Parity Violation in Neutron Capture Reactions

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Abstract

In the last decade, the scattering of polarized neutrons on compound nucleus resonances proved to be a powerful experimental technique for probing nuclear parity violation. Longitudinal analyzing powers in neutron transmission measurements on p-wave resonances in nuclei such as $^{139}$La and $^{232}$Th were found to be as large as 10%. Here we examine the possibilities of carrying out a parallel program to measure asymmetries in the $(n, \gamma)$ reaction on these same compound nuclear resonances. Symmetry-violating $(n, \gamma)$ studies can also show asymmetries as large as 10%, and have the advantage over transmission experiments of allowing parity-odd asymmetries in several different gamma-decay branches from the same resonance. Thus, studies of parity violation in the $(n, \gamma)$ reaction using high efficiency germanium detectors at the Los Alamos Lujan facility, for example, could determine the parity-odd nucleon-nucleon matrix elements in complex nuclei with high accuracy. Additionally, simultaneous studies of the $E_1$ and $V_{PNC}$ matrix elements involved in these decays could be used to help constrain the statistical theory of parity non-conservation in compound nuclei.

I. INTRODUCTION

The main goals of studies of parity violation in the nucleus are to determine the strength of the coupling constants for the weak nucleon-nucleon (NN) interaction, and to understand the interplay between the strong and weak interactions in the nuclear many-body system. To date, most of our knowledge on the parity-nonconserving NN potentials in the nucleus has come from few-body systems, from parity-violating asymmetries in $\gamma$-decays in light nuclei ($^{18}$F, $^{19}$F, and $^{21}$Ne), from the scattering of polarized neutrons from heavy nuclei, and from measurements of nuclear anapole moments. All three of $^{18}$F, $^{19}$F, and $^{21}$Ne exhibit low-lying parity doublets, and to extract information on the magnitude of the PNC coupling constants from these measurements very detailed shell model analyses have been carried out [1]. Haxton has exploited the similarity between the two-body operators for first forbidden beta-decay and parity violation, together with a measurement of the beta-decay of $^{18}$Ne, to extract a value for the isovector weak PNC pion coupling constant, $F_\pi$. The resulting upper
limit on the value of $F_π$ from $^{18}\text{F}$ is considerably lower than that expected from calculations of the underlying weak interaction for the nucleon, see for example [3].

To analyze the measurements of parity violation in heavy nucleus compound resonances the statistical shell model, originally developed by French et al. [3], has been extended [4] to incorporate the essential physics needed to study negative parity operators, particularly the parity violating NN interaction. An uncertainty arises in the statistical shell model description of parity violation in compound resonances in how to treat the effective one-body PNC interaction. Systematic studies of PNC in the $(n, \gamma)$ reaction on these same resonances could constrain this aspect of the theory.

In neutron transmission experiments on heavy nuclei, the parity-violating asymmetries, which are defined as the fractional difference of the resonance cross section for neutrons polarized parallel and anti-parallel to their momentum,

$$A_n^L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

(1)

can be as large as 10%. These represent by far the largest parity violating asymmetries observed in nuclei. The measurements have been carried out by the TRIPLE collaboration on $p$-wave resonances in compound nuclear systems such as $^{238}\text{U}$, $^{232}\text{Th}$, $^{133}\text{Cs}$, $^{127}\text{I}$, $^{115}\text{In}$, $^{113}\text{Cd}$, natural Ag, $^{108,106}\text{Pd}$, $^{103}\text{Rh}$, and $^{93}\text{Nb}$. In these systems the energy separation between opposite parity $s$-wave and $p$-wave resonances ranges from 0.1-100 eV. The parity violating mixing of $s$-wave states into a $p$-wave state leads to a longitudinal asymmetry

$$A_n^L \approx 2 \sum_s < \phi_s | V_{\text{PNC}} | \phi_p > \sqrt{\frac{\Gamma_n^s}{\Gamma_n^p}} \sqrt{\frac{\Gamma_n^s}{\Gamma_n^p}}$$

