Parity Nonconservation in Neutron Resonances in 133Cs

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Parity Nonconservation in Neutron Resonances in 133Cs

Abstract
Spatial parity nonconservation (PNC) has been studied in the compound-nuclear states of $^{134}$Cs by measuring the helicity dependence of the neutron total cross section. Transmission measurements on a thick $^{133}$Cs 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 from 5 to 400 eV. A total of 28 new p-wave resonances were found, their neutron widths determined, and the PNC longitudinal asymmetries of the resonance cross sections measured. The value obtained for the root-mean-square PNC element $M=(0.06^{+0.25}_{-0.02})$ meV in $^{133}$Cs is the smallest among all targets studied. This value corresponds to a weak spreading width $\Gamma_w=(0.006^{+0.154}_{-0.003})\times10^{-7}$ eV.

Disciplines
Atomic, Molecular and Optical Physics | Physics

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Parity nonconservation in neutron resonances in $^{133}\text{Cs}$


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Spatial parity nonconservation (PNC) has been studied in the compound-nuclear states of $^{133}\text{Cs}$ by measuring the helicity dependence of the neutron total cross section. Transmission measurements on a thick $^{133}\text{Cs}$ 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 from 5 to 400 eV. A total of 28 new p-wave resonances were found, their neutron widths determined, and the PNC longitudinal asymmetries of the resonance cross sections measured. The value obtained for the root-mean-square PNC element $\Gamma_w = \left(0.006_{-0.003}^{+0.014}\right) \times 10^{-7}$ eV. [S0556-2813(99)03503-7]

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I. INTRODUCTION

Parity violation (PV) research in nuclear physics has always pursued two goals: the study of the fundamental weak interaction itself and, as stressed in a new review [1], application of PV for improved understanding of nuclear structure and nuclear reactions. The discovery of a large enhancement for the parity nonconservation (PNC) signal in neutron p-wave resonances by the Dubna group [2] opened new possibilities for development in this field. The best method to study parity violation in the compound nucleus is the transmission measurement of longitudinally polarized neutrons through an isotopically pure target. The quantities measured in such experiments are the longitudinal asymmetries of cross sections for p-wave resonances, defined as $\sigma_p^\pm = \sigma_p(1 \pm p)$, where $\sigma_p^+$ is the resonance cross section for $+ \text{ and } -$ neutron helicities, and $\sigma_p$ is the resonance part of the p-wave cross section. The Time Reversal Invariance and Parity at Low Energies (TRIPLE) Collaboration initiated a program to study parity violation in the compound nucleus using the high epithermal neutron flux available at the Manuel Lujan Neutron Scattering Center at the Los Alamos Neutron Science Center (LANSCE). The TRIPLE Collaboration developed new techniques to produce and utilize a longitudinally polarized beam of resonance neutrons and measured a number of PNC asymmetries in several of several nuclei. The status of our earlier measurements is summarized by Bowman et al. [3] and by Frankle et al. [4]. Recently the TRIPLE Collaboration has published new PNC results for $^{238}\text{U}$ [5], $^{232}\text{Th}$ [6], $^{113}\text{Cd}$ [7], $^{107}\text{Ag}$ and $^{109}\text{Ag}$ [8], and $^{95}\text{Nb}$ [9].

One milestone was the development of a statistical approach to the analysis of the PNC data [10,11]. The TRIPLE Collaboration introduced a new procedure to extract the root-mean-square matrix element of the weak interaction (and the weak spreading width in the compound nucleus) from the measured PNC asymmetries of neutron cross sections. The details of this analysis are given by Bowman et al. [12]. In this new approach the symmetry-breaking matrix elements $V_{ik}$, which connect the $i$th p-wave resonance with the $k$th s-wave resonance of the same spin $J$, are random variables with mean value zero and variance $\overline{\sigma^2}$. Experimental PNC asymmetries $p_i$ are realizations of a Gaussian variable with variance $\overline{\sigma^2}$. It was shown that

