Nearby Doorway States, Parity Doublets, and Parity Mixing in Compound Nuclear States

N. Auerbach,[1] J. D. Bowman,[2] and V. Spevak[1]
[1]*School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel*
[2]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
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We discuss the implications of a doorway state model for parity mixing in compound nuclear states. We argue that in order to explain the tendency of parity violating asymmetries measured in ^{233}Th to have a common sign, doorway states that contribute to parity mixing must be found in the same energy neighborhood of the measured resonance. The work concentrates on novel nuclear structure input, namely, that in the region of interest (^{233}Th) nuclei exhibit octupole deformations which leads to the existence of nearby parity doublets. These parity doublets are then used as doorway states in a model for parity mixing.

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Recent experiments on parity violation in compound nuclear (CN) states [1,2] are providing new information on the parity nonconserving (PNC) interaction. The experimental results for ^{232}Th showed that measured PNC asymmetries fluctuated about nonzero average, in contradiction to the purely random behavior expected on the basis of the statistical model of the CN. The understanding of PNC phenomena challenges theory to treat simultaneously the chaotic and regular aspects of the CN system. A number of attempts were made to explain the new results in the framework of statistical models [3] or in models that combine nuclear dynamics with the statistical aspects [4,5]. Among the latter the doorway state approach was used in several theoretical works [4,5]. In Ref. [4] the spin-dipole (SD) resonance was used as the doorway to describe the PNC spreading width of the compound resonances. Later the same model was applied [6] in the calculation of the average longitudinal asymmetry. In Ref. [5] the $s_{1/2}$ and $p_{1/2}$ single-particle states were used as the doorway states in an attempt to explain the constancy of signs. The common feature of these models is that they deal with distant doorways and involve only the one-body part of the PNC interaction. The term "distant doorways" refers to the fact that the position of the doorways is removed by $1\hbar\omega \sim 7$ MeV from the CN resonances under consideration. The model in Ref. [4] which involved the collective effects of the spin-dipole resonance was able to account for the PNC spreading width when a reasonable [7] value for the one-body PNC matrix element was used. However, when the same size matrix element was used, the average asymmetry was 2 orders of magnitude smaller than measured. Recently more extensive theoretical investigations characterized several terms that could contribute to PNC asymmetries in the CN [8,9]. However, the new terms were not large enough to explain the large nonfluctuating asymmetry.

The quantity measured in the experiments with polarized epithermal neutrons is the longitudinal asymmetry

$$P(E_r) = \frac{\sigma^+(E_r) - \sigma^-(E_r)}{\sigma^+(E_r) + \sigma^-(E_r)}, \qquad (1)$$

where σ^+, σ^- are the resonance part of the total cross sections for neutrons with positive and negative helicities, respectively. The scattering is to a compound resonance $|r\rangle$ at energy E_r, carrying the quantum numbers $J = \frac{1}{2}^-$. We will refer to these resonances as $p_{1/2}$. The leading term of the asymmetry P can be written [6,9]

$$P(E_r) = -2\sum_s \frac{\langle s|V^{\rm PNC}|r\rangle}{E_r - E_s}\frac{\gamma_s}{\gamma_r}, \qquad (2)$$

where γ_r and γ_s denote the escape amplitudes from resonances $|r\rangle$ and $|s\rangle$ due to the strong interaction force $\gamma_r = \langle\Phi_p^{(+)}|H|r\rangle, \gamma_s = \langle\Phi_s^{(-)}|H|s\rangle$, where $\Phi_p^{(+)}$ and $\Phi_s^{(-)}$ denote the continuum p- and s-wave functions in the elastic channels. The sum in Eq. (2) extends in principle over all states $|s\rangle$ that have the quantum numbers $J = \frac{1}{2}^+$. To reduce the sum in the equation one often introduces the doorway state approximation [10,11]. One seeks a subspace of states $|s\rangle$, denoted by $|d\rangle$, such that the coupling between these states and the states $|r\rangle - \langle r|V^{\rm PNC}|d\rangle$ is sizable or that the coupling between $|d\rangle$ and the continuum is strong or that both conditions are fulfilled so that when the sum in Eq. (2) is replaced by the partial sum over states $|d\rangle$ the result will be a good approximation to Eq. (2). In a formal treatment [9–11] one divides the space of states $|s\rangle$ into $\{s\} = \{d\} + \{s'\}$. Assuming that the signs of the matrix elements $\langle r|V^{\rm PNC}|s'\rangle$ are randomly distributed one derives [9–11] the following expression:

$$P(E_r) \simeq -2\sum_d \frac{(E_r - E_d)\langle d|V^{\rm PNC}|r\rangle\gamma_d}{[(E_r - E_d)^2 + \Gamma_d^2/4]\gamma_r}, \qquad (3)$$

where γ_d is the escape amplitude of the doorway. Here Γ_d is the width of the doorway resulting from the coupling of $|d\rangle$ to the states $|s'\rangle$.

The PNC spreading width in the doorway approximation is given by [4]

$$\Gamma_r^{\downarrow\rm PNC} = \sum_d \frac{|\langle r|V^{\rm PNC}|d\rangle|^2}{(E_d - E_r)^2 + \Gamma_d^2/4}\Gamma_d^{\downarrow}, \qquad (4)$$

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where $\Gamma_d^{\downarrow}$ is the spreading width of the doorway.

In the analysis of the recent class of experiments two basic quantities are determined [1,2]. Taking the ensemble of states $|r\rangle$ one determines the average asymmetry $\overline{P}$; the fluctuating part of the measured asymmetries yields the PNC spreading width in a given nucleus. In ^{233}Th the analysis [2] yields for $\Gamma_r^{\downarrow PNC} \simeq 7.4 \times 10^{-7}$ eV and $\overline{P} \simeq (8 \pm 6)\%$. Equations (3) and (4) will be the basis of our discussion of the above two quantities. Let us first apply these equations to the case of "distant" doorway states. This was already the subject of study in Refs. [5] and [9], and we repeat this case in order to emphasize the difficulty one faces. Consider a one-body PNC potential of the form [12]

$$V^{\mathrm{PNC}} = \epsilon 10^{-7} \tfrac{1}{2} \sum_i \{f(r_i), \boldsymbol{\sigma}_i \cdot \boldsymbol{p}_i c\}, \tag{5}$$

where $f(r)$ is some function of the distance r and the curly brackets denote the anticommutation operation. For this potential the doorway that will couple strongly to the state $|r\rangle$ is the giant spin-dipole resonance (see Refs. [4,9]). The energy centroid of the spin-dipole resonance built on $|r\rangle$ is in ^{233}Th about 7 MeV above E_0. The width of the spin dipole is several MeV, and for the sake of an estimate let us take $\Gamma_{\mathrm{SD}}^{\downarrow} = 3$ MeV. (In our estimates we do not distinguish between the total Γ_d and spreading $\Gamma_d^{\downarrow}$ widths since the two are numerically not very different in reality for the cases we consider in this work.) In Refs. [6,9] the ratio of the escape amplitudes in Eq. (3) was shown to be

$$\frac{\gamma_{\mathrm{SD}}}{\gamma_r} \simeq \frac{1}{\sqrt{N}} \frac{\sqrt{3}}{kR} \simeq \frac{1}{\sqrt{N}} \times 10^3, \tag{6}$$

where $\sqrt{3}/kR$ is the ratio of penetrabilities and $N \sim 100$ is the number of particle-hole excitations that make up the collective spin dipole in ^{232}Th. Using Eq. (3) and the value for $\overline{P}$ of 8% and the above values for the width and energy of the SD doorway we find

$$\langle r|V^{\mathrm{PNC}}|\mathrm{SD}\rangle = 3000 \text{ eV}. \tag{7}$$

If we now use Eq. (4) to estimate the collective PNC matrix element with the above values for E_d and $\Gamma_d^{\downarrow}$, we find that $\langle r|V^{\mathrm{PNC}}|\mathrm{SD}\rangle = 3$ eV. There is a discrepancy of *3 orders of magnitude* with the value obtained in Eq. (7).

