Parity Nonconservation in 106Pd and 108Pd Neutron Resonances

Bret E. Crawford
Gettysburg College

J D. Bowman
Los Alamos National Laboratory

P P J. Delheij
TRIUMF

See next page for additional authors

Follow this and additional works at: http://cupola.gettysburg.edu/physfac

Part of the Atomic, Molecular and Optical Physics Commons

Share feedback about the accessibility of this item.


This is the publisher's version of the work. This publication appears in Gettysburg College's institutional repository by permission of the copyright owner for personal use, not for redistribution. Cupola permanent link: http://cupola.gettysburg.edu/physfac/13

This open access article is brought to you by The Cupola: Scholarship at Gettysburg College. It has been accepted for inclusion by an authorized administrator of The Cupola. For more information, please contact cupola@gettysburg.edu.
Parity Nonconservation in $^{106}$Pd and $^{108}$Pd Neutron Resonances

Abstract
Parity nonconservation (PNC) has been studied in the neutron p-wave resonances of $^{106}$Pd and $^{108}$Pd in the energy range of 20 to 2000 eV. Longitudinal asymmetries in p-wave capture cross sections are measured using longitudinally polarized neutrons incident on $\sim$ 20-g metal-powder targets at LANSCE. A CsI $\gamma$-ray detector array measures capture cross section asymmetries as a function of neutron energy which is determined by the neutron time-of-flight method. A total of 21 p-wave resonances in $^{106}$Pd and 21 p-wave resonances in $^{108}$Pd were studied. One statistically significant PNC effect was observed in $^{106}$Pd, and no effects were observed in $^{108}$Pd. For $^{106}$Pd a weak spreading width of $\Gamma_w=34^{+47}_{-28}\times10^{-7}$ eV was obtained. For $^{108}$Pd an upper limit on the weak spreading width of $\Gamma_w<12\times10^{-7}$ eV was determined at the 68% confidence level.

Disciplines
Atomic, Molecular and Optical Physics | Physics

Authors

This article is available at The Cupola: Scholarship at Gettysburg College: http://cupola.gettysburg.edu/physfac/13
Parity nonconservation in $^{106}$Pd and $^{108}$Pd neutron resonances

B. E. Crawford,1,* J. D. Bowman,2 P. P. J. Delheij,3 T. Haseyama,4 J. N. Knudson,2 L. Y. Lowie,5,† A. Masaïke,4,‡ Y. Matsuda,4,§ G. E. Mitchell,5 S. I. Penttilä,6 H. Postma,6 N. R. Roberson,1 S. J. Seestrom,2 E. I. Sharapov,7 S. L. Stephenson,5,8 and V. W. Yuan2

1Duke University, Durham, North Carolina 27708 and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308
2Los Alamos National Laboratory, Los Alamos, New Mexico 87545
3TRIUMF, Vancouver, British Columbia, Canada V6T 2A3
4Physics Department, Kyoto University, Kyoto 606-01, Japan
5North Carolina State University, Raleigh, North Carolina 27695-8202 and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308
6Delft University of Technology, Delft, 2629 JB, The Netherlands
7Joint Institute for Nuclear Research, 141980 Dubna, Russia

(Received 8 July 1999; published 19 October 1999)

Parity nonconservation (PNC) has been studied in the neutron $p$-wave resonances of $^{106}$Pd and $^{108}$Pd in the energy range of 20 to 2000 eV. Longitudinal asymmetries in $p$-wave capture cross sections are measured using longitudinally polarized neutrons incident on $\sim$20-g metal-powder targets at LANSCE. A CsI γ-ray detector array measures capture cross section asymmetries as a function of neutron energy which is determined by the neutron time-of-flight method. A total of 21 $p$-wave resonances in $^{106}$Pd and 21 $p$-wave resonances in $^{108}$Pd were studied. One statistically significant PNC effect was observed in $^{106}$Pd, and no effects were observed in $^{108}$Pd. For $^{106}$Pd a weak spreading width of $\Gamma_w = 34.4^{+4.7}_{-2.9} \times 10^{-7}$ eV was obtained. For $^{108}$Pd an upper limit on the weak spreading width of $\Gamma_w < 12 \times 10^{-7}$ eV was determined at the 68% confidence level.