$$\overline{p_i} = \mathcal{E} \sum_k A_{ik} \overline{V_{ik}},$$

where the expectation value $\mathcal{E}$ is taken with respect to both $i$ and $k$ ensembles and the so-called "amplification param-
permit extraction of the root-mean-square matrix element $M_J$ from the PNC asymmetries $p$. In practice, likelihood analysis is used to obtain $M_J$ [12]. Conversely, one can use Eq. (1) to estimate the size of PNC longitudinal asymmetries: $p = \sqrt{u_p^2} = (0.2 - 10)\%$ for a typical value of $M_J = 2$ meV and a range of values (1 - 50) eV$^{-1}$ for $A_{ik}$. Because the mean-square matrix element $u_p^2$ is expected [13] to be proportional to the mean level spacing $D_J$, it is customary to introduce the weak spreading width

$$\Gamma_w = 2\pi M_J^2/D_J,$$

which has a typical value of $\sim 10^{-7}$ eV. One expects that the spreading width for any symmetry-breaking interaction is approximately the same for all nuclei. We note that local fluctuations have been observed in the spreading width for isotopic spin mixing [14]. One major goal of the present work and of other experiments by the TRIPLE Collaboration is to measure the weak interaction spreading width for a number of nuclei and to determine the global and local properties of the weak spreading width.

For low energy neutrons the $p$-wave resonance neutron widths are very small. Our previous studies of the mass dependence of parity violation were performed for targets with masses $A \sim 100$ and $A \sim 230$. These targets are close to the $3p$ and $4p$ neutron strength function maxima. Only near these strength function maxima can $p$-wave resonances be observed and studied with satisfactory precision. However, in order to observe possible local fluctuations, it is important to extend measurements for targets away from these neutron strength function maxima. This was one of the motivations for our choice of cesium as a target for PV study. Cesium has only one stable isotope, 133 Cs, with nearly the same ($\sim 100$ eV) $s$-wave spacing as 238 U and almost no known $p$-wave resonances [15]. We felt that the apparent absence of $p$-wave resonances in cesium was due to the insufficient sensitivity of previous measurements, the latest of which was published in 1977 [16]. Our interpretation proved correct: we observed 28 extremely weak $p$-wave resonances up to 400 eV. In many cases, the neutron spectroscopic analysis of the observed $p$-wave resonances led to large amplification parameters $A_{ik}$ favorable for PNC. However, the experimental longitudinal asymmetries have rather small values. From this result, the conclusion is that cesium has an exceptionally small value of the weak matrix element $M$ and the spreading width $\Gamma_w$.

II. EXPERIMENTAL METHOD

The experiment was performed by the time-of-flight method at the pulsed spallation neutron source [17] of the Manuel Lujan Neutron Scattering Center at the Los Alamos Neutron Science Center. We refer to earlier papers [5–9] for a detailed description of the experimental method; here we provide only a brief summary. Transmission data on a thick cesium target were measured with a longitudinally polarized neutron beam. 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 a 5-T field of a split-coil superconducting magnet. The proton polarization direction relative to the polarizing magnetic field (positive and negative proton polarization) was 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 3He and 4He 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.

Care was taken to remove the water of hydration from the CsF which was canned in a hermetically sealed environment. The 99.999% chemically pure target of CsF was contained in an aluminum cylinder of length 29.80 cm and diameter 11.50 cm. The target mass was 6338 g, which corresponds to an areal density of $2.42 \times 10^{23}$ cesium atoms/cm$^2$. Neutrons were detected at 56.74 m from the source by a large 10B-loaded liquid scintillation detector segmented into 55 cells. The 55 separately discriminated signals were linearly summed. An analog-to-digital converter (ADC) transient recorder was used to sample the summed signal in 8192 time-of-flight channels of 200-ns width. After 20 eight-step sequences, the data from this approximately 30-minute period were stored as a "run." In the final data analysis 104 runs with positive proton polarization and 90 runs with negative proton polarization were used. A sample of a neutron time-of-flight spectrum for 45 runs is shown in Fig. 1. As can be seen in Fig. 1, the spectrum contains exceptionally small transmission dips. We list all of them in Sec. III, Table I. We do not include resonances from the latest measurements on cesium [16]. Resonances in Table I are either known or new resonances in cesium or resonances in target contaminants. In the latter case, the peaks should correspond to strong reso-

![Time-of-Flight Spectrum](Image)
### TABLE I. Neutron resonance parameters for $^{133}$Cs.

