On-resonance deformation effect measurements: A probe of order within chaos in the nucleus

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The statistics of on-resonance measurements of the deformation effect cross section σ_{02} in unpolarized neutron transmission through an aligned ^{165}Ho target is discussed. Under the standard Porter-Thomas assumption about reduced partial width amplitudes, the sign of σ_{02} is random at s-wave resonances with d-wave admixtures. Motivated by the observation of sign correlations in epithermal parity-violation studies, conditions under which a doorway state will give rise to σ_{02}'s of nonrandom sign are identified. Oblate shape isomers lying at excitation energies in the isolated resonance regime could meet these conditions. [S0556-2813(98)00602-5]

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I. INTRODUCTION

The availability of polarized neutron beams and polarized or aligned nuclear targets over the last decade or so has opened new areas of fundamental investigation in neutron physics. Novel transmission tests of space-time symmetries [1] have attracted much attention [2] because of the enormous enhancements predicted [3] and observed [4], but other experiments are of interest.

Neutron transmission studies with an unpolarized beam and an aligned target can be used to study deformation effect cross sections [5]. In the isolated resonance regime, deformation effect cross sections permit the identification of d-wave admixtures in (predominantly) s-wave resonances [6] which are important for the implementation of the on-resonance five-fold correlation test of time reversal [7]. Through its dependence (for on-resonance measurements) on the interference between different neutron partial width amplitudes of a resonance, the deformation effect can also be used to look for correlations in the signs of these amplitudes.

Sign correlations are not expected in the standard reaction models for neutron-induced reactions in the isolated resonance regime. However, the huge volume of data on which these models are based derives from experiments which do not isolate the same combinations of partial width amplitudes as reactions with polarized or aligned participants. Indeed, significant sign correlations which conventional approaches are unable to explain [8–10] have been observed in epithermal polarized neutron transmission studies of parity violation with a ^{232}Th target [11].

It would seem that the sign correlation in parity-violation data can be accounted for as an intermediate structure effect involving hyperdeformed collective nuclear degrees of freedom related to the fission path of ^{233}Th [12]. Since epithermal neutrons probe the nuclear many-body system in what is thought of as the quantum equivalent of a fully developed state of chaos (the compound nucleus), it is not usual to consider correlated collective degrees of freedom relevant [13]. However, the fragmentation of a hyperdeformed fission doorway (unlike a generic collective doorway) is quenched by the presence of fission barriers, making it conceivable that the associated intermediate structure could be visible.

It is tempting to interpret an intermediate structure of this kind as a manifestation at the quantum level of an island of regularity in the otherwise chaotic sea of the phase portrait of a chaotic system. If this is the case, then, since such islands of regularity are generic, it seems reasonable to suppose that there should be other instances of phenomena near to the neutron threshold where collectivity leaves its trace. In fact, intermediate structure in the fission of some actinide isotopes is a well-established example [14]. Measurements of on-resonance deformation effect cross sections are possibly another way to investigate this issue experimentally.

Statistically significant evidence of a sign correlation would be the observation at ten or more consecutive s-wave resonances of deformation effect cross sections (which can be of either sign) of the same sign: In the absence of any correlation in the sign of amplitudes, the probability of observing deformation effect cross sections of the same sign at ten (or more) consecutive resonances would be $1/2^9$ (or less). In neutron transmission experiments with a ^{165}Ho target (which is strongly deformed and readily aligned cryogenically), it would be possible to conduct a systematic high-resolution scan for such clusters of resonances over an interval spanning 1000 or so resonances (the average spacing of s-wave resonances is about 5 eV and isolated resonances have been identified up to more than 10 keV).

In this paper, we determine the statistics of on-resonance deformation effect cross sections when the standard distribution for reduced partial width amplitudes is adopted and only the resonant contribution to the S matrix is taken into account (Secs. II and III). We identify the fragmentation properties of doorway states which would be responsible for a nonrandomness in the sign of deformation effect cross sections at s-wave resonances (Sec. IV). With experiments with the aligned ^{165}Ho target constructed at TUNL [5] in mind, we show that low-lying *oblate* collective excitations of a nucleus, which in its ground state is prolate (like ^{166}Ho), could possess these fragmentation properties (Sec. V). We discuss briefly the experimental feasibility of using neutron transmission measurements with ^{165}Ho to observe a sign correlation in deformation effect cross sections and comment on the implications of our work for spectroscopy close to neutron threshold (Sec. VI).