This leads us to the conclusion that one must go beyond the idea of distant doorway states and address the question of the role of nearby doorway states. Let us consider the following physical scenario: The compound state, which shows up in experiment as parity mixed, is close to a doorway so that the difference $|E_r - E_d| < \Gamma_d$ and that $\Gamma_d \simeq 100$ eV. Let us take for the sake of the estimate the value of $|E_r - E_d| = \Gamma_d/2$. Let us also assume that the ratio γ_d/γ_r is as before 10^3 due to the penetrability effect. Using again Eq. (3) we find for the PNC matrix element the value $\langle r|V^{\mathrm{PNC}}|d\rangle = 4 \times 10^{-3}$ eV, while then using Eq. (4) we estimate for this matrix element the value $\langle r|V^{\mathrm{PNC}}|d\rangle = 6 \times 10^{-3}$ eV. The two numbers are not contradictory as they were in the previous distant doorway case.

Let us now develop this idea further. In various reactions with low energy protrons or neutrons and with good resolution one observes in the excitation functions structures that have a width Γ_d that is intermediate between the single-particle $\Gamma_{\mathrm{s.p.}}$ and the compound width Γ_r, $\Gamma_{\mathrm{s.d.}} \gg \Gamma_d \gg \Gamma_r$ [11,13]. These intermediate resonances are usually nonoverlapping, and their spacings D_d are such that $D_{\mathrm{s.p.}} \gg D_d > D_r$.

In heavy nuclei in the vicinity of $A = 240$ intermediate structure was seen and studied extensively. The most striking and most intriguing example is the intermediate structure observed in neutron-induced fission (n,f). The cross section seen in these reactions shows groupings of compound states that are enhanced. The width of each such enhanced bump is about $\Gamma_d = 200$ eV, and the bumps are spaced about $D_d = 700$ eV. A very elegant explanation of this behavior of the (n,f) excitation function was given in terms of a double hump fission barrier [14].

Let us now use this information about the intermediate structure to consider some models for parity violation in these heavy nuclei. We first consider a model which connects to the observation of intermediate structure in the (n,f) reaction. The fact that the (n,f) process shows intermediate structure at some excitation energies indicates that the mixing is enhanced for some positive parity compound states $|q^+\rangle$ that are in the vicinity of the fissioning positive parity states $|f^+\rangle$.

The two-body effective PNC interaction derived using the meson-exchange models [7] and the two-body nuclear force have both similar ranges. We therefore assume that the strong interaction matrix element that couples $|f^+\rangle$ and $|q^+\rangle$, $\langle f^+|H|q^+\rangle$, and the weak matrix element $\langle r|V^{\mathrm{PNC}}|f^+\rangle$ are related.

One can write

$$T = \sum_r \frac{\langle\Phi_s^{(-)}|H|f^+\rangle\langle f^+|V^{\mathrm{PNC}}|r\rangle\langle r|H|\Phi_p^{(+)}\rangle}{(E - E_r + i\Gamma_r/2)(E - E_{f^+} + i\Gamma_{f^+}/2)}, \tag{8}$$

which is the PNC T matrix for neutron scattering in the doorway state approximation [9] with the doorway being the fission state $|f^+\rangle$. The corresponding asymmetry is then

$$P(E_r) = -2 \frac{(E_r - E_{f^+})\langle\Phi_s^{(-)}|H|f^+\rangle\langle f^+|V^{\mathrm{PNC}}|r\rangle}{\langle\Phi_p^{(+)}|H|r\rangle[(E_r - E_{f^+})^2 + \frac{1}{4}\Gamma_{f^+}^2]}. \tag{9}$$

The enhancements observed in the (n,f) reaction will also occur in the asymmetry given in Eq. (9) if the compound state $|r\rangle$ is in the vicinity of the doorway $|f^+\rangle$.

It is remarkable that in ^{233}Th (as well as in ^{231}Th) one finds [14–16] that the energy potential as a function of deformation is triple humped. It has been shown

[15] that the existence of the third minimum in the potential is related to the appearance of *pearlike octupole deformations* in the body frame of reference. This spontaneous breaking of reflection symmetry implies the existence of nearby (a few tens of keV apart) parity doublets [17–19]. In fact, at somewhat higher energies than considered here such doublets were observed in ^{233}Th in the (n,f) experiments [16]. It is worth mentioning that the states in the third minima belong to the class of hyperdeformed states with large quadrupole and octupole deformations [15,20].