<table>
<thead>
<tr>
<th>$E$ (eV)</th>
<th>$g\Gamma_n$ (meV)</th>
<th>$l$</th>
<th>$J^a$</th>
<th>$A_{J=3}$ (1/eV)</th>
<th>$A_{J=4}$ (1/eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.91 ± 0.01</td>
<td>3.23 ± 0.15</td>
<td>0</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.50 ± 0.01</td>
<td>(0.95 ± 0.10) $\times 10^{-3}$</td>
<td>1</td>
<td>3</td>
<td>38.0</td>
<td>9.6</td>
</tr>
<tr>
<td>16.77 ± 0.02</td>
<td>(0.77 ± 0.08) $\times 10^{-4}$</td>
<td>1</td>
<td></td>
<td>88.8</td>
<td>34.2</td>
</tr>
<tr>
<td>18.86 ± 0.02</td>
<td>(0.68 ± 0.09) $\times 10^{-4}$</td>
<td>1</td>
<td></td>
<td>133</td>
<td>36.7</td>
</tr>
<tr>
<td>19.98 ± 0.02</td>
<td>(0.38 ± 0.04) $\times 10^{-3}$</td>
<td>1</td>
<td></td>
<td>79.4</td>
<td>15.8</td>
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<tr>
<td>22.52 ± 0.02</td>
<td>3.38 ± 0.20</td>
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<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30.00 ± 0.03</td>
<td>(0.55 ± 0.07) $\times 10^{-4}$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33.00 ± 0.03</td>
<td>(2.90 ± 0.40) $\times 10^{-4}$</td>
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<td></td>
<td>35.7</td>
<td>18.2</td>
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<tr>
<td>42.75 ± 0.04</td>
<td>(0.65 ± 0.08) $\times 10^{-3}$</td>
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<td>49.0</td>
<td>12.4</td>
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<td>(3.40 ± 0.40) $\times 10^{-3}$</td>
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<td></td>
<td>34.9</td>
<td>54.6</td>
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<tr>
<td>47.52 ± 0.04</td>
<td>8.72 ± 0.71</td>
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<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>58.09 ± 0.04</td>
<td>(0.4 ± 0.1) $\times 10^{-3}$</td>
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<td></td>
<td>51.4</td>
<td>17.3</td>
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<td>59.61 ± 0.04</td>
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<td>60.24 ± 0.04</td>
<td>(1.95 ± 0.23) $\times 10^{-3}$</td>
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<td></td>
<td>44.4</td>
<td>7.90</td>
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<td>78.52 ± 0.05</td>
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<td>22.4</td>
<td>24.6</td>
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<td>80.00 ± 0.05</td>
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<td>13.6</td>
<td>15.6</td>
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<tr>
<td>82.71 ± 0.05</td>
<td>3.18 ± 0.47</td>
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<tr>
<td>88.96 ± 0.06</td>
<td>(1.60 ± 0.13) $\times 10^{-2}$</td>
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<td></td>
<td>10.3</td>
<td>23.0</td>
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<td>94.21 ± 0.06</td>
<td>11.6 ± 1.0</td>
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<tr>
<td>110.45 ± 0.07</td>
<td>(0.16 ± 0.02) $\times 10^{-2}$</td>
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<td></td>
<td>8.8</td>
<td>18.9</td>
</tr>
<tr>
<td>115.00 ± 0.07</td>
<td>(0.41 ± 0.05) $\times 10^{-2}$</td>
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<td>5.7</td>
<td>20.4</td>
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<td>117.51 ± 0.07</td>
<td>(0.40 ± 0.06) $\times 10^{-2}$</td>
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<td>7.5</td>
<td>37.3</td>
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<tr>
<td>119.92 ± 0.08</td>
<td>(5.40 ± 0.45) $\times 10^{-2}$</td>
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<td></td>