(2)

Here $\sqrt{\Gamma_n^s}$ and $\sqrt{\Gamma_n^p}$ are the neutron partial width amplitudes for the $p$- and $s$-wave resonances, and $< V_{\text{PNC}} >$ is the matrix element of the two-body PNC NN interaction between these resonances. This approximate expression for $A_n^L$ is obtained by taking the neutron energy to be the center of the $p$-wave resonance, and neglecting the $p$-wave and $s$-wave widths in the denominator of the more complete expression. The large size of the PNC asymmetries in compound systems arises in part because of the small energy denominators involved and because of the very favorable ratio of $s$-wave to $p$-wave neutron widths.

The close spacing between the resonances reflects their complexity and the wave functions of these resonances typically involve more than $10^6$ components. Thus, a diagonalization of the model space involved is not possible, and the structure and properties of compound resonances can only be described statistically. In a statistical analysis of the parity-violating asymmetries, the neutron reduced width amplitudes and the PNC mixing matrix element $< V_{\text{PNC}} >$ are treated as independent Gaussian-distributed random variables with zero mean. From the known values of the resonance energies and reduced widths, the root-mean-squared PNC mixing matrix elements ($M^2 = | V_{\text{PNC}} |^2$) for the different nuclei have been determined by the TRIPLE collaboration directly from experimental values of $A_n^L$. Using the standard Desplanques, Donoghue, and Holstein [6] estimates of the weak PNC meson-nucleon coupling constants, Tomsovic et al. find that calculated values of $M$ and of the corresponding weak spreading widths are in qualitative agreement with experiment; about a factor of 3 smaller than the experimental value for $^{238}\text{U}$ and about a factor of 1.7 smaller for
the Pd isotopes. More generally, the TRIPLE measurements provide a correlated constraint on the squared PNC coupling constants. New data from an independent statistical probe, namely, \((n, \gamma)\) measurements, would provide both more precise measurements of the mean PNC matrix elements and a valuable check on the application of the statistical shell model to parity violation.

II. THE \((N, \gamma)\) REACTION FOR PNC STUDIES

A. A More Precise extraction of \(M^2\)

One of the main advantages of the TRIPLE program was the ability to measure PNC asymmetries on several resonances in the same nucleus, thus allowing a likelihood analysis of the data to extract \(M^2\). Here we examine the possibility of a complementary systematic study of PNC in compound nuclear resonances using the \((n, \gamma)\) reaction.

The general expressions for parity-odd correlations in the \((n, \gamma)\) reaction have been derived by Flambaum and Sushkov [7]. We concentrate on the P-odd correlation in the \((n, \gamma)\) cross section that depends on the neutron helicity and direction of the neutron’s momentum, namely, \(\vec{\sigma}_n \cdot \vec{k}_n\). The helicity asymmetry \(A^\gamma_L\), which is the ratio of this parity-odd to the parity-allowed contribution to differential cross section, is

\[
A^\gamma_L = 2 \sum_s < \phi_s | V_{PNC} | \phi_p > \sqrt{\frac{\Gamma_p}{\Gamma_p}} \left(\frac{\Gamma_p + \Gamma_s}{\Gamma_s} (E - E_p) + \frac{\Gamma_p}{\Gamma_s} (E - E_s)^2 + \frac{\Gamma_s^2}{4} \right).
\]