II. ISOLATED RESONANCE DEFORMATION EFFECT MEASUREMENTS

We consider an unpolarized neutron beam of momentum $\boldsymbol{p}$ incident on a aligned target of nuclei with spin I (below, $\hat{\boldsymbol{I}}$ denotes the unit vector specifying the orientation of the aligned target). Deformation effect cross sections σ_{0K}, which (in the notation of [15]) are related to the total cross section σ_{tot} observed in neutron transmission with an unpolarized beam by [the $\tilde{t}_{K0}(I)$'s are statistical tensor elements describing the alignment state of the target]

$$\sigma_{\mathrm{tot}}=\sum_{K\ \mathrm{even}}\sigma_{0K}\tilde{t}_{K0}(I),$$

can be identified through their distinctive dependence on $\hat{\boldsymbol{I}}\cdot\hat{\mathbf{p}}$ [$\sigma_{0K}\propto P_K(\hat{\boldsymbol{I}}\cdot\hat{\mathbf{p}})$, P_K being the Legendre polynomial of order K]. For epithermal neutrons, the dominant deformation effect cross section is σ_{02}, which, in this regime, is associated with transitions between s and d partial waves and p partial waves (barrier penetrabilities suppress contributions from higher partial waves and the higher-order deformation cross sections σ_{0K}, $K\geqslant 4$). Order of magnitude estimates [6] indicate that the ratio of cross sections σ_{02}/σ_{00} can be used in the absence of spin-parity assignments to distinguish measurements at p-wave resonances from measurements at weak s-wave resonances: $\sigma_{02}/\sigma_{00}\sim 1$ ($\ll 1$) for p-wave (weak s-wave) resonances.

In the simplest reaction model for an on-resonance measurement of the deformation cross section σ_{02}, only the contribution to the S matrix of the resonance at which the measurement is performed is taken into account. If E_J and Γ_J denote the energy and total width, respectively, of this resonance, then, for $E\simeq E_J$,

$$\sigma_{02}=2\pi\lambda\!\!\!^{-2}\hat{I}P_2(\hat{\boldsymbol{I}}\cdot\hat{\boldsymbol{p}})\frac{g_J\Gamma_J}{(E-E_J)^2+\Gamma_J^2/4}C(J),$$

where the statistical weight $g_J=(2J+1)/[2(2I+1)]$ and, in terms of the neutron partial width amplitudes γ_{nlj} of the resonance,

$$C(J)=C_{sd}$$
$$=-2W(J\,\tfrac{1}{2}\,I2;I\,\tfrac{3}{2})\gamma_{n0(1/2)}\gamma_{n2(3/2)}$$
$$+\sqrt{6}W(J\,\tfrac{1}{2}\,I2;I\,\tfrac{5}{2})\gamma_{n0(1/2)}\gamma_{n2(5/2)}$$

for measurements at an s-wave resonance (with a d-wave admixture) and

$$C(J)=C_{pp}=-2W(J\,\tfrac{1}{2}\,I2;I\,\tfrac{3}{2})\gamma_{n1(1/2)}\gamma_{n1(3/2)}$$
$$-W(J\,\tfrac{3}{2}\,I2;I\,\tfrac{3}{2})\big(\gamma_{n1(3/2)}\big)^2$$

for measurements at a p-wave resonance, respectively [6].

III. STANDARD ANALYSIS OF ON-RESONANCE MEASUREMENTS

For measurements at s-wave resonances, we anticipate that there will be no spectroscopic data to constrain the partial width amplitudes γ_{n2j} [even the d-wave neutron partial width $\Gamma_{n2}=(\gamma_{n2(3/2)})^2+(\gamma_{n2(5/2)})^2$ of a predominantly s-wave resonance will be unobservable], but one can take advantage of the fact that s-wave partial widths $\Gamma_{n0(1/2)}$ will be measurable to extract values of

$$D_s\equiv g_JC_{sd}/\sqrt{\Gamma_{n0(1/2)}P_d(E_J)}$$
$$=-g_J\sum_{j=3/2,5/2}(-1)^{(2j+1)/2}\hat{j}W(J\,\tfrac{1}{2}\,I2;Ij)\gamma_{n2j}^{(0)},$$

where $P_d(E_J)$ is the d-wave penetrability factor required to convert d-wave partial widths Γ_{n2j} to reduced partial widths $\Gamma_{n2j}^{(0)}$ (we assume phases are chosen so that $\gamma_{n0(1/2)}^{(0)}=\sqrt{\Gamma_{n0(1/2)}^{(0)}}$). Elimination of the dependence on s-wave partial amplitudes $\gamma_{n0(1/2)}$ guarantees that the fluctuations in D_s are far simpler than those of C_{sd} [division by $P_d(E_J)$ ensures that D_s is ergodic and, hence, a suitable candidate for modeling within the ensemble formulation of statistical nuclear theory [16]].