PACS number(s): 24.80.+y, 25.40.Ny, 27.60.+j, 11.30.Er

I. INTRODUCTION

Since the discovery of large parity nonconserving (PNC) effects in compound nuclear resonances by Alfimenkov et al. [1] at Dubna, interest has focused on the compound nucleus as a laboratory for studying not only the weak interaction itself but also the role of parity nonconservation in our understanding of nuclear structure [2]. The Dubna group measured the longitudinal asymmetries in $p$-wave resonances by neutron transmission through a variety of targets, observing asymmetries as large as 7% with neutron energies up to 10 eV.

Parity nonconservation arises from the mixing of $s$- and $p$-wave neutron resonances and results in a helicity dependence in the total $p$-wave cross section for longitudinally polarized neutrons incident on unpolarized targets. The helicity dependent cross section is given by

$$\sigma_p^{\pm} = \sigma_p(1 \pm f_n P),$$

where $\sigma_p$ is the unpolarized cross section and $f_n$ is the degree of neutron polarization. By measuring the helicity dependent asymmetry in the $p$-wave cross section, one determines the PNC asymmetry $P$.

The main limitation of the work by the Dubna group is the narrow energy range, restricting the measurement to only a few resonances per nucleus. Because of the statistical nature of the compound nucleus it is desirable to measure several PNC asymmetries in each nucleus studied. Using the high-flux, pulsed, epithermal neutron facility at the Los Alamos Neutron Science Center (LANSCE) and the apparatus described below, the TRIPLE (time reversal and parity at low energies) Collaboration developed a system to extend the energy range of these measurements to significantly increase the number of resonances studied in each nucleus. In addition, the TRIPLE Collaboration developed analysis techniques which exploit the statistical nature of the compound nucleus [3,4]. From the collection of measured PNC-asymmetry values our analysis extracts the root-mean-squared parity-nonconserving matrix element $M$ for the given nuclide. In order to compare PNC matrix elements from different nuclei, one forms a weak spreading width

$$\Gamma_w = \frac{2\pi M^2}{D},$$

where $D$ is the energy spacing between levels with the same spin for the nuclide in question. By analogy with similar studies with isospin [5] it is expected that $\Gamma_w$ is essentially constant as a function of nuclear mass, although local fluctuations are possible [6,7]. The TRIPLE Collaboration has focused its efforts in two regions of the periodic chart, places

---

*Present address: Gettysburg College, Gettysburg, PA 17325.
†Present address: McKinsey and Company, Atlanta, GA 30303.
‡Present address: Fukui University of Technology, 3-6-1 Gakuen, Fukui-shi 910-8505, Japan.
§Present address: Institute of Physical and Chemical Research (RIKEN), Saitama 351-0198, Japan.
where the \( p \)-wave strength function peaks, the mass-100 and mass-230 regions. The current measurements are part of an effort to determine \( \Gamma_{
u} \) in the mass-100 region. Results of studies with several targets have recently been published: \(^{238}\text{U}\) \cite{8}, \(^{232}\text{Th}\) \cite{9}, \(^{113}\text{Cd}\) \cite{10}, \(^{107}\text{Ag}\) and \(^{109}\text{Ag}\) \cite{11}, \(^{93}\text{Nb}\) \cite{6}, \(^{131}\text{Cs}\) \cite{7}, and \(^{103}\text{Rh}\) \cite{12}.

The traditional transmission experiments use large (several kg) targets, and the difference in neutron transmission between positive and negative helicity neutrons is measured. However, it is not always possible to obtain isotopically pure targets of sufficient mass to perform a transmission experiment. For small areal density isotopically pure targets, the capture method has been shown to be more sensitive than transmission measurements for observing both the \( p \)-wave resonances themselves and the parity nonconserving asymmetries in these resonances \cite{13,14}.

II. EXPERIMENTAL APPARATUS

The experiments are performed on flight path 2 at the Manuel Lujan Jr. Neutron Scattering Center (MLNSC). An overview of much of the apparatus is given in Ref. \cite{15}.

An 800-MeV proton beam from the LANSCE linac is bunched and stored in a proton storage ring (PSR) forming a 20-Hz pulsed beam with an average current of 70 \( \mu \text{A} \). The shape of the beam pulse is that of an isosceles triangle with a base of 250 ns. After exiting the PSR, the protons are deposited on a pair of tungsten spallation targets producing approximately 17 neutrons for each incident proton. A water moderator is used to produce thermal and epithermal energy neutrons \cite{16}. Each neutron pulse, therefore, contains a range of energies. The TRIPLE beam line shown in Fig. 1 uses a 60-m flight path to separate the neutron energies by the neutron time-of-flight method.