Here \(E\) is the neutron energy, \(\Gamma_p, \Gamma_s\) are the neutron partial widths, and \(\Gamma_p, \Gamma_s\) are the total resonance widths. We note that the index \(i\) appearing in (3) refers to \(i^{th}\) gamma transition from the \(p\)-wave resonance under consideration. The partial gamma widths \(\Gamma^\gamma_p\) are for individual gamma transitions from the same \(p\)-wave resonance to different final states. If \(\Gamma^\gamma_p/\Gamma^\gamma_s\) is not too small (i.e., not \(<< 1\)) a good approximation to \(A^\gamma_L\) is obtained by setting \(E = E_p\) and neglecting the total widths, \(\Gamma_s\) and \(\Gamma_p\), in the denominator, in which case the longitudinal asymmetry in neutron capture becomes

\[
A^\gamma_L = A^\gamma_L = 2 \sum_s < V_{PNC} > \sqrt{\frac{\Gamma_p}{\Gamma_p}} \left(\frac{\Gamma_p + \Gamma_s}{\Gamma_s} (E - E_p) + \frac{\Gamma_s^2}{4} \right).
\]

The average ratio of the E1 strength from \(p\)-wave resonances to the M1 strength from \(s\)-wave resonances for primary gamma-rays is typically greater than one. In such cases eq. (4) is usually a good approximation, and \(A^\gamma_L\) is independent of the partial \(\gamma\)-widths involved. The longitudinal asymmetry corresponding to the observable \(\vec{\sigma}_n \cdot \vec{k}_n\) takes on the same value in both neutron capture and transmission measurements, and is quite enhanced in both cases.

There have been several successful measurements of parity violation in the \((n, \gamma)\) reaction, where the total capture cross section was measured. In \(^{139}\)La an asymmetry \(A^\gamma_L\) of 9.5 \pm 0.3\% has been measured [8]. Seestrom et al. [9] developed a neutron-capture detector, consisting of 24 CsI scintillators, for parity-violation studies at LANSCE. A measurement [10] of parity non-conservation in neutron capture on \(^{111}\)Cd and \(^{113}\)Cd observed large asymmetries, and a
PNC mean-squared matrix element $M = 2.9^{+1.3}_{-0.9}$ meV was obtained from the $J = 1$ levels in $^{114}$Cd. These sets of measurements showed that the $(n, \gamma)$ reaction could be used to obtain the same level of information as the TRIPLE neutron transmission experiments, but on thinner targets. In the present paper we examine the advantages that can be gained by using high resolution gamma-detectors, allowing measurements of individual gamma-rays.

The gamma-widths that appear in eq. (3), as mentioned above, are partial gamma-widths for the gamma-decay to an individual final state. Thus, neutron capture measurements have an additional advantage over transmission that a measurement of $A_L^n$ could be made for several individual gamma-decays from a given $p$-wave resonance. Assuming that the parity violation is not arising from mixing in the final state, and as long as equation (4) is a good approximation, several determinations of $M^2$ can be made for the same resonance. In the next section we examine some particular examples that display this possibility more explicitly.

We note that if $\Gamma_p^n / \Gamma_s^\gamma << 1$, equation (3) shows that the asymmetry becomes negligible at $E = E_p$, and the approximation to $A_L^n$ given in (4) is no longer valid. Thus, caution must be used in using the approximation (4) in place of (3). No enhancement of $A_L^n$ is expected for such transitions. In general, it is always better to use (3) over (4) in any likelihood analysis.

B. Constraints on Theory

There are two important unresolved theoretical issues in studies of parity violation in compound nuclear resonances, on which $(n, \gamma)$ measurements could shed light. The first of these is the issue of a possible sign correlation in the asymmetries $A_L^n$ measured by the TRIPLE collaboration, and the second is the issue of how to treat the effective one-body piece of $V_{PNC}$ in compound nuclei. In the case of $^{232}$Th the measured asymmetries were all observed to have positive sign. The statistical nature of the compound nucleus makes theoretical interpretation of this common sign very difficult [12,13]. A comparison of both the sign and the magnitude of the asymmetries measured in the neutron transmission and neutron capture reactions or these resonances would be very valuable. Indeed, the approximations made in deriving expression (4) for $A_L^n$ are the same as those used in deriving expression (1) for $A_L^p$. A measurement of the asymmetries in the $(n, \gamma)$ reaction for the same resonances studied by the TRIPLE collaboration may shed light on the validity of the theory and on the origin of the sign problem.