<td>1.6</td>
<td>86.7</td>
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<td>126.1 ± 0.09</td>
<td>58.6 ± 0.5</td>
<td>0</td>
<td>4</td>
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<tr>
<td>140.2 ± 0.1</td>
<td>3.72 ± 0.35</td>
<td>0</td>
<td>3</td>
<td></td>
<td></td>
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<tr>
<td>146.0 ± 0.1</td>
<td>13.6 ± 1.2</td>
<td>0</td>
<td>4</td>
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<tr>
<td>155.3 ± 0.1</td>
<td>(0.88 ± 0.09) $\times 10^{-1}$</td>
<td>1</td>
<td></td>
<td>1.2</td>
<td>7.2</td>
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<tr>
<td>167.0 ± 0.1</td>
<td>(0.20 ± 0.02) $\times 10^{-1}$</td>
<td>1</td>
<td></td>
<td>1.9</td>
<td>5.2</td>
</tr>
<tr>
<td>181.5 ± 0.1</td>
<td>1.04 ± 0.11</td>
<td>0</td>
<td>3</td>
<td></td>
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<tr>
<td>201.1 ± 0.2</td>
<td>10.6 ± 1.0</td>
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<tr>
<td>207.5 ± 0.2</td>
<td>2.08 ± 0.21</td>
<td>0</td>
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<tr>
<td>217.1 ± 0.2</td>
<td>0.27 ± 0.03</td>
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<td>4</td>
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<tr>
<td>220.5 ± 0.2</td>
<td>11.1 ± 1.3</td>
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<tr>
<td>234.1 ± 0.2</td>
<td>193.3 ± 15.0</td>
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<td>4</td>
<td></td>
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<tr>
<td>238.4 ± 0.2</td>
<td>7.0 ± 0.8</td>
<td>0</td>
<td>4</td>
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<td>267.5 ± 0.2</td>
<td>(8.2 ± 1.0) $\times 10^{-2}$</td>
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<td></td>
<td>0.7</td>
<td>3.8</td>
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<td>271.0 ± 0.2</td>
<td>(3.6 ± 0.5) $\times 10^{-2}$</td>
<td>1</td>
<td></td>
<td>1.2</td>
<td>5.7</td>
</tr>
<tr>
<td>273.6 ± 0.3</td>
<td>(1.40 ± 0.13) $\times 10^{-2}$</td>
<td>1</td>
<td></td>
<td>2.1</td>
<td>9.0</td>
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<td>284.9 ± 0.3</td>
<td>(12.6 ± 1.1) $\times 10^{-2}$</td>
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<td></td>
<td>2.2</td>
<td>4.3</td>
</tr>
<tr>
<td>288.4 ± 0.3</td>
<td>(28.6 ± 3.1) $\times 10^{-2}$</td>
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<tr>
<td>295.5 ± 0.3</td>
<td>61.2 ± 6.0</td>
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<td>4</td>
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<tr>
<td>312.0 ± 0.3</td>
<td>(4.0 ± 0.4) $\times 10^{-2}$</td>
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<td></td>
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<tr>
<td>324.0 ± 0.3</td>
<td>(3.0 ± 0.4) $\times 10^{-2}$</td>
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<tr>
<td>328.0 ± 0.3</td>
<td>(3.0 ± 0.4) $\times 10^{-1}$</td>
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<tr>
<td>330.2 ± 0.3</td>
<td>(1.6 ± 0.2) $\times 10^{-1}$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>359.1 ± 0.4</td>
<td>18.6 ± 1.6</td>
<td>0</td>
<td>4</td>
<td></td>
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<tr>
<td>362.8 ± 0.4</td>
<td>(1.6 ± 0.2) $\times 10^{-1}$</td>
<td>1</td>
<td></td>
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</tr>
<tr>
<td>377.1 ± 0.4</td>
<td>8.9 ± 0.9</td>
<td>0</td>
<td>3</td>
<td></td>
<td></td>
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<tr>
<td>386.3 ± 0.4</td>
<td>(0.30 ± 0.03) $\times 10^{-1}$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400.5 ± 0.4</td>
<td>132.0 ± 18.0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Values from [15].

