Parity violation in partial neutron capture reactions

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We point out that, in the standard resonance theory of parity violation in the compound nucleus, the longitudinal parity violating asymmetry in partial neutron capture cross sections is essentially independent of the partial gamma widths involved. Thus, the same asymmetry is expected for each partial cross section involving the same *p*-wave resonance. The asymmetries are expected to be enhanced (~10%), and asymmetry measurements for several partial capture cross sections from a given *p*-wave resonance would provide a very strong test of the theory. In particular, such a measurement could shed light on the origin of the sign problem observed in ^{232}Th and could provide more accurate determinations of the parity violating matrix elements between compound resonances. We propose a class of experiments and examine their feasibility.

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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 antiparallel to their momentum,

$$A_L^n=\frac{\sigma^+-\sigma^-}{\sigma^++\sigma^-}, \tag{1}$$

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 [1] on *p*-wave resonances in compound nuclear systems such as ^{238}U, ^{232}Th, ^{133}Cs, ^{127}I, ^{115}In, ^{113}Cd, natural Ag, ^{108,106}Pd, ^{103}Rh, and ^{93}Nb. In these systems the energy separation between opposite parity *s*-wave and *p*-wave resonances ranges from 0.1 to 100 eV. The parity violating mixing of *s*-wave states into a *p*-wave state leads to a longitudinal asymmetry

$$A_L^n=2\sum_s \frac{\langle \phi_s|V_{PNC}|\phi_p\rangle}{E_s-E_p}\sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}}. \tag{2}$$

Here $\sqrt{\Gamma_s^n}$ and $\sqrt{\Gamma_p^n}$ are the neutron partial width amplitudes for the *p*- and *s*-wave resonances, and $\langle \phi_s|V_{PNC}|\phi_p\rangle$ is the matrix element of the two-body parity nonconservation (PNC) *NN* interaction between these resonances. 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.

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 the mean squared PNC matrix element, $M^2=\overline{|V_{PNC}|^2}$. The mean-squared matrix element is defined as $M^2\equiv(1/N_pN_s)\Sigma_{s,p}\langle\phi_s|V_{PNC}|\phi_p\rangle$, where N_p and N_s are the number of *p*- and *s*-wave resonances occurring in a specified energy window. Here we examine the possibility of a complementary systematic study of PNC in compound nuclear resonances using the (n,γ) reaction. In particular we emphasize the advantages of partial capture cross section measurements, where PNC asymmetries could be measured for several gamma-decay branches of the same *p*-wave resonance.

The general expressions for parity-odd (*P*-odd) correlations in the (n,γ) reaction have been derived by Flambaum and Sushkov (FS) [2]. We concentrate on the *P*-odd correlation in the (n,γ) cross section that depends on the neutron helicity and direction of the neutron's momentum: namely, $\vec{\sigma}_n\cdot\vec{k}_n$. The dominant contribution to parity violation in neutron capture is usually assumed to arise from mixing between the *p*- and *s*-wave resonances in the entrance channel. There are two *P*-odd amplitudes that contribute to the asymmetry. In the first (denoted V_3 by FS) the neutron is captured by an *s*-wave resonance and the photon is emitted by a *P*-odd *p*-wave component in the resonance wave function. In the second (denoted V_4) the neutron is captured by a *p*-wave resonance and the photon emitted by a *P*-odd *s*-wave component. The amplitudes for both of these involves a product of matrix elements for a strong interaction neutron capture, a weak interaction parity mixing, and electromagnetic interaction photon emission. The full expressions for V_3 and V_4 and the corresponding *P*-even amplitudes for s-$(p$-$)$ wave neutron capture with emission of the photon from the same s-$(p$-$)$ resonance $[V_1(V_2)]$ are given in FS. The $\vec{\sigma}_n\cdot\vec{k}_n$ *P*-odd correlation in the cross section is then $2\mathrm{Re}(V_2V_3^*+V_1V_4^*)$. Starting with these four amplitudes, we obtain an expression for the helicity asymmetry $A_L^{\gamma_i}$ in partial neutron capture,