The standard (Porter-Thomas) assumption about the reduced partial width amplitudes $\gamma_{n2(3/2)}^{(0)}$ and $\gamma_{n2(5/2)}^{(0)}$ of a set of s-wave resonances of a given spin J would be that they are sampled from independent Gaussian distributions of zero mean and variances $\langle\Gamma_{n2(3/2)}^{(0)}\rangle$ and $\langle\Gamma_{n2(5/2)}^{(0)}\rangle$, respectively, where $\langle\Gamma_{n2j}^{(0)}\rangle$ denotes the running energy average of the reduced partial widths $\Gamma_{n2j}^{(0)}$ of the s-wave resonances (this average can, in principle, be estimated using optical model strength functions). Under this assumption, the prediction for measurements of σ_{02} restricted to resonances of a given spin J is that the values of D_s are drawn from a Gaussian distribution of zero mean and variance

$$v_J^2=g_J^2\sum_j(2j+1)[W(J\,\tfrac{1}{2}\,I2;Ij)]^2\langle\Gamma_{n2j}^{(0)}\rangle$$
$$\simeq g_J^2\langle\Gamma_{n2j}^{(0)}\rangle/(2I+1)$$

if $\langle\Gamma_{nlj}^{(0)}\rangle$ is approximately independent of j. In practice, the spins of the s-wave resonances are unlikely to be identified, in which case the measured values of D_s have probability density

$$p_s(x)=\sum_{J=I-1/2,I+1/2}\frac{p_J}{\sqrt{2\pi v_J^2}}\exp\left(-\frac{x^2}{2v_J^2}\right),$$

where p_J is the probability an s-wave resonance has spin J [the ratio $p_{I+1/2}/p_{I-1/2}\simeq(1+1/I)\exp[-(2I+1)/(4\sigma^2)]$, where σ is the appropriate level-density spin cut off factor).

Fluctuations in σ_{02} for measurements at p-wave resonances are more difficult to characterize for arbitrary averages $\langle\Gamma_{n1j}^{(0)}\rangle$. However, in the case that $\langle\Gamma_{n1(1/2)}^{(0)}\rangle=\langle\Gamma_{n1(3/2)}^{(0)}\rangle$ (this equality should hold to about 10% or so), a simple result for

$$D_p \equiv g_J C_{pp}/\Gamma_{n1}$$
$$= -\frac{g_J}{\Gamma_{1n}^{(0)}}[2W(J\,\tfrac{1}{2}\,I2;I\,\tfrac{3}{2})\,\gamma_{n1(1/2)}^{(0)}\,\gamma_{n1(3/2)}^{(0)}$$
$$+W(J\,\tfrac{3}{2}\,I2;I\,\tfrac{3}{2})(\gamma_{n1(3/2)}^{(0)})^2]$$

applies [we assume that the p-wave partial width $\Gamma_{n1}(=\Gamma_{n1(1/2)}+\Gamma_{n1(3/2)})$ is known from measurements of σ_{00}]. In terms of the polar parametrization $\xi_+=\sqrt{\Gamma_{n1}^{(0)}}\cos\varphi$ and $\xi_-=\sqrt{\Gamma_{n1}^{(0)}}\sin\varphi$ of the combinations $\xi_\pm$ of reduced partial amplitudes $\gamma_{n1j}^{(0)}$ which diagonalize the quadratic form in D_p above,

$$D_p = a_J - b_J\cos 2\varphi,$$

where $a_J=-g_J W(J\tfrac{3}{2}I2;I\tfrac{3}{2})/2$ and

$$b_J = g_J\sqrt{[W(J\,\tfrac{1}{2}\,I2;I\,\tfrac{3}{2})^2+\tfrac{1}{4}[W(J\,\tfrac{3}{2}\,I2;I\,\tfrac{3}{2})^2}.$$

Under the Porter-Thomas assumption for reduced partial amplitudes, the probability distribution for φ is uniform if $\langle\Gamma_{n1(1/2)}^{(0)}\rangle=\langle\Gamma_{n1(3/2)}^{(0)}\rangle$. [When $\langle\Gamma_{n1(1/2)}^{(0)}\rangle\neq\langle\Gamma_{n1(3/2)}^{(0)}\rangle$, not only is the distribution of φ non-uniform, but it also depends on the value of the reduced partial width $\Gamma_{1n}^{(0)}$ of the resonance at which a measurement is made, meaning that D_p is no longer ergodic.] The corresponding prediction for the measured values of D_{p} is that they have probability density

$$p_p(x)=\frac{1}{\pi}\sum_J p_J\frac{b_J}{\sqrt{b_J^2+(x-a_J)^2}}\Theta(|b_J|-|x-a_J|),$$

where p_J now denotes the probability a p-wave resonance has spin J and Θ is the Heaviside step function.