$^b$ New resonances.
nances. We checked the energies and strengths against all
known strong resonances in other elements [15] and con-
cluded that the newly observed weak dips belong to cesium.
It is not surprising that they were not observed earlier [16],
because we used a sample about 10 times thicker than in the
previous measurements and the spallation source at
LANSCE produced a much more intense neutron beam.

III. p-WAVE RESONANCES IN 133Cs
After correction for dead time count losses, the experi-
mental spectra were analyzed to obtain resonance parameters
$E_0$ and $g\Gamma_p$ using the multilevel fitting code FITXS [19] de-
veloped for fitting time-of-flight (TOF) spectra measured at
the LANSCE pulsed spallation neutron source. Details of the
fitting procedures are given by Matsuda [20] and by Craw-
ford et al. [21]. The final fitting function is written as

$$F_i(t) = \left[ B_i(t) \otimes \left( \frac{\alpha}{E^2} e^{-\sigma_D(t)} \right) \right] + \sum_{i=0}^{n} \frac{a_i}{t^i}. \quad (4)$$

Here $\sigma_D(t)$ is the Doppler-broadened total cross section for
$s$- and $p$-wave resonances written using the Reich-Moore ap-
proximation [22]. $B_i(t)$ is the instrumental response func-
tion, which includes line broadening due to the initial width of
the proton pulse, neutron moderation time in the water
moderator, finite TOF channel width, and time of the neutron
moderation time in the water
moderator. The energy dependence of the neutron flux
at epithermal energies is given by $\alpha/E^B$. The second term on
the right side of Eq. (4) represents a polynomial fit to the
background. The symbol $\otimes$ indicates a convolution. Sample
multilevel fits are shown in Figs. 1 and 2.

The resonance parameters were determined by fitting the
time-of-flight spectra summed for both helicity states. Since
the initial time-of-flight spectra were taken with unknown
detector efficiency and neutron flux, a normalization pro-
cedure was performed using known resonance parameters [15]
for several low-energy cesium resonances. This procedure
was the main source of the systematic uncertainty of 9% in
our $g\Gamma_n$ values. The neutron energy scale was calibrated
against the resonance energies of $^{232}$Th [6]. The large values of the amplification parameters make
$^{133}$Cs a good candidate for PNC study.

Before describing the PNC data analysis we first consider
the neutron spectroscopic results. Figures 3 and 4 show the
cumulative number of levels and Figs. 5 and 6 the cumula-
tive reduced neutron width distributions for the $s$- and
$p$-wave resonances. Both $s$-wave distributions have a typical
resulting resonance energies of $^{133}$Cs have better accuracy
than in previous measurements. Most of the $s$-wave reso-
nance parameters agree with those given in the compilation
by Mughabghab et al. [15]. For new resonances we assigned
the orbital angular momentum $l$ probabilistically, following
Bollinger and Thomas [23]. This procedure applies the
Bayes theorem to the Porter-Thomas distributions of neutron
widths for $s$- and $p$-wave resonances. Our application of this
procedure is described in Ref. [21].

Our resonance parameters are listed in Table I. The reso-
nance energy, neutron width, orbital angular momentum $l$, and
total angular momentum $J$ are given for all resonances for
which they were measured, while the quantity $A_i$
$=\sum_i A_i^2$ is listed for those $p$-wave resonances for which
the longitudinal asymmetry was measured. Because the spins of
the $p$-wave resonances are unknown, there are two entries for
$A_i$ corresponding to spins $J=3$ and $J=4$ for which mixing
of $p$- and $s$-wave levels by the weak interaction is possible.
The $A_i$ values are zero for spins $J=2$ and $J=5$ because such
$p$-wave resonances cannot exhibit parity violation. The am-
plification parameters $A_i$ for cesium $p$-wave resonances have
nearly the same size as for $A_i$ $p$-wave resonances in $^{232}$Th
[6]. The large values of the amplification parameters make
$^{133}$Cs a good candidate for PNC study.