The pulsed epithermal neutron beam is monitored by a pair of \(^{3}\text{He}\) and \(^{4}\text{He}\) ionization chambers. Since both chambers are sensitive to \( \gamma \)-rays, but only the \(^{3}\text{He}\) chamber is sensitive to neutrons, a subtraction of the two signals measures the incident flux. The monitors do not provide an absolute measurement of the flux but rather monitor the stability of the incoming beam.

The neutrons pass through a dynamically polarized proton target that is cooled to 1 K in a 5-T magnetic field \cite{17}. The resulting neutron beam is polarized to \( \sim 85\% \) by the spin-dependent scattering of the unpolarized neutrons by the polarized protons.

The neutron spin direction is reversed every 10 s by a spin flipper composed of a system of longitudinal and transverse magnetic fields \cite{18}. Turning off or on a transverse magnetic field, the spin flipper either leaves the neutrons polarized along the beam direction or adiabatically rotates the spins to the opposite direction. The efficiency of adiabatic rotation of the neutrons is discussed in Ref. \cite{18} and is essentially constant from 1 eV to several hundred eV.

Since the Earth’s magnetic field will precess the neutron spins during the 60-m flight path and thus depolarize the beam, a 10-G solenoidal field is used to preserve the longitudinal spin of the neutrons. The depolarization due to the combination of the Earth’s magnetic field and the discontiguities in the solenoidal windings is discussed in Ref. \cite{19} and is on the order of a few percent.

The neutron energy is determined by the time-of-flight method, where the neutrons are “detected” by measuring the \( \gamma \)-rays produced during neutron capture in the target. The capture \( \gamma \)-ray detector consists of 24 15-cm long CsI crystal wedges that form two annular rings of 12 sections each. The target sits at the center of the two rings such that the total solid angle of the detector is 85% of \( 4\pi \). A 5-cm thick cylinder of \(^{6}\text{Li}\)-loaded polyethylene between the target and detector shields the neutron-sensitive CsI crystals from scattered neutrons. Signals from the up-stream and down-stream halves of the detector are combined so that electronically the detector consists of one 12-detector ring. The detector signals are shaped by 30-ns passive filters to aid in signal discrimination by constant fraction discriminators (CFDs) which are set with a threshold corresponding to a \( \gamma \)-ray energy of 0.3 MeV. The CFD outputs are cabled to the data room where the signals are rediscriminated and fed into a linear summer. The linear sum of the 125-ns wide pulses are then discriminated at a voltage level such that only events with two or more pulses in coincidence are counted. Thus we reduce our background signal by requiring a \( \gamma \) multiplicity of 2. The output of this last discriminator is shaped by a 100-ns filter and fed to a transient digitizer which samples the combined detector signal every 100 ns. This results in an 8192-channel \( \gamma \)-ray spectrum. A typical \( \gamma \)-ray spectrum after neutron time-of-flight has been converted to energy is shown in

![FIG. 1. Schematic of the TRIPLE beam line set up for a capture \( \gamma \)-ray measurement.](image-url)
The polarization cross section, \( \sigma_{\text{pol}} \), is given by

\[
\sigma_{\text{pol}} = (\sigma_- - \sigma_+)/2,
\]

where the \( n-p \) cross sections for singlet (spin \( J_\pi = 0 \)) and triplet (spin \( J_\pi = 1 \)) scattering states are given by \( \sigma_+ \) and \( \sigma_- \), respectively. Since the neutron polarization depends on the same quantities,

\[
f_n = \tanh(n \sigma_{\text{pol}} f_p),
\]

the neutron polarization \( f_n \) can be calibrated to an NMR measurement of \( f_p \) by measuring the neutron transmission for polarized and unpolarized beam. This is illustrated in Fig. 3. The expression found from the fit of the data in Fig. 3 that relates the actual \( n\sigma_{\text{pol}} f_p \) to the NMR measurement of the proton polarization is used to calibrate the neutron polarization to the NMR signal following Eq. (5). The neutron polarization was quite stable at about 85 and 82% for positive and negative proton polarization, respectively. The uncertainty in the determination of the neutron polarization is 3%.

The second method for determining the neutron polarization involves a transmission measurement of the PNC effect at the 0.75-eV \( p \)-wave resonance in \(^{139}\text{La}\). By dividing the experimental asymmetry by the known value of the PNC asymmetry [22], one can determine the neutron polarization. This is the basis of a neutron polarimeter positioned at the end of the beam line. A 0.06534-atoms/\( b \) \(^{139}\text{La}\) target is placed \( \approx 1 \) m downstream from the capture detector. A 1-cm thick, 13-cm diameter, 6% by weight \(^6\text{Li}\)-glass neutron detector monitors neutrons transmitted through the \(^{139}\text{La}\) target. By counting neutrons in each helicity state in the region of the 0.75-eV \( p \)-wave resonance, a PNC asymmetry is determined from which the neutron polarization is inferred. This method provides an approximately 20% measurement of the neutron polarization per 30-min run and thus serves as a monitor of the preservation of the neutron polarization by spin transport system.

