obtain M_J^2. The likelihood function for several resonances is the product of their likelihood functions each of which is defined by the probability density function for the longitudinal asymmetry p

$$P(p \mid M_J A) = \frac{1}{\sqrt{2\pi} M_J A} \exp\left(-\frac{p^2}{2M_J^2 A^2}\right), \tag{3}$$

with $A_\mu^2 = \sum_\nu 4\Gamma_\nu/\Gamma_\mu(E_\nu - E_\mu)^2$. Here $A^2 M_J^2$ is the variance of p which, according to Eq. (2), is a sum of Gaussian random variables $V_{\nu\mu}^J$ each multiplied by fixed coefficients.

The analysis for $I \neq 0$ targets is more complicated, it is described in [14]. By definition, the weak spreading width is $\Gamma_w = M_J^2/2\pi$, where D_J is the average spacing for spin J levels.

3. RESULTS

The Table lists the parity violations observed by the TRIPLE Collaboration and their relative sign. The TRIPLE Collaboration studied 20 different nuclides and measured the longitudinal asymmetries for several hundred p-wave resonances. Statistically significant PNC effects were found in 75 resonances. There is a nonstatistical anomaly in ^{232}Th, where the 10 longitudinal asymmetries observed up to 250 eV all have the same sign. As reviewed in [27], theoretical explanations of this effect led to unreasonably large values of the weak single particle matrix element. The observation of PNC effects with the opposite sign at higher energies in ^{232}Th [28] support a local doorway of Feshbach type [29].

Results for the weak spreading widths are shown in the Figure. In order to obtain at least an estimate of Γ_w for ^{81}Br, ^{131}Xe, and ^{139}La, where only one p-wave resonance (and parity violation) was observed, we determined the spreading width for these nuclei assuming $M \simeq V_{sp}$ and using the appropriate level spacing D_J. For ^{35}Cl and ^{56}Fe the M_J values from Bunakov's et al. [30] analysis of thermal neutron PNC data are used. The least square analysis [5] of measured spreading widths shows that although the complete set of data is not consistent with one common value, the data set without ^{93}Nb and ^{133}Cs can be described with a single value of $\Gamma_w = 1.8^{+0.4}_{-0.3} \cdot 10^{-7}$ eV.

Table 1. **Parity violations observed by TRIPLE**

Target	Reference	All	p^+	p^-
^{81}Br	[15]	1	1	0
^{93}Nb	[16]	0	0	0
^{103}Rh	[17]	4	3	1
^{104}Pd	[18]	1	0	1
^{105}Pd	[18]	3	3	0
^{106}Pd	[18, 19]	2	0	2
^{108}Pd	[18, 19]	0	0	0
^{107}Ag	[20]	8	5	3
^{109}Ag	[20]	4	2	2
^{113}Cd	[21]	2	2	0
^{115}In	[22]	9	5	4
^{117}Sn	[18]	4	2	2
^{121}Sb	[23]	5	3	2
^{123}Sb	[23]	1	0	1
^{127}I	[23]	7	5	2
^{131}Xe	[24]	1	0	1
^{133}Cs	[25]	1	1	0
^{139}La	[26]	1	1	0
^{232}Th below 250 eV	[27]	10	10	0
^{232}Th above 250 eV	[28]	6	2	4
^{238}U	[13]	5	3	2
Total		75	48	27
Total excluding Th		59	36	23

The measured r.m.s. weak matrix elements are qualitatively consistent with calculations by Rodin and Urin [31] and by Flambaum and Vorov [32]. The average weak spreading width of $1.8 \cdot 10^{-7}$ eV agrees qualitatively with theoretical expectations, e.g., with a result for ^{238}U [33] in the framework of the statistical spectroscopy approach. Globally the weak spreading widths are consistent with a constant value or with a slowly varying mass dependence and there is evidence for local fluctuations.

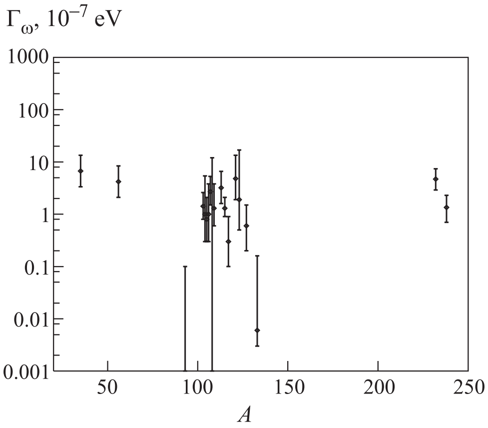

Fig. 1. Weak interaction spreading width Γ_w versus mass number A

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