Superficially, it would appear that there is a striking difference between the predicted fluctuation properties of D_s and D_p: The prediction for D_s is that it has zero mean and hence random sign, whereas D_p is predicted to have the nonzero mean

$$\langle D_p\rangle=\sum_J p_J a_J\equiv\overline{a}.$$

However, the variance

$$\langle(D_p-\langle D_p\rangle)^2\rangle\geqslant\tfrac{1}{2}(\langle D_p\rangle)^2$$

since

$$\langle(D_p-\langle D_p\rangle)^2\rangle=\sum_J p_J(a_J-\overline{a})^2+\frac{1}{2}\sum_J p_J b_J^2$$
$$\geqslant\frac{1}{2}\sum_J p_J b_J^2\geqslant\frac{1}{2}\sum_J p_J a_J^2$$
$$=\frac{1}{2}\sum_J p_J(a_J-\overline{a})^2+\frac{1}{2}\overline{a}^2.$$

Furthermore, in the approximation (reasonable for the large I targets which can be readily aligned) that the probability p_J is the same for all four values of J relevant (namely, 0.25), $\langle D_p\rangle$ vanishes identically ($\Sigma_J a_J=0$). So the Porter-Thomas assumption about reduced amplitudes implies that it would, in practice, be difficult to discern that the sign of D_p is not random.

Below, we focus on deformation effect measurements at s-wave resonances because the default (Porter-Thomas) prediction for the sign of the effect is more clear-cut in this case.

IV. SCENARIO FOR SIGN CORRELATIONS

We consider the standard (formal) partition of the Hilbert space $\mathcal{H}$ into three orthogonal subspaces: $\mathcal{H}=\mathcal{P}+\mathcal{D}+\mathcal{Q}'$, where $\mathcal{P}$ contains the (prompt) open channels, $\mathcal{D}$ doorway states, and $\mathcal{Q}'$ more complex states [17]. We recall that an eigenstate $|\Phi_\mu\rangle$ of the nuclear Hamiltonian $\hat{H}$ in the space $\mathcal{Q}=\mathcal{D}+\mathcal{Q}'$ is identified as the progenitor of a compound nucleus resonance (coupling to $\mathcal{P}$ has to be included). In terms of $\hat{H}$, the partial width amplitudes of this resonance $\gamma_a=\sqrt{2\pi}\langle\Phi_\mu|\hat{H}|\chi_a^{(+)}\rangle$, where $\chi_a^{(+)}$ is the (distorted) incident wave function in channel a satisfying outgoing wave boundary conditions (evaluated at the energy of the resonance).

To show that there exists, at least in principle, a situation in which there is a correlation in the signs of deformation effect cross sections at different s wave resonances, we adopt, for simplicity, the *strong doorway assumption*, namely, that, in a first approximation, $\hat{H}$ couples states in $\mathcal{P}$ directly to states in $\mathcal{D}$ but not in $\mathcal{Q}'$. Then,

$$\gamma_a\approx\sqrt{2\pi}\sum_i\langle\psi_i^{(D)}|\hat{H}|\chi_a^{(+)}\rangle\langle\Phi_\mu|\psi_i^{(D)}\rangle,$$

where $\{|\psi_i^{(D)}\rangle\}$ is a physically appropriate basis for $\mathcal{D}$. Let us now suppose (in the spirit of Refs. [8,9,12] on the sign correlation for parity-violating transmission asymmetries) that, for one term in the sum over doorway states above, the overlap $\langle\Phi_\mu|\psi_i^{(D)}\rangle$ is unusually large [below we denote the corresponding state by $|\psi_D\rangle$ and its partial width amplitudes by $\gamma_a(D)\equiv\sqrt{2\pi}\langle\psi_D|\hat{H}|\chi_a^{(+)}\rangle$]. Retaining only this term in the partial width amplitudes appearing in the deformation cross section σ_{02}, we have, for measurements at s-wave resonances

$$C(J)\approx C^{\mathrm{corr}}\equiv C_{sd}(D)(\langle\Phi_\mu|\psi_D\rangle)^2,$$

with

$$C_{sd}(D)=-2W(J\,\tfrac{1}{2}\,I2;I\,\tfrac{3}{2})\,\gamma_{n0(1/2)}(D)\,\gamma_{n2(3/2)}(D)$$
$$+\sqrt{6}W(J\,\tfrac{1}{2}\,I2;I\,\tfrac{5}{2})\,\gamma_{n0(1/2)}(D)\,\gamma_{n2(5/2)}(D).$$