### III. Analysis

Discussion of the analysis is divided into three sections: fitting resonance data to determine the neutron resonance parameters, extracting the PNC asymmetries in the \( p \)-wave resonances, and determining the rms PNC matrix element and the weak spreading width \( \Gamma_w \).

#### A. Fitting code and resonance parameters

The TRIPLE Collaboration has developed a fitting code, FITXS [23], to determine the neutron resonance parameters for neutron time-of-flight measurements carried out on flight-path 2 at MLNSC using either transmission or capture experiments.
and 108 Pd from transmission and capture measurements are
the 108 Pd target only positive polarization was used, and 350
resonances are included in Tables I and II. Figure 4 shows a
@

material, FITXS accurately fits the observed line shape
source, as well as Doppler broadening from the target mate-
R

- matrix formalism of Reich and Moore
detectors. The neutron cross sections are calculated using the

R-matrix formalism of Reich and Moore [24]. By modeling
the response of the neutron moderator at the spallation
source, as well as Doppler broadening from the target material,
FITXS accurately fits the observed line shape [25]. By
fitting the sum of data from the two helicity states, the reso-
nance parameters are determined for all resonances of inter-
fitting the sum of data from the two helicity states, the reso-
nance parameters are determined for all resonances of inter-

PNC asymmetries can be averaged with the appropriate errors from the

random fluctuations in the value of the asymmetries contrib-
ute to the width of the histogram. The uncertainty in P due to
random fluctuations is calculated from the standard deviation
divided by the square root of the number of 30-min runs,
\( \sigma_{\text{dev}} / \sqrt{N} \). Calculating the uncertainty in P from the histo-
gram in this way gives the most conservative estimate of the
uncertainty in the PNC asymmetry. The size of the statistical
errors for these measurements is comparable to errors in
other TRIPLE measurements. The primary possible system-
atic error could arise from uncertainty in the neutron polar-
ization. However, the two methods of determining the neu-
tron polarization described above give us confidence that the
neutron polarization is well known and that this systematic
error is much smaller than the statistical errors. In addition,
the neutron polarimeter at the end of the beam line showed
stable neutron polarization throughout the run. Since the po-
larimeter uses the same electronics as the PNC measure-
ments, this implies that the electronics are not producing
systematic effects. The system was also frequently tested by
verifying that transmission measurements of the PNC asym-
mphy the 0.75-eV resonance in the 139 La target positioned
just after the spin flipper agreed with the asymmetry mea-
sures can be averaged with the appropriate errors from the

TABLE I. PNC Asymmetries for 106 Pd.