FIG. 3. Cumulative number of levels for $^{133}$Cs $s$-wave reso-
nances. A linear fit was used to extract the $s$-wave level spacing.

FIG. 4. Cumulative number of levels for $^{133}$Cs $p$-wave reso-
nances. The linear fit indicates that some levels are missed above
120 eV.
shape, while the plot of the cumulative number of levels for the $p$-wave resonances indicates that some levels are being missed above 120 eV. The $p$-wave reduced width distribution in the limited energy region up to 120 eV is reasonable considering the relatively small number of levels involved. From linear least-squares fits of the curves in Figs. 3 and 4 the average $s$- and $p$-wave level spacings were determined to be $20.5 \pm 1.9$ eV and $8.0 \pm 1.0$ eV, respectively. Neutron strength functions were obtained from these data according to the definition

$$S_l = \frac{\sum_i g_i \Gamma_i^l}{(2l+1)\Delta E},$$

where the summation is over the reduced neutron widths $g_i \Gamma_i^l$ values in the energy interval $\Delta E$ and $l$ is the orbital momentum ($l = 0$ for $s$ waves and $l = 1$ for $p$ waves). The results are $S_0 = (0.80 \pm 0.17) \times 10^{-4}$ and $S_1 = (1.1 \pm 0.3) \times 10^{-4}$. The value of the $p$-wave neutron strength function for cesium was not known prior to the present measurement. We include the present value in the plot in Fig. 7, which shows the mass dependence of the $S_0$ neutron strength function versus $A$ in the region of the $3p$ strength function maximum. TRIPLE data are presented by solid circles.

IV. PNC DATA ANALYSIS AND RESULTS

A. PNC data

Longitudinal asymmetries were determined using the fitting code FITXS with fixed resonance parameters which were obtained first by fitting to the summed $(+)$ and $(-)$ helicity spectra. We introduced asymmetries $p_1$ and $p_2$ for the separate $+1$ and $-1$ helicity spectra by the definition $\sigma_p = \sigma_p(1 + p^2)$, and determined $p_1$ and $p_2$ from the fits. The resulting longitudinal asymmetries $p$ were determined from $p = (p_1 - p_2)/(2 + p_1 + p_2)$. Details concerning the application of the FITXS code to PV data are given by Crawford et al. [5]. For each $p$-wave resonance studied the PV longitudinal asymmetries from separate runs were histogrammed for positive and negative proton polarization to obtain a mean value of the asymmetry $p$ and its uncertainty.
TABLE II. Longitudinal PNC asymmetries for neutron resonances in $^{133}$Cs.