Observe that the sign of C^{corr} is determined by $C_{sd}(D)$, which, as it is related to a doorway state (namely, $|\psi_D\rangle$), will not change sign over a scale on the order of the separation between adjacent compound resonances. Thus, we can anticipate a sign correlation in deformation effect cross sections when there is a doorway state which has a large overlap with several of the progenitors $|\Phi_\mu\rangle$ of the s-wave resonances in its immediate vicinity. A doorway state with an atypically small spreading width $\Gamma^{\downarrow}$ of the order of a few tens of interresonance spacings or so ($\sim$100 eV for ^{166}Ho) would possess these features. The signature of such a doorway would be the occurrence of a cluster of ten or so consecutive resonances for which the deformation effect cross section has the same sign.

In a more quantitative discussion of a sign correlation of this type, it is appropriate to factor out the trivial energy dependence arising from the threshold behavior of the s- and d-wave penetrabilities (P_s and P_d, respectively) and introduce

$$D(J)=g_J C(J)/\sqrt{P_s(E_J)P_d(E_J)}.$$

In terms of the decomposition

$$\gamma_a^{(0)}=\gamma_a^{(0)}(D)\langle\Phi_\mu|\psi_D\rangle+\tilde{\gamma}_a^{(0)}$$

of reduced partial amplitudes $\gamma_a^{(0)}$ of a resonance, $D(J)$ will have a correlated part

$$D^{\mathrm{corr}}(J)=g_J C_{sd}^{(0)}(D)(\langle\Phi_\mu|\psi_D\rangle)^2$$

and a fluctuating part

$$D^{\mathrm{fl}}(J)=g_J\{\tilde{C}_{sd}^{(0)}(D)\langle\Phi_\mu|\psi_D\rangle+\tilde{C}_{sd}^{(0)}\},$$

where

$$\tilde{C}_{sd}^{(0)}(D)=\sum_{j=3/2,\,5/2}(-1)^{(2j+1)/2}\hat{j}W(J\tfrac{1}{2}I2;Ij)\times[\tilde{\gamma}_{n0(1/2)}^{(0)}\gamma_{n2j}^{(0)}(D)+\tilde{\gamma}_{n2j}^{(0)}\gamma_{n0(1/2)}^{(0)}(D)]$$

and, paralleling the definition of $C_{sd}(D)$, $C_{sd}^{(0)}$ and $\tilde{C}_{\mathrm{sd}}^{(0)}$ denote the combination of reduced partial widths obtained by replacing each partial width amplitude γ_a in C_{sd} by $\gamma_a^{(0)}(D)$ and $\tilde{\gamma}_a^{(0)}$, respectively.

For s-wave resonances in an interval which includes the doorway state $|\psi_D\rangle$ resonance energy and which is large in comparison to the average spacing d of the resonances but small in comparison to the width $\Gamma_D^{\downarrow}$ of the doorway, the average of values of $D(J)$,

$$\langle D(J)\rangle=\langle D_{\mathrm{corr}}(J)\rangle\approx p_J(D)g_J C_{sd}^{(0)}(D)S(D)_{|\max},$$

where $p_J(D)$ is the probability the s-wave resonances have the spin J of the doorway state and $S(D)_{|\max}$ denotes the maximum value of the strength function $S(D)$ of the doorway $|\psi_D\rangle$ [$S(D)$ is the local average of $(\langle\Phi_\mu|\psi_D\rangle)^2$].

For measurements in other intervals, $D^{\mathrm{corr}}(J)$ is negligible. Measured values of $D(J)$ have average zero and variance

$$\langle[D(J)]^2\rangle=\sum_J p_J v_J^2\left\langle\Gamma_{n0(1/2)}^{(0)}\right\rangle,$$

where p_J and v_J^2 were introduced above in connection with the distribution of D_s or, more precisely, the probability density

$$p_D(x)=\frac{1}{\pi}\sum_J\frac{p_J}{w_J}K_0(x/w_J),$$

where $w_J^2\equiv v_J^2\langle\Gamma_{n0(1/2)}^{(0)}\rangle$ and K_0 is a modified Bessel function (we adopt the notation of Ref. [18]).