<table>
<thead>
<tr>
<th>E (eV)</th>
<th>l</th>
<th>( g\Gamma_{\nu} ) (meV)</th>
<th>( A_p ) (1/eV)</th>
<th>P (%)</th>
<th>( P / \Delta P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>63.43±0.04</td>
<td>1</td>
<td>0.010±0.001</td>
<td>1.55</td>
<td>0.03±0.20</td>
<td>0.1</td>
</tr>
<tr>
<td>146.36±0.07</td>
<td>1</td>
<td>0.53±0.04</td>
<td>0.406</td>
<td>0.035±0.045</td>
<td>0.8</td>
</tr>
<tr>
<td>156.88±0.07</td>
<td>1</td>
<td>0.24±0.02</td>
<td>0.661</td>
<td>0.047±0.075</td>
<td>0.6</td>
</tr>
<tr>
<td>300.0±0.2</td>
<td>1</td>
<td>0.18±0.02</td>
<td>5.80</td>
<td>0.19±0.24</td>
<td>0.8</td>
</tr>
<tr>
<td>406.7±0.3</td>
<td>1</td>
<td>0.86±0.04</td>
<td>0.456</td>
<td>-0.07±0.12</td>
<td>-0.6</td>
</tr>
<tr>
<td>462.3±0.3</td>
<td>1</td>
<td>1.14±0.05</td>
<td>0.310</td>
<td>-0.04±0.13</td>
<td>-0.3</td>
</tr>
<tr>
<td>521.9±0.4</td>
<td>1</td>
<td>6.0±0.3</td>
<td>0.122</td>
<td>-0.057±0.058</td>
<td>-1.0</td>
</tr>
<tr>
<td>563.4±0.5</td>
<td>1</td>
<td>5.3±0.3</td>
<td>0.130</td>
<td>-0.044±0.066</td>
<td>-0.7</td>
</tr>
<tr>
<td>593.4±0.5</td>
<td>1 ( b )</td>
<td>12.5±0.6</td>
<td>0.088</td>
<td>-0.174±0.044</td>
<td>-4.0</td>
</tr>
<tr>
<td>644.9±0.6</td>
<td>1</td>
<td>0.52±0.05</td>
<td>0.488</td>
<td>0.60±0.038</td>
<td>1.6</td>
</tr>
<tr>
<td>967.5±0.6</td>
<td>1</td>
<td>16.1</td>
<td>0.357</td>
<td>0.119±0.069</td>
<td>1.7</td>
</tr>
<tr>
<td>1147.9±0.9</td>
<td>1</td>
<td>4.0±0.4</td>
<td>0.200</td>
<td>0.58±0.24</td>
<td>2.4</td>
</tr>
<tr>
<td>1206.2±0.9</td>
<td>1</td>
<td>10.0±0.7</td>
<td>0.113</td>
<td>-0.11±0.15</td>
<td>-0.7</td>
</tr>
<tr>
<td>1306±1</td>
<td>1</td>
<td>3.4±0.3</td>
<td>0.229</td>
<td>0.36±0.40</td>
<td>0.9</td>
</tr>
<tr>
<td>1323±1</td>
<td>1</td>
<td>7.8±0.8</td>
<td>0.172</td>
<td>-0.17±0.21</td>
<td>-0.8</td>
</tr>
<tr>
<td>1377±1</td>
<td>1</td>
<td>2.2±0.2</td>
<td>1.00</td>
<td>-0.53±0.66</td>
<td>-0.8</td>
</tr>
<tr>
<td>1511±2</td>
<td>1</td>
<td>28.2</td>
<td>0.094</td>
<td>0.09±0.12</td>
<td>0.8</td>
</tr>
<tr>
<td>1557±2</td>
<td>1</td>
<td>1.7±0.2</td>
<td>0.738</td>
<td>-1.2±1.2</td>
<td>-1.0</td>
</tr>
<tr>
<td>1597±2</td>
<td>1</td>
<td>12.1</td>
<td>0.618</td>
<td>-0.17±0.22</td>
<td>-0.8</td>
</tr>
<tr>
<td>1624±2</td>
<td>1</td>
<td>10.1</td>
<td>0.229</td>
<td>-0.12±0.28</td>
<td>-0.4</td>
</tr>
<tr>
<td>1764±2</td>
<td>1</td>
<td>18.2</td>
<td>0.195</td>
<td>-0.15±0.21</td>
<td>0.7</td>
</tr>
</tbody>
</table>

\( a \) From Ref. [26].
\( b \) See text regarding the l assignment for this resonance.

\( \text{B. PNC asymmetries} \)

Once the resonance parameters are determined, the data
are used to obtain PNC asymmetries. After eliminating data
runs with unstable run conditions, 430 30-min runs with
positive proton target polarization and 354 30-min runs with
negative polarization were analyzed for the 106Pd target. For
the 108Pd target only positive polarization was used, and 350
30-min runs were analyzed.

Using the resonance parameters determined by the
method described in the previous section, data from the two
helicity states for each p-wave resonance are fit varying only
the PNC asymmetry P. By fitting data for each resonance for
every data run, a collection of P values are determined and
corrected for neutron polarization. The P values then are
histogramed as shown in Fig. 5. By analyzing the data in
small sections (30-min runs) in this way, all nonstatistical

\( \text{PHYSICAL REVIEW C} \)
show one statistically significant effect (ΔP/P > 3) at the 593.4-eV resonance in 106Pd. The Bayesian probability for the 593.4-eV resonance to be p wave is 72%, making the orbital-angular momentum assignment inconclusive [26]. The fact that this resonance shows parity nonconservation implies that the resonance is a p wave. The subsequent analysis assumes the p-wave assignment.

C. PNC matrix elements and weak spreading width

Before determining the weak spreading width, we first determine the root-mean-squared PNC matrix element $M$. We use a likelihood analysis to extract the most likely value for $M$ from the distribution of PNC effects. The likelihood function is formed from a product of Gaussian probability density functions for each p-wave resonance studied, with the width of each distribution given by a combination of $M$ and the measurement error.