$$A_L^{\gamma_i}=\frac{\sigma_i^+-\sigma_i^-}{\sigma_i^++\sigma_i^-}=2\sum_s\frac{\langle\phi_s|V_{PNC}|\phi_p\rangle\sqrt{\frac{\Gamma_p^n}{\Gamma_s^n}}\left(E-E_p+\frac{\Gamma_p^{\gamma_i}}{\Gamma_s^{\gamma_i}}(E-E_s)\right)}{(E-E_p)^2+\frac{\Gamma_p^2}{4}+\frac{\Gamma_p^n}{\Gamma_s^n}\frac{\Gamma_p^{\gamma_i}}{\Gamma_s^{\gamma_i}}\left((E-E_s)^2+\frac{\Gamma_s^2}{4}\right)}. \tag{3}$$

Here E is the neutron energy, Γ_p^n, Γ_s^n are the neutron partial widths, and Γ_p, Γ_s are the total resonance widths. The index i appearing in Eq. (3) refers to the ith gamma transition from the p-wave resonance under consideration. The partial gamma widths $\Gamma_p^{\gamma_i}$ are for individual gamma transitions from the same p-wave resonance to different final states. Expression (3) is completely symmetric in p and s and is exactly analogous to the corresponding expression for neutron transmission [see Eq. (28) in Bunakov and Gudkov [3]]. If $\Gamma_p^{\gamma_i}/\Gamma_s^{\gamma_i} \gg 1$, a good approximation to $A_L^{\gamma_i}$ is obtained by setting $E=E_p$ and neglecting the total widths Γ_s and Γ_p, in the denominator, in which case the longitudinal asymmetry in neutron capture becomes

$$A_L^{\gamma_i}=A_L^{\gamma}=2\sum_s \frac{\langle \phi_s|V_{PNC}|\phi_p\rangle \sqrt{\dfrac{\Gamma_s^n}{\Gamma_p^n}}}{(Es-Ep)}. \tag{4}$$

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 1. In such cases Eq. (4) is a good approximation, and A_L^{γ} is independent of the partial γ widths involved. The longitudinal asymmetry corresponding to the observable $\vec{\sigma}_n \cdot \vec{k}_n$ takes on the *same* value in both partial neutron capture and transmission measurements, and is quite enhanced in both cases. The TRIPLE Collaboration usually quote cross section asymmetries as a fraction of the parity conserving p-wave cross section $\sigma_p(E)$, as opposed to as a fraction of the total cross section at E_p. In this case the expression for A_L^{γ} is simpler than Eq. (3) and is not symmetric in p and s. However, Eq. (4) is remains a good approximation.

There have been a few successful measurements of parity violation in the (n,γ) reaction, where the *total* capture cross section was measured. In ^{139}La an asymmetry A_L^{γ} of 9.5% ± 0.3% has been measured [4]. Seestrom *et al.* [5] developed a neutron capture detector, consisting of 24 CsI scintillators, for parity violation studies at LANSCE. A measurement [6] of parity nonconservation 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,γ) 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.

Measurements of asymmetries for partial gamma decays to individual final states would provide several measurements of A_L^{γ} from a given p-wave resonance. The requirement that the asymmetries be independent of the final state and all have the same value is a very strong test of the underlying theory. An observation of deviations from this prediction would imply that contributions from other neglected amplitudes may not be as small as previously assumed; there are some hints from the TRIPLE measurements that other reaction mechanisms may play a role.

In the case of ^{232}Th the measured asymmetries were all observed to have positive sign. The statistical nature of the compound nucleus and the assumption that the neutron width amplitudes and PNC matrix elements are independent variables makes theoretical interpretation of this common sign very difficult [7–9]. The assumptions made in deriving expression (4) for A_L^{γ} are the same as those used in deriving expression (1) for A_L^n. The main approximation made is the assumption that parity mixing all takes place when the neutron is captured into a p-wave resonance, i.e., that the p-wave resonance that is formed has a parity violating s-wave component. Within this approximation, once a neutron is captured into a parity-mixed resonance, the asymmetry arising from the P-odd $\vec{\sigma}_n \cdot \vec{k}_n$ correlation no longer depends on the decay channel of the resonance. This assumes, for example, that there is no parity violation in the final state. While this is very physically reasonable, it cannot explain the sign correlation observed in ^{232}Th.