V. CANDIDATE FOR A DOORWAY STATE

A feature of microscopic potential energy surface (PES) calculations for even-even nuclei (like ^{168}Yb and ^{170}Yb) adjacent to ^{166}Ho is the appearance of a secondary oblate minimum in addition to the well-developed principal prolate minimum [19]. Even allowing for configuration-dependent polarization by unpaired quasiparticles [20], the PES's for the odd-odd nucleus ^{166}Ho should not be too different from those of its even-even neighbors since these are amongst the most deformed nuclei in the rare earth region. Low-lying collective excitations in the oblate pocket of a ^{166}Ho PES, which should lie at excitation energies comparable with the neutron separation energy (in the PES's of neighbouring even-even nuclei, the oblate minimum is some 5–6 MeV higher than the prolate minimum), could possess the unusual properties demanded of doorway states responsible for a sign correlation in on-resonance deformation effect measurements. If there is a large barrier between the oblate and prolate minima like that found in the PES's of neighboring even-even nuclei, then the mixing of an oblate excitation into the high density of prolate-well excitations at this energy will be small except for states which are almost exactly degenerate with the oblate excitation. For these few states, the mixing will typically be substantial.

A. Identification of an oblate doorway $|\psi_D^{\mathrm{Ob}}\rangle$

In view of the considerations above, we take the partition of Hilbert space invoked in Sec. IV to include in the space of doorway states $\mathcal{D}$ the subspace $\mathcal{D}_{\mathrm{coll}}$ of quasistationary collective states found in the vicinity of the neutron separation energy. The success of recent generator coordinate method (GCM) studies in heavy nuclei of shape isomerism [21–24] suggests that, in principle, one could attempt to identify these collective states using the GCM with a microscopic two-body Hamiltonian and a basis set of constrained Hartree-Fock (HF)+BCS or, better still, Hartree-Fock-Bogoliubov (HFB) wave functions.

The GCM will automatically mix HF+BCS (or HFB) states $|\phi(q)\rangle$ of similar energy to approximate collective intrinsic states by a superposition of the form

$$\int f_n(q)|\phi(q)\rangle dq,$$

where q is a schematic notation for the variables needed to label the states $|\phi(q)\rangle$. We are interested in an oblate shape isomer with an intrinsic state for which the GCM weight function $f_n(q)$ is a rather diffuse function of q peaking for configurations in the oblate well but with a substantial tail in the prolate well. As GCM calculations confirm [21,24], such states will arise through the coupling of a collective oblate-well excitation $|\psi_{\mathrm{ob}}\rangle$ to collective prolate-well excitations $|\psi_{\mathrm{pr}}^{(i)}\rangle$ which happen to be almost degenerate with the oblate state. (The intrinsic states for $|\psi_{\mathrm{ob}}\rangle$ and $|\psi_{\mathrm{pr}}^{(i)}\rangle$, which prove a convenient basis below, could be generated within a GCM calculation by constructing eigenstates of the quadrupole operator in the space of GCM eigenstates [21].)

In discussing the fragmentation of our doorway $|\psi_D^{\rm ob}\rangle$, we shall suppose, for the sake of simplicity, that the state $|\psi_{\rm ob}\rangle$ couples strongly with only one prolate collective state $|\psi_{\rm pr}\rangle$. In addition, we include the coupling of these two states to the background of (prolate) $\mathcal{Q}'$-space eigenstates $|\Phi_s'\rangle$. In the basis comprising the states $|\psi_{\rm ob}\rangle$, $|\psi_{\rm pr}\rangle$, and $\{|\Phi_s'\rangle\}$, the Hamiltonian $\hat{H}$ has diagonal matrix elements

$$\langle\psi_{\rm Ob}|\hat{H}|\psi_{\rm ob}\rangle=E_{\rm ob}\,,\quad \langle\psi_{\rm pr}|\hat{H}|\psi_{\rm pr}\rangle=E_{\rm pr}\,,$$

$$\langle\Phi_s'|\hat{H}|\Phi_s'\rangle=E_s'\,,$$

and nonzero off-diagonal matrix elements

$$\langle\psi_{\rm ob}|\hat{H}|\psi_{\rm pr}\rangle=v=\langle\psi_{\rm pr}|\hat{H}|\psi_{\rm ob}\rangle,$$

$$\langle\psi_{\rm pr}|\hat{H}|\Phi_s'\rangle=V_s^{\rm pr}=\langle\Phi_s'|\hat{H}|\psi_{\rm pr}\rangle,$$

$$\langle\psi_{\rm ob}|\hat{H}|\Phi_s'\rangle=v_s^{\rm ob}=\langle\Phi_s'|\hat{H}|\psi_{\rm ob}\rangle.$$