<table>
<thead>
<tr>
<th>$E_n$ (eV)</th>
<th>$p$ (%)</th>
<th>$p/\delta p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.50</td>
<td>0.242±0.023</td>
<td>10.4</td>
</tr>
<tr>
<td>16.77</td>
<td>-0.35±0.47</td>
<td>-0.8</td>
</tr>
<tr>
<td>18.86</td>
<td>-0.28±0.62</td>
<td>-0.5</td>
</tr>
<tr>
<td>19.98</td>
<td>-0.01±0.14</td>
<td>-0.1</td>
</tr>
<tr>
<td>33.11</td>
<td>0.05±0.30</td>
<td>0.1</td>
</tr>
<tr>
<td>42.75</td>
<td>-0.17±0.18</td>
<td>-0.9</td>
</tr>
<tr>
<td>44.63</td>
<td>0.06±0.15</td>
<td>0.4</td>
</tr>
<tr>
<td>58.09</td>
<td>1.20±1.74</td>
<td>0.7</td>
</tr>
<tr>
<td>60.24</td>
<td>-0.08±0.14</td>
<td>-0.5</td>
</tr>
<tr>
<td>78.52</td>
<td>-1.20±1.35</td>
<td>-0.9</td>
</tr>
<tr>
<td>80.00</td>
<td>-0.17±0.29</td>
<td>-0.6</td>
</tr>
<tr>
<td>88.96</td>
<td>-0.05±0.03</td>
<td>-1.6</td>
</tr>
<tr>
<td>110.5</td>
<td>0.62±0.44</td>
<td>1.4</td>
</tr>
<tr>
<td>115.2</td>
<td>0.02±0.27</td>
<td>0.1</td>
</tr>
<tr>
<td>117.7</td>
<td>0.12±0.23</td>
<td>0.5</td>
</tr>
<tr>
<td>119.9</td>
<td>0.05±0.03</td>
<td>1.7</td>
</tr>
<tr>
<td>155.3</td>
<td>-0.070±0.028</td>
<td>2.5</td>
</tr>
<tr>
<td>167.0</td>
<td>-0.08±0.10</td>
<td>-0.8</td>
</tr>
<tr>
<td>267.5</td>
<td>-0.07±0.08</td>
<td>-0.9</td>
</tr>
<tr>
<td>271.0</td>
<td>0.05±0.20</td>
<td>0.2</td>
</tr>
<tr>
<td>273.6</td>
<td>-0.45±0.50</td>
<td>-0.9</td>
</tr>
<tr>
<td>284.9</td>
<td>0.02±0.06</td>
<td>0.3</td>
</tr>
</tbody>
</table>

ample of such a histogram is shown in Fig. 8 for the 9.50-eV resonance. The values of the longitudinal asymmetries determined for $p$-wave resonances in $^{133}$Cs are listed in Table II.

B. PNC analysis and results

Finally, we constructed the Bayesian likelihood function $L$ versus $\Gamma_w$ using the asymmetries from Table II and Eq. (28) from the work of Bowman et al. [12]:

$$L(\Gamma_w) = \prod_i \left[ \sum_{j=1/2}^{1} P^0(M_j) r(J) P^i(p_i, M_j A_i(J), a, \sigma) \right. $$

$$\left. + \sum_{j=1/2}^{3/2} r(J) G(p_i, \sigma_i^2) \right] ,$$

(6)

where $M_j$ is expressed through $\Gamma_w$ as $M_j = \Gamma_w D_j / 2\pi$. Here $P^0(M_j)$ is the prior probability density function for $M_j$, and the value $P^0(M_j) = 1$ is assumed; $r(J)$ is the relative probability of spin $J$, $G(p_i, \sigma_i^2)$ is a Gaussian with experimental asymmetry $p_i$ and corresponding uncertainty $\sigma_i$, the quantity $a^2$ is the ratio of the $p_{3/2}$ and $p_{1/2}$ neutron strength functions, and $P^i$ is the appropriate probability density function discussed in detail in Ref. [12]. This expression holds for our particular case: $s$-wave spins known, most $p$-wave spins unknown, and the $j = 1/2$ and $j = 3/2$ projectile-spin amplitudes unknown. These uncertainties were accounted for in a statistical manner as described by Bowman et al. The value of the parameter $a$ was taken to be 0.70 ± 0.10 [28]. The weak interaction mixes states of the opposite parity but with the same spin $J$. For a $^{133}$Cs target (target spin $I = 7/2$), $p$-wave neutrons excite compound states with spins $J = 2, 3, 4$, or 5, while $s$-wave neutrons excite states with spins $J = 3$ or 4. Resonances with $J = 2$ and $J = 5$ cannot mix with $s$-wave resonances. Therefore only the $J = 3$ and $J = 4$ states in the compound nucleus $^{133}$Cs can exhibit PNC longitudinal asymmetries. Their contribution to $L(\Gamma_w)$ is accounted for by the first term in Eq. (6) while the second term corresponds to the $J = 2$ and $J = 5$ states. Since the spins of the $p$-wave resonances are not known, terms with all four possible $J$ values occur in Eq. (6). The terms with $J = 3$ and $J = 4$ depend on $M_j$, while terms with $J = 2$ and $J = 5$ do not. If a measured asymmetry is nonzero, then the terms with $J = 2$ and $J = 5$ play a small role. If a measured asymmetry is statistically consistent with zero, then all four terms are important. The nonzero asymmetry may be small because the matrix elements for the particular $J = 3$ or $J = 4$ states are small by chance. Application of Eq. (6) to the $p$-wave resonances with unknown spins requires knowledge of the spacings $D_j$. We used the values $D_{j=3} = 47$ eV and $D_{j=4} = 36$ eV which we obtained from $D_0 = 20.5$ eV by applying the $(2J+1)$ law for level densities.