Consider now such a $I = \frac{1}{2}^{\pm}$ doublet denoted by $|f^{\pm}\rangle$. The energy difference $|E_{f^+} - E_{f^-}|$ is equal to a few tens of keV, which is, of course, small but larger than $|E_r - E_{f^+}|$ or Γ_{f^+}. Let us now single out the $|f^-\rangle$ component in the wave function of $|r\rangle$,

$$|r\rangle = a_{rf^-}|f^-\rangle + |r'\rangle. \tag{10}$$

Then

$$\langle f^+|V^{\mathrm{PNC}}|r\rangle \simeq a_{rf^-}\langle f^+|V^{\mathrm{PNC}}|f^-\rangle. \tag{11}$$

We drop the contribution of $|r'\rangle$ to the matrix element in the above equation (i) because in view of the (n,f) experimental results the coupling of $|r\rangle$ to $|f^-\rangle$ should dominate, meaning that a_{rf^-} is relatively large and (ii) because of the close relation between $|f^+\rangle$ and $|f^-\rangle$ the PNC matrix element should also be relatively large. Substituting Eq. (11) into Eq. (9) we find

$$P = -2\frac{\langle f^+|V^{\mathrm{PNC}}|f^-\rangle(E_r - E_{f^+})\langle\Phi_s^{(-)}|H|f^+\rangle a_{rf^-}}{[(E_r - E_{f^+})^2 + \frac{1}{4}\Gamma_{f^+}^2]\langle\Phi_p^{(+)}|H|r\rangle}. \tag{12}$$

In order to evaluate the average part of $P(E_r)$ let us proceed with this model and use Eq. (10) to estimate $\langle\Phi_p^{(+)}|H|r\rangle$. Recognizing as before that the component of $|f^-\rangle$ in $|r\rangle$ is relatively large and that $|f^-\rangle$ connects to the exit channel as the (n,f) experiments show we may write

$$\langle\Phi_p^{(+)}|H|r\rangle \simeq a_{rf^-}\langle\Phi_p^{(+)}|H|f^-\rangle. \tag{13}$$

Substituting this into Eq. (12) we find

$$P(E_r) = -2\frac{\langle f^+|V^{\mathrm{PNC}}|f^-\rangle(E_r - E_{f^+})\langle\Phi_s^{(-)}|H|f^+\rangle}{[(E_r - E_{f^+})^2 + \frac{1}{4}\Gamma_{f^+}^2]\langle\Phi_p^{(+)}|H|f^-\rangle}. \tag{14}$$

We see that except for the energy difference in the numerator the sign of P is independent of $|r\rangle$ and is fixed. Also, within a limited range of E_r the value of $P(E_r)$ will not change much. If the compound states $|r\rangle$ observed in experiment are located on one side of E_{f^+}, the asymmetries P will have the same sign. A change in sign should occur when the energies E_r cross E_{f^+}. This is similar to the circumstances that occur in isobaric analog resonances [11,13]. It would be of considerable interest to extend the measurements of $\overline{P}$ in ^{233}Th to somewhat higher energies ($E_n > 500$ eV) and see whether the sign of the asymmetry is reversed for resonances that can be found at these higher energies. We should stress that these properties are quite general and independent on the particular nature of the doorways involved. (See also Refs. [6] and [9].)

Realizing the fact that we deal with parity doublets having similar structure we take the ratio of the two escape amplitudes from $|f^+\rangle$ and $|f^-\rangle$ to depend only on the penetrability factor which is about 10^3. Taking from the experiment [2] the value $\overline{P} \simeq 8 \times 10^{-2}$ and using $|E_r - E_{f^+}| = \Gamma_{f^+}/2$ we derive from Eq. (14)

$$\frac{\langle f^+|V^{\mathrm{PNC}}|f^-\rangle}{\Gamma_{f^+}} \simeq 4 \times 10^{-5}. \tag{15}$$