Under the assumption that there is a sizable PES barrier separating prolate and oblate configurations, the $v_s^{\rm ob}$'s are many orders of magnitude less than the $V_s^{\rm pr}$'s. Similarly, v is much smaller than a typical nondiagonal matrix element between multiparticle states; for the fission isomers studied in [24], the analogous matrix element was found to be $\lesssim 1$ keV.

The basis adopted above has the advantage that the relative sizes of the matrix elements of the Hamiltonian are transparent. A basis which is more physically appropriate in as much as its members correspond more closely to excitations of the system comprises the $\mathcal{Q}'$-space eigenstates $\{|\Phi_s'\rangle\}$ and the eigenstates $|\psi_{\rm I}\rangle$ and $|\psi_{\rm II}\rangle$ of $\hat{H}$ in the truncated collective subspace spanned by $|\psi_{\rm ob}\rangle$ and $|\psi_{\rm pr}\rangle$. Exact diagonalization of $\hat{H}$ in the collective subspace yields ($E_{\rm I}$ and $E_{\rm II}$ denote the corresponding eigenenergies, $\Delta E\equiv E_{\rm ob}-E_{\rm pr}$)

$$|\psi_{\rm I}\rangle=\cos\,\theta|\psi_{\rm ob}\rangle+\sin\,\theta|\psi_{\rm pr}\rangle,$$

$$E_{\rm I}=\frac{E_{\rm pr}+E_{\rm ob}}{2}+\frac{\Delta E}{2}\sqrt{1+\left(\frac{2v}{\Delta E}\right)^2},$$

$$|\psi_{\rm II}\rangle=-\sin\,\theta|\psi_{\rm ob}\rangle+\cos\,\theta|\psi_{\rm pr}\rangle,$$

$$E_{\rm II}=\frac{E_{\rm pr}+E_{\rm ob}}{2}-\frac{\Delta E}{2}\sqrt{1+\left(\frac{2v}{\Delta E}\right)^2},$$

where $\tan 2\theta=2v/\Delta E$. In the problem at hand, we expect that $v\ll\Delta E$ (barring improbable almost exact degeneracies, $\Delta E>10$ keV), so that

$$E_{\rm I}=E_{\rm ob}+O(v^2/\Delta E),\quad E_{\rm II}=E_{\rm pr}+O(v^2/\Delta E)\,,$$

and $\theta\approx v/\Delta E(\ll 1)$.

We identify $|\psi_{\rm I}\rangle$ as the oblate doorway $|\psi_D^{\rm ob}\rangle$. The probability for the excitation in neutron resonance reactions of this doorway as opposed to $|\psi_{\rm ob}\rangle$ is enhanced by the small prolate admixture. (Although we have appealed to the results of GCM calculations above, our construction of $|\psi_I\rangle$ is formal and does not presuppose $|\psi_{\rm ob}\rangle$ and $|\psi_{\rm pr}\rangle$ to have been obtained within the GCM formalism. Any appropriate approximation scheme will suffice.)

B. Fragmentation of $|\psi_D^{\rm ob}\rangle$

The states $|\psi_{\rm I}\rangle$ and $|\psi_{\rm II}\rangle$ are coupled to the background of states $\{|\Phi_s'\rangle\}$ via matrix elements

$$\langle\psi_{\rm I}|\hat{H}|\Phi_s'\rangle=\cos\,\theta v_s^{\rm ob}+\sin\,\theta V_s^{\rm pr}\approx\frac{v}{\Delta E}V_s^{\rm pr}\,,$$

$$\langle\psi_{\rm II}|\hat{H}|\Phi_s'\rangle=-\sin\,\theta v_s^{\rm ob}+\cos\,\theta V_s^{\rm pr}\approx V_s^{\rm pr}.$$

The coupling of the prolate doorway $|\psi_{\rm II}\rangle$ to other prolate excitations is strong and any intermediate structure associated with it will be completely washed out. By contrast, although the oblate collective doorway $|\psi_{\rm I}\rangle$ is coupled to as many prolate-well excitations as $|\psi_{\rm II}\rangle$, the coupling is smaller by a global factor of $v/\Delta E$.