The second issue involves testing the validity of the approximations used to describe the effective one-body PNC interaction in heavy nuclei. The two-body parity-violating interaction can be split into two pieces, namely, an effective one-body piece and a valence two-body piece. The one-body component refers to the situation where one of the particles involved in the interaction is always in an (assumed) inert core orbital, i.e., it refers to matrix elements of the type $< j_a j_c | V_{PNC} | j_b j_c >$, where $j_a$ and $j_b$ are valence orbits and $j_c$ is a core orbit. In light nuclei ($^{18}$F, $^{19}$F and $^{21}$Ne) the one-body component of the parity violating interaction is a dominant contribution.

The situation in heavy nuclei is very different. In heavy nuclei the opposite parity states are determined by the so-called intruder orbital. The model space used by Tomsovic et al.
to describe the TRIPLE measurements on $^{238}$U is listed in Table I. The proton and neutron model spaces involve one opposite intruder parity orbital, $i_{13/2}$ and $j_{15/2}$, respectively. These opposite parity orbitals are key to determining the structure of the resonances and, particularly, the positive and negative parity level densities. However, the high spin of the intruder orbital relative to the rest of the model space means that no $\Delta J = 0^-,1^-$ transitions are allowed within the model space. Therefore, while this model space is reasonable for predicting level densities in the resonance region, it predicts vanishing $E1$ and one-body $V_{PNC}$ matrix elements. Tomsovic et al. used effective operator theory to incorporate the one-body $J = 0^-$ transitions through perturbation theory. The $E1$ operator ($\vec{r}\tau$) and the one-body approximation to PNC ($\sim \vec{\sigma}\vec{p}$ and $\vec{\sigma}\vec{p}\tau$) have similar properties, and both exhibit a giant resonance. Thus, a very strong test of the model would be provided by a simultaneous measurement of the $E1$ and PNC strengths for the same resonances.

III. EXPERIMENTAL CONSIDERATIONS

A. The Energy and multipolarity of $\gamma$-rays of interest

In the $\gamma$-decay of the compound nucleus, the primary transitions of known multipolarity which can give information on PV are usually of high energy ($E \approx 5 - 7$ MeV), because they correspond to transitions from the capturing states to low-lying levels of known spin and parity. In contrast, the lower energy $\gamma$-rays fall in the unresolved energy region of excitation, where no spectroscopic information is available on the individual energy levels.

Restricting ourselves to these higher-energy $\gamma$-rays, the $E1$ transitions are on the average 7 times stronger than the $M1$ transitions [14], and several $E1$ transitions from a given $p$-wave resonance can be associated with enhanced parity-violating asymmetries. Partial radiation widths exhibit strong fluctuations as described by the Porter-Thomas distribution; thus, the relative intensity of specific $E1$ and $M1$ $\gamma$-transitions of the similar energy can differ considerably from the average value of 7, and in some cases it can have very large values. This can be an advantage and facilitate the observation of specific transitions, as shown below.

In the case of many of the nuclei studied by the TRIPLE collaboration, e.g., $^{106}$Pd, $^{108}$Pd, $^{232}$Th and $^{238}$U, several $E1$ transitions from $p$-wave capture states to low-energy levels with opposite parity have been observed. The study of $^{139}$La would be more difficult, however, since all the low-energy states have the same parity as the $p$-resonances. Thus, only $M1$ transitions could be observed, making PNC measurements more difficult.