The PNC effects arise from the mixing of s- and p-wave resonances with the same spin. Since both of the targets considered here have target spin zero, only s-wave resonances with spin 1/2 are formed. However, p-wave resonances are formed with both $J = 1/2$ and $J = 3/2$, implying that only a fraction of the p-wave resonances can mix with the s-wave resonances to cause parity nonconservation. The spins for the Pd resonances are not known, but the resonance analysis may proceed by assigning a probability for the p-wave resonances being either $p_{1/2}$ or $p_{3/2}$ [27].

<table>
<thead>
<tr>
<th>$E$ (eV)</th>
<th>$l$</th>
<th>$g\Gamma_n$ (meV)</th>
<th>$A_p$ (1/eV)</th>
<th>$P$ (%)</th>
<th>$P/\Delta P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>112.70±0.07</td>
<td>1</td>
<td>0.96±0.08</td>
<td>1.44</td>
<td>0.037±0.040</td>
<td>0.9</td>
</tr>
<tr>
<td>149.76±0.07</td>
<td>1</td>
<td>0.060±0.006</td>
<td>2.54</td>
<td>0.06±0.30</td>
<td>0.2</td>
</tr>
<tr>
<td>302.9±0.2</td>
<td>1</td>
<td>3.2±0.2</td>
<td>0.221</td>
<td>0.026±0.057</td>
<td>0.5</td>
</tr>
<tr>
<td>411.0±0.3</td>
<td>1</td>
<td>0.65±0.03</td>
<td>3.07</td>
<td>-0.22±0.25</td>
<td>-0.9</td>
</tr>
<tr>
<td>480.5±0.4</td>
<td>1</td>
<td>0.57±0.03</td>
<td>1.09</td>
<td>0.03±0.31</td>
<td>0.1</td>
</tr>
<tr>
<td>544.4±0.4</td>
<td>1</td>
<td>5.6±0.3</td>
<td>0.254</td>
<td>-0.036±0.090</td>
<td>-0.4</td>
</tr>
<tr>
<td>642.2±0.6</td>
<td>1</td>
<td>1.3±0.1</td>
<td>5.31</td>
<td>0.37±0.34</td>
<td>1.1</td>
</tr>
<tr>
<td>797.4±0.8</td>
<td>1</td>
<td>6.3±0.4</td>
<td>0.206</td>
<td>0.12±0.14</td>
<td>0.8</td>
</tr>
<tr>
<td>843.4±0.9</td>
<td>1</td>
<td>0.83±0.08</td>
<td>0.712</td>
<td>-0.45±0.65</td>
<td>-0.7</td>
</tr>
<tr>
<td>1082.3±0.8</td>
<td>1</td>
<td>17±1</td>
<td>0.151</td>
<td>0.09±0.12</td>
<td>0.7</td>
</tr>
<tr>
<td>1121±2</td>
<td>1</td>
<td>0.51±0.05</td>
<td>0.864</td>
<td>0.7±2.3</td>
<td>0.3</td>
</tr>
<tr>
<td>1140±2</td>
<td>1</td>
<td>0.08±0.02</td>
<td>2.39</td>
<td>-5.0±5.7</td>
<td>-0.9</td>
</tr>
<tr>
<td>1359±1</td>
<td>1</td>
<td>28±2</td>
<td>0.102</td>
<td>0.03±0.14</td>
<td>0.2</td>
</tr>
<tr>
<td>1456±1</td>
<td>1</td>
<td>4.5±0.5</td>
<td>0.543</td>
<td>0.45±0.54</td>
<td>0.8</td>
</tr>
<tr>
<td>1505±2</td>
<td>1</td>
<td>0.33±0.05</td>
<td>1.11</td>
<td>-1.2±5.2</td>
<td>-0.2</td>
</tr>
<tr>
<td>1523±2</td>
<td>1</td>
<td>2.8±0.3</td>
<td>0.393</td>
<td>-0.11±0.93</td>
<td>-0.1</td>
</tr>
<tr>
<td>1743±2</td>
<td>1</td>
<td>0.47±0.07</td>
<td>1.45</td>
<td>-8.7±4.9</td>
<td>-1.8</td>
</tr>
<tr>
<td>1815±2</td>
<td>1</td>
<td>2.4±0.2</td>
<td>0.371</td>
<td>1.2±1.8</td>
<td>0.7</td>
</tr>
<tr>
<td>2118±3</td>
<td>1</td>
<td>7.5±0.8</td>
<td>0.193</td>
<td>0.23±0.81</td>
<td>0.3</td>
</tr>
<tr>
<td>2165±3</td>
<td>1</td>
<td>2.6±0.3</td>
<td>0.243</td>
<td>0.4±2.5</td>
<td>0.2</td>
</tr>
<tr>
<td>2287±4</td>
<td>1</td>
<td>37±4</td>
<td>0.0418</td>
<td>-0.31±0.29</td>
<td>-1.1</td>
</tr>
</tbody>
</table>

*From Ref. [26].