Here we are proposing a set of experiments measuring parity violation in partial neutron capture in both ^{232}Th and in the better-understood compound nuclei to resolve the issue. A measurement of the asymmetries in the (n,γ) reaction for the same resonances studied by the TRIPLE Collaboration would test the validity of the theory and shed light on the origin of the sign problem. An additional advantage of such measurements is that they could provide a more accurate determination of the parity mixing matrix element M, since several independent measurements of A_L could be made for each resonance.

We now turn to the question of the feasibility of these experiments. In the γ decay of the compound nucleus, the primary transitions of known multipolarity that 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 γ 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 γ rays, the $E1$ transitions are on the average 7 times stronger than the $M1$ transitions [10], and several $E1$ transitions from a given p-wave resonance have been seen from resonances 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 $M1$ γ transitions of similar energy can differ considerably from the average value of 7 and in some cases can be very large.

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.

Previously measured capture γ-ray spectroscopy studies on p resonances give some indications of the feasibility of

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

E_γ (keV)	E_0 *p*-wave (eV)	I_γ^p (%)	E_0 *s*-wave (eV)	I_γ^s (%)
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
6760.8		0.21 ± 0.06		0.087 ± 0.002[a]
6803.5		0.35 ± 0.09		0.016 ± 0.002
6890.1		0.21 ± 0.06		Not observed
6760.8	107.6	0.68 ± 0.15	51.6	0.011 ± 0.002[a]
6590.5	125.1	2.2 ± 0.4	144.2	0.022 ± 0.005
6803.5	183.5	0.37 ± 0.06	202.6	0.003 ± 0.001
6309.3	259.9	0.22 ± 0.04	251.3	Not observed
6504.0		0.23 ± 0.04		0.020 ± 0.003
7190.0		0.93 ± 0.05		0.015 ± 0.003
6803.5	269.9	0.44 ± 0.08	251.3	Not observed
6890.1	422.5	1.7 ± 0.4	444.0	Not observed

[a]Close to the single escape line from the 7269.4 keV transition.

the class of experiments we are proposing. To explore the potential for parity violation studies using the (n,γ) reaction, we consider the example of $E1$ and $M1$ γ rays from neutron capture on ^{107}Ag, which have been studied at Geel [11]. Gamma rays from several *p* resonances in the energy region of interest for PNC asymmetries [12] were studied. The emphasis in these experiments was on measurements of low-energy γ transitions, and thin samples were used to avoid absorption of low-energy γ rays from the sample itself. This meant that data in the high-energy region of the γ 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 [13]. In Table I the absolute intensities of high-energy transitions from eight *p*-wave resonances in the $p+{}^{107}$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 γ 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 I, 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 $\Gamma_p^\gamma/\Gamma_s^\gamma$ ratio cannot be determined. Nonetheless, it is clear from Table I that the requirement for an enhanced PNC asymmetry A_L^γ—namely, that $\Gamma_p^\gamma/\Gamma_s^\gamma \geqslant 1$—is met. Then detailed knowledge of the partial gamma widths is not necessary to extract a value of M^2 from a set of measurements of $A_L^{\gamma_i}$.

We note that several other nuclei have been studied, and, in particular, similar results to the ones presented have been obtained for ^{232}Th [14], proving that a measurement with a radioactive target is possible.

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,γ) 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. A measurement of this correlation in total neutron capture cross sections have found asymmetries A_L^γ of the order of 10%. We emphasize that this asymmetry can be measured in the (n,γ) reaction for several individual γ transitions from the same *p*-wave resonance. Partial neutron capture measurements would allow high-precision measurements of $\langle V_{PNC}\rangle$ and would provide an independent probe of important theoretical issues raised by observations and analyses of the sign problem in ^{232}h.

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