B. Indications from existing data in $p$-wave capture

Previously measured capture $\gamma$-ray spectroscopy studies on $p$-resonances give some indications on the feasibility of the class of experiments we are proposing. To explore the potential for parity violation studies using the $(n, \gamma)$ reaction, we consider the example of $E1$ and $M1$ $\gamma$-rays from neutron capture on $^{107}$Ag, which have been studied at Geel [16]. Gamma-rays from several $p$-resonances in the energy region of interest for PNC asymmetries [17] were studied. The emphasis in these experiments was on measurements of low-
energy $\gamma$-transitions, and thin samples were used to avoid absorption of low-energy $\gamma$-rays from the sample itself. This meant that data in the high-energy region of the $\gamma$-spectrum were available with good statistics for many $s$-wave resonances, but for only a few of the $p$-wave resonances. Nevertheless, from these data we can estimate the ratio of partial radiation widths for a number of different pairs of E1 and M1 transitions.

The absolute intensity of a transition can be obtained by dividing the measured number of observed counts by the sum of the intensities of all the transitions directly feeding the ground state and the isomeric states [19]. In Table 2 the absolute intensities of high-energy transitions from eight $p$-wave resonances in the $p^{+}{^{107}\text{Ag}}$ system are listed. Four of these $p$-wave resonances, at 125.1, 259.9, 269.9 and 422.5 eV, exhibit PNC effects in transmission experiments, and all the observed $\gamma$-transitions are of E1 character. We compare these with intensities of M1 transitions of the same energy from the close lying $s$-wave resonances with the same spin; our assumption being that parity mixing is dominated by mixing between neighboring opposite parity resonances. As can be seen from Table II, the observed ratio of transition intensities from $p$-wave versus $s$-wave resonances can be as large as 100. In the cases where the M1 transitions from $s$-resonances were not observed at all, despite the high statistics available for $s$-resonances, the $\Gamma^s_{\gamma}/\Gamma^p_{\gamma}$ ratio cannot be determined. Nonetheless, it is clear from Table II that the requirement for an enhanced PNC asymmetry $A^L_{\gamma}$, namely, that $\Gamma^p_{\gamma}/\Gamma^s_{\gamma} \geq 1$, is met. Then, as long as eq. (4) is a good approximation to eq. (3), detailed knowledge of the partial gamma-widths is not necessary to extract a value of $M^2$ from a set of measurements of $A^L_{\gamma}$.

We note that several other nuclei have been studied, and, in particular, similar results to the ones presented have been obtained for $^{232}\text{Th}$ [18], proving that a measurement with a radioactive target is possible.

C. Experimental setup

As mentioned above, in the Geel measurements for $p$-wave capture only the stronger primary transitions were observed. For systematic PNC studies, measurements optimizing the detection high-energy transitions are needed. Let us consider an experimental setup as shown in Fig. 1. As in the TRIPLE measurements, moderated neutrons are polarized through a polarizer, with the possibility reversing the spin by means of a spin flipper. Captured neutrons are viewed by an array of germanium detectors. Neutron energies are measured by time-of-flight. In order to have sufficient statistics, it is important to have a high neutron flux at the measuring station, which will be placed at a far enough distance to allow the resonances of interest to be resolved. The main contribution to the degradation of the energy resolution in a spallation neutron source is the moderator. At the Lujan facility, for instance, to measure up to 500 eV requires a distance of 72 m [14]. The availability of a longer flight path (184 m) at the nTOF facility at CERN would be an advantage in this respect.

Thus, optimize the count rate, the ideal measurements should (a) use a sample with higher mass than used in the Geel measurement, and (b) use germanium detectors with high efficiency. Additionally, a higher flux of neutrons in the energy range of interest that was available at Geel would be needed to maximize the number of observable $\gamma$ lines. Our
estimates indicated that the neutron fluxes available at the LANSCE facility make high precision measurements feasible.

In the cases of $^{232}$Th and $^{238}$U an additional difficulty arises from the fact that these nuclei involve radioactive targets. In this case it would be preferable to operate with a small duty factor, such as at the nTOF facility at CERN, in order to reduce the background and increase the signal to noise ratio.