For $\Gamma_{f^+} \simeq 200$ eV the PNC matrix element is $|\langle f^+|V^{\mathrm{PNC}}|f^-\rangle| \simeq 10^{-2}$ eV. This is not an unreasonable value for such a matrix element. In order to write down an expression for the above PNC matrix element we use the formalism of Ref. [21] to write the wave functions of the parity doublets. We consider an odd-mass nucleus. Let us denote by χ_0^+ and χ_0^- the wave functions of the intrinsic core states on which the two opposite parity $K = 0$ core bands are built. Denoting the odd-particle opposite parity states as ϕ_K^+ and ϕ_K^- the wave functions $|f^+\rangle$ and $|f^-\rangle$ for a given K in this model are

$$\begin{aligned}
|f^+\rangle_{MK}^I &= [(2I+1)/16\pi^2]^{1/2} \\
&\quad\times\{a_+\chi_0^+[\phi_K^+D_{MK}^I(\omega) + (-1)^{I+K}\phi_{\overline{K}}^+D_{M-K}^I(\omega)] \\
&\quad+ b_+\chi_0^-[\phi_K^-D_{MK}^I(\omega) + (-1)^{I+K}\phi_{\overline{K}}^-D_{M-K}^I(\omega)]\},\\
|f^-\rangle_{MK}^I &= [(2I+1)/16\pi^2]^{1/2} \\
&\quad\times\{a_-\chi_0^+[\phi_K^-D_{MK}^I(\omega) - (-1)^{I+K}\phi_{\overline{K}}^-D_{M-K}^I(\omega)] \\
&\quad+ b_-\chi_0^-[\phi_K^+D_{MK}^I(\omega) - (-1)^{I+K}\phi_{\overline{K}}^+D_{M-K}^I(\omega)]\},
\end{aligned} \tag{16}$$

where D_{MK}^I denote the Wigner rotational matrix and $\overline{K}$ indicates the time reversed state. Simple algebra leads to the following expression for the PNC matric element:

$$\langle f_{MK}^{+I}|V^{\mathrm{PNC}}|f_{MK}^{-I}\rangle = (a_+a_- - b_+b_-)\langle\phi_K^+|V^{\mathrm{PNC}}|\phi_K^-\rangle. \tag{17}$$

Finite matrix elements are obtained when there is an energy splitting between members of the doublet. The matrix element in Eq. (17) was calculated using the PNC interaction of Eq. (5) and wave functions calculated in a Nilsson potential for a deformation corresponding to the third minimum of ^{233}Th [15]. Using a value for ϵ that gives a single-particle PNC matrix element of the size of 3 eV we obtain here PNC matrix elements that range typically between 10^{-2} and 10^{-3} eV. This is in the range of the estimate given in Eq. (15). We should remark that using the model in Ref. [21] we calculate the corresponding energy splitting between $|f^+\rangle$ and $|f^-\rangle$ to be in the range of 1–40 keV in agreement with the measured ones [16].

It is interesting to evaluate the contribution of the $|f^+\rangle$ doorway to the spreading width. Using the same parameter as in the estimate of Eq. (15) we obtain with the help of Eqs. (4) and (11) a spreading width of $\Gamma_r^{\downarrow \mathrm{PNC}} \simeq 6.4 \times 10^{-7} a_{rf^-}^2$ eV. Since $a_{rf^-}^2 < 1$, the contribution of the $|f^+\rangle$ doorway to the $\Gamma_r^{\downarrow \mathrm{PNC}}$ does not exceed the experimental spreading width. It should be understood, however, that the mechanism involving distant doorway states does contribute substantially to the PNC spreading width of $|r\rangle$ when a reasonable PNC matrix element is used [4,6].

We should mention that the breaking of reflection symmetry in the body frame of reference in actinides $A \leq 229$ is well established. These nuclei exhibit [22] (see Ref. [18]) at low energies octupole deformations $\beta_3 \simeq 0 - 0.12$, enhanced $E1$ transitions, and large dipole moments in the body frame of reference. Experiments that probe parity violation at the energies near the ground states of these nuclei could be designed [23].

We also note that effects of parity violation were observed in fission reactions induced by polarized neutrons [24,25]. A theoretical discussion of this phenomenon was presented some years ago [25] in which the notion of octupole deformations and parity doublets was invoked. The connection between PNC effects in the (n,f) reactions and the PNC experiments discussed in the present work should therefore not be overlooked. The experimental study of parity violation in the $^{232}\mathrm{Th}(n,f)$ reaction should shed additional light on the role of shape isomerism played in parity mixing in these nuclei.

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