FIG. 4. Sample fit of the capture $\gamma$-ray yield versus neutron energy for the 593.4-eV resonance in 106Pd. The dashed line shows a polynomial fit to the $\gamma$-ray background.

FIG. 5. Histogram of the $P$ values for the 593.4-eV resonance in 106Pd for 784 30-min runs. The mean value from the distribution is given by $P = 0.174 ± 0.044$, where the uncertainty is given by $\sigma_{\text{meas}}/\sqrt{784}$. 

055503-5
Neglecting experimental limitations, the probability $p$ that the $p$-wave resonance has spin $J = 1/2$ and the probability $q$ that the resonance has spin $J = 3/2$ can be obtained from the spin distribution $F(J)$ [28]

$$F(J) \approx \frac{2J+1}{2\sigma_c^2} \exp\left(-\frac{(J+1/2)^2}{2\sigma_c^2}\right),$$  \hspace{1cm} (6)

where the spin cutoff parameter $\sigma_c$ [29] is given by

$$\sigma_c = 0.98 A^{0.29},$$  \hspace{1cm} (7)

and $A$ is the target mass number. The probabilities $p$ and $q$ can be written

$$p = \frac{F(1/2)}{F(1/2) + F(3/2)} \quad \text{and} \quad q = \frac{F(3/2)}{F(1/2) + F(3/2)}.$$  \hspace{1cm} (8)

In a measurement only resonances above a certain minimum size will be observed. The fraction of the total number of $p$-wave resonances that are measured $f$ can be estimated as the ratio of the number of $p$-wave resonances observed to the total number expected. For a spin-zero target the total number of $p$-wave resonances is expected to be $\sim 3E/D$, where $\Delta E$ is the range of energies analyzed and $D$ is the $s$-wave level spacing. The fraction $f$ also can be related to a minimum width parameter, $u = \Gamma_{1/2}^{\text{max}}/(\Gamma_{1/2})$, by integrating Porter-Thomas distributions in the $y$ parameter $y = \gamma^2/(\gamma_0^2)$, for the $p_{1/2}$ and $p_{3/2}$ resonances

$$f = p \int_{u^2/2}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy + q \int_{(q/p)u^2/2}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy$$

$$= p \text{erfc}(u/\sqrt{2}) + q \text{erfc}\left(\sqrt{\frac{q}{2p}}u\right).$$  \hspace{1cm} (9)

Given the experimental value for $f$, this equation can be solved for $u$. Finally, a new $p'$ and a new $q' = 1 - p'$ are found from the $u$ and $f$ values using

$$p' = p \text{erfc}\left(\frac{u}{\sqrt{2}}\right)/f.$$  \hspace{1cm} (10)

Using $s$-wave level spacings of $D_0 = 217$ eV and $D_0 = 182$ eV for $^{106}$Pd and $^{108}$Pd, respectively [26], we find $p' = 0.34$ and $q' = 0.66$ for $^{106}$Pd and $p' = 0.38$ and $q' = 0.62$ for $^{108}$Pd.

Following Ref. [27], one can write the likelihood function for $M$ for the case where the resonance spins are not known as

$$L(m) = P_M(m) \prod_p \sum_q \frac{p'^q \Gamma_n^{\text{max}}}{\sqrt{2\pi}A_p m^2 + \Delta P_p^2} e^{-p'^2/(2A_p m^2 + \Delta P_p^2)}$$

$$+ \frac{q' \Gamma_n^{\text{max}}}{\sqrt{2\pi} \Delta P_p^2} e^{-q'^2/2\Delta P_p^2},$$  \hspace{1cm} (11)

where $P_M(m)$ is the $a$ priori distribution of $m$. The root mean square PNC matrix element $M$ corresponds to the value of $m$ at which the likelihood function peaks. The likelihood function in Eq. (11) is not normalizable unless $P_M(m)$ tends to zero for large $m$. In practice we resolve the normalization issue by setting $P_M(m)$ equal to a constant up to some value of $m_{\text{max}}$ and zero otherwise. For palladium, based on results in other nuclides [6–12], we used an upper limit of 40 meV. The detailed properties of the resonances are contained in the parameter $A_p$, defined by