The likelihood function with all $p$-wave resonance spins unknown is shown in Fig. 9. The maximum likelihood estimate and the 68% confidence interval obtained from this plot are

$$\Gamma_w = (0.006^{+0.154}_{-0.03}) \times 10^{-7} \, \text{eV}. $$

(7)

The large value of the confidence interval in this result is due to only two statistically significant asymmetries and uncertainty in the $A_i$ coefficients associated with unknown spins of resonances. The uncertainties in the $A_i$’s associated with the uncertainties in other resonance parameters were not included because they were about 10% for each resonance and the likelihood analysis reduces their influence.

Neglecting any possible differences in $M_j$ and $D_j$ between states with $J = 3$ and $J = 4$, that is, using Eq. (3) with $D = 2D_0 = 41$ eV, we obtain a value of the root-mean-square matrix element $M = (0.06^{+0.25}_{-0.05})$ meV. The likelihood function $L(\Gamma_w)$ has a relatively long tail. We could have chosen $\gamma = \ln \Gamma_w$ as the independent variable in the likelihood analysis. The likelihood function for this choice is shown in Fig. 10. This likelihood function is more nearly symmetric than the likelihood function for $\Gamma_w$ and to a good approximation.
the likelihood function $L(z)$ is Gaussian. Accepting the definition of standard error as for a Gaussian gives $z = \ln \Gamma_w = 5.12 \pm 1.39$ with $\Gamma_w$ expressed in units of $10^{-7}$ eV. Spins $J = 3$ and $J = 4$ are both possible for the 9.5-eV resonance. For $J = 3$, we obtain the same value as in Eq. (7) for the maximum likelihood estimate of $\Gamma_w$, although the function $L(\Gamma_w)$ is narrower than in Fig. 9. For $J = 4$, we obtain the likelihood function shown in Fig. 11. The larger value of the maximum likelihood estimate in this case is due to the smaller $A_{f=4}$ value (see Table I) as compared to the $J = 3$ case. The maximum is inside the 68% confidence interval for the value of Eq. (7). However, a spin assignment for the 9.5-eV $p$-wave resonance would be useful.

V. SUMMARY

With the polarized pulsed neutron beam at LANSCE, we have measured transmission through a thick cesium sample and observed for the first time many $p$-wave resonances in the neutron energy range of 5–400 eV. We measured the neutron widths and determined the $p$-wave strength function $S_1 = (1.1 \pm 0.3) \times 10^{-4}$, which is the smallest value of $S_1$ measured by the TRIPLE Collaboration. The PNC longitudinal asymmetries were obtained for 22 $p$-wave resonances in the energy range up to 285 eV. Parity violation is observed at the 9.50-eV resonance with $10\sigma$ statistical significance and at the 155-eV resonance with $2.5\sigma$ statistical significance. The other $p$-wave resonances that did not show any PNC effect are also important in establishing the weak matrix element because PNC amplification parameters are large for many of them. The values of the root-mean-square PNC element $M = (0.06 \pm 0.25)\, \text{meV}$ and the weak spreading width $\Gamma_w = (0.008 \pm 0.003) \times 10^{-7}$ eV in $^{133}\text{Cs}$ are the smallest of all the targets studied by the TRIPLE Collaboration. These results together with similar conclusions from PNC results for niobium [9] provide additional evidence that there exist local fluctuations in the mass dependence of the weak interaction in compound nuclei. More detailed study including spins and $S_{1/2}, S_{3/2}$ strength function measurements for $p$-wave resonances is needed to understand this behavior.

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