IV. SUMMARY

As noted by Flambaum and Sushkov, parity-odd correlations in radiative neutron capture can be very enhanced. Of the eight possible P-odd correlations that can occur in the $(n, \gamma)$ reaction we have concentrated here on the correlation $\vec{\sigma}_n \cdot \vec{k}_n$. To a good approximation this leads to an asymmetry that is the same as the longitudinal asymmetry measured in neutron transmission experiments. (Important exceptions to this rule are discussed in the text). A measurement of this correlation in total neutron capture cross sections have found asymmetries $A^L_\gamma$ of the order of 10%. However, we emphasize that this asymmetry can be measured in the $(n, \gamma)$ reaction for several individual $\gamma$-transitions from the same $p$-wave resonance. The latter would allow high precision measurements of $< V_{PNC} >$, and would provide an independent probe of important theoretical issues raised by the observations and analyses of the TRIPLE [5] measurements.
TABLES

TABLE I. Model space used in the statistical shell model analysis for Mass region \( A \sim 230 \). While the model space describes the positive and negative parity level spacing, the high spin of the proton (\( i_{13/2} \)) and neutron (\( j_{15/2} \)) orbitals does not allow any E1 or one-body PNC matrix elements. A simultaneous measurement of both of these in \((n, \gamma)\) would provide a strong constraint on theory.

| Particle | Orbit  | \((n,\ell)\) | Parity |
|----------|--------|--------------|--------|
| P        | \( h_{9/2} \) | (0,5)         | -      |
| P        | \( i_{13/2} \) | (0,6)         | +      |
| P        | \( f_{7/2} \) | (1,3)         | -      |
| N        | \( i_{11/2} \) | (0,6)         | +      |
| N        | \( j_{15/2} \) | (0,7)         | -      |
| N        | \( g_{9/2} \)  | (1,4)         | +      |
| N        | \( d_{5/2} \)  | (2,2)         | +      |

TABLE II. Absolute intensities in photons per 100 neutron captures of high-energy transitions in \(^{107}\)Ag for neighboring \( p \)-wave and \( s \)-wave resonances with same spin. Statistical uncertainties only are indicated. The transitions from the \( p \)-wave (\( s \)-wave) resonances are E1 (M1) in character. Several strong primary \( \gamma \)-rays from a given \( p \)-wave resonance are observed, suggesting that systematic studies of high precision PNC measurements may be possible.

| \( E_\gamma \) (keV) | \( E_0 \) \( p \)-wave (eV) | \( I^p_\gamma \) (%) | \( E_0 \) \( s \)-wave (eV) | \( I^s_\gamma \) (%) |
|---------------------|--------------------------|-----------------|--------------------------|-----------------|
| 6450.4             | 64.2                     | 0.36 ± 0.05     | 51.6                     | 0.0071 ± 0.0012 |
| 6590.5             | 73.2                     | 0.42 ± 0.09     | 51.6                     | not observed    |
| 6690.4             | 0.37 ± 0.06              | 0.018 ± 0.001   | 0.087 ± 0.002†           |
| 6760.8             | 0.21 ± 0.06              | 0.016 ± 0.002   | 0.011 ± 0.002†           |
| 6803.5             | 0.35 ± 0.09              | 0.022 ± 0.005   | 0.003 ± 0.001            |
| 6890.1             | 0.21 ± 0.06              | 0.020 ± 0.003   | 0.015 ± 0.003            |
| 6760.8             | 107.6                    | 0.68 ± 0.15     | 51.6                     | not observed    |
| 6590.5             | 183.5                    | 0.37 ± 0.06     | 202.6                     | 0.044 ± 0.008   |
| 6803.5             | 259.9                    | 0.22 ± 0.04     | 251.3                     | not observed    |
| 6890.1             | 422.5                    | 1.7 ± 0.4       | 444.0                     | not observed    |

† Close to the single escape line from the 7269.4 keV transition
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FIG. 1. Schematic diagram of the experimental setup for the $(n,\gamma)$ measurement.