$$A_p^2 = \sum_q \left[ \frac{2}{(E_q - E_p)} \sqrt{\frac{\Gamma_n}{\Gamma_n^0}} \right]^2,$$  \hspace{1cm} (12)

where $E_q$, $E_p$, $\Gamma_n$, and $\Gamma_n^0$ are the resonance energies and neutron widths for the $s$- and $p$-wave resonances, respectively. Note that the width of the Gaussian in the second term in Eq. (11) is due only to the uncertainty in the PNC effect. This is because the $p_{3/2}$ resonances cannot cause parity violation.

The likelihood function for $^{106}$Pd is shown in Fig. 6, yielding $M = 10.9_{-4.5}^{+7.5}$ meV. This implies $\Gamma_n = 34_{-28}^{+47} \times 10^{-7}$ eV. The uncertainties for $M$ are obtained following Eadie [30] by solving the equation

$$\ln \left(\frac{L(m_{\pm})}{L(M)}\right) = \frac{1}{2}.$$  \hspace{1cm} (13)

One could also determine the uncertainties by numerically integrating the likelihood function and finding the most compact interval which contains 68% of the probability. With this approach we obtain $M = 10.9_{-4.5}^{+7.5}$ meV, i.e., the same value of $M$ and slightly larger errors.

The weak spreading width determined for $^{106}$Pd is significantly larger than the results obtained in most other nuclides. Unusually large and small values have been observed before, as discussed by Smith et al. [12]. These authors find an average spreading width in the mass-100 region of $\bar{\Gamma}_w = 2.56 \pm 0.83 \times 10^{-7}$ eV, where the largest value is $\Gamma_w = 16.2_{-8.3}^{+17.7} \times 10^{-7}$ eV ($^{113}$Cd) and the smallest value is $\Gamma_w = 0.006_{-0.003}^{+0.154} \times 10^{-7}$ eV ($^{133}$Cs). For $^{106}$Pd the likeli-
data, we expect the likelihood function to peak at zero. Using
inance as
In addition, although the current analysis treats this reso-
the numerous resonances that do not show parity violation.
shows a small second peak near zero due to the influence of
the PNC asymmetry. In this case the size of the PNC matrix
be an unresolved
- and
wave, there must
assignment for this resonance is un-
neutrons. A 10-G solenoidal field was used to preserve the
result for the weak spreading width, 
max in the
- mate the sensitivity of the upper limit to the cutoff value
m
max in the a priori distribution we performed calculations with different 
m
max . For the 68% confidence intervals in 
we find values of 3.2, 5.8, and 7.2 meV for 
m
max values of 10, 40, and 100 meV, respectively. We conclude that the
108 Pd upper limit is not very sensitive to the cutoff.

IV. SUMMARY

The capture \( \gamma \)-ray method has been used to measure parity
nonconservation in \( ^{106} \)Pd and \( ^{108} \)Pd targets. A nearly \( 4 \pi \)
CsI detector was used to measure helicity-dependent \( \gamma \) yields
from neutron capture of longitudinally polarized epithermal
neutrons. A 10-G solenoidal field was used to preserve the
neutron spins during the 50-m flight from where they are
polarized to the target and detector assembly. A transmission
measurement of the PNC asymmetry at 0.75-eV in \( ^{199} \)La was
used as an in situ monitor of the neutron polarization at the
target position. One statistically significant parity nonconser-
vation effect was observed in the 593.4-eV \( p \)-wave resonance
in \( ^{106} \)Pd; no effects were observed in \( ^{108} \)Pd. The \( ^{106} \)Pd result for the weak spreading width, \( \Gamma_w = 34^{+17}_{-28} \times 10^{-7} \) eV, suggests a local mass dependence. The \( ^{108} \)Pd results provide
an upper limit on the weak spreading width, \( \Gamma_w < 12 \times 10^{-7} \) eV, that is consistent with measurements on other
targets in this mass region.

ACKNOWLEDGMENTS

This work was supported in part by the U.S. Department of
Energy, Office of High Energy and Nuclear Physics, under
Grant Nos. DE-FG02-97-ER41042 and DE-FG02-97-
ER41033, and by the U.S. Department of Energy, Office of
Research, under Contract No. W-7405-ENG-36.