Because the coupling is weak, the standard discussion [25] of the fragmentation of a single (collective) state applies [26] to $|\psi_D^{\rm ob}\rangle$. Treating all prolate excitations including the collective state $|\psi_{\rm II}\rangle$ as background states, the spreading width of the oblate doorway

$$\Gamma_{\rm ob}^{\downarrow}\simeq\left(\frac{v}{\Delta E}\right)^2\Gamma_{\rm pr}^{\downarrow},$$

where $\Gamma_{\rm pr}^{\downarrow}$ is the spreading width of a typical prolate state. Hence, provided $v/\Delta E$ is small enough that $\Gamma_{\rm ob}^{\downarrow}\sim 10d$, where $d(\sim 10$ eV) is the average separation between s-wave resonances of a given spin, the state $|\psi_{\rm I}\rangle$ satisfies the criteria of Sec. IV for a doorway capable of giving rise to sign correlations in deformation effect cross-section measurements.

If $|\psi_{\rm ob}\rangle$ is assumed to couple to a few *collective* prolate-well states $|\psi_{\rm pr}^{(i)}\rangle$ instead of just one, then

$$\langle\psi_D^{\rm ob}|\hat{H}|\Phi_s'\rangle\approx\sum_i\frac{v_i}{E_{\rm ob}-E_{\rm pr}^{(i)}}\langle\psi_{\rm pr}^{(i)}|\hat{H}|\Phi_s'\rangle,$$

where $E_{\rm pr}^{(i)}=\langle\psi_{\rm pr}^{(i)}|\hat{H}|\psi_{\rm pr}^{(i)}\rangle$, $v_i=\langle\psi_{\rm ob}|\hat{H}|\psi_{\rm pr}^{(i)}\rangle$, and we assume each $v_i\ll E_{\rm ob}-E_{\rm pr}^{(i)}$ (so that first-order perturbation theory applies). Using the randomness of the sign of the matrix elements $\langle\psi_{\rm pr}^{(i)}|\hat{H}|\Phi_s'\rangle$, we now find that

$$\Gamma_{\rm ob}^{\downarrow}\simeq\left\{\sum_i\left(\frac{v_i}{E_{\rm ob}-E_{\rm pr}^{(i)}}\right)^2\right\}\Gamma_{\rm pr}^{\downarrow}.$$

The spreading width of the oblate doorway is larger but only by a factor of order unity (approximately, the number of states $|\psi_{\rm pr}^{(i)}\rangle$ to which $|\psi_{\rm ob}\rangle$ couples).

VI. CONCLUSIONS

Our work suggests that it would be worthwhile to use the aligned ^{165}Ho target constructed at TUNL to look for sign correlations in neutron transmission measurements of on-resonance deformation effect cross sections. Statistically significant sign correlations will be found if ^{166}Ho possesses an oblate collective 3^+ or 4^+ excitation which lies in the isolated resonance regime, the fragmentation of which is sufficiently quenched by an oblate-to-prolate shape transition barrier that its spreading width $\Gamma^{\downarrow} \sim 100$ eV. The systematics of potential energy surfaces of nuclei adjacent to ^{166}Ho suggest that such an oblate excitation could well be present. Hence, on-resonance deformation effect measurements would help to constrain the global features of potential energy surfaces in this part of the rare earth region.

We believe that, as a sign correlation in asymmetries measured in neutron transmission studies of parity violation has been seen, it should be experimentally feasible to find a sign correlation in deformation effect cross-section measurements with a ^{165}Ho target. High-resolution deformation effect cross-section measurements can be carried out over a wide range of energies, up to 10 keV or more. A systematic scan of 1000 or more s-wave resonances (as opposed to the 20 or so of the parity-violation work) is possible and a cluster of ten or more consecutive resonances with deformation effect cross sections of the same sign would stand out clearly.

Some of the considerations of this paper lend themselves to immediate generalization.

The scenario for sign correlations in σ_{20} we have explored amounts to the requirement that there be a doorway state which has an abnormally large overlap with several isolated resonances in its immediate vicinity. With hindsight it is obvious that such doorways *must* give rise to observable intermediate structure whatever the context (fission, depopulation of superdeformed states, neutron transmission, etc.). The need for fragmentation of this nature would also appear to be ubiquitous. For example, both the doorways (in the notation of [12], $|f^+\rangle$ and $|f^-\rangle$) invoked in the explanation of the sign correlation in ^{233}Th parity violation data presented in [12] are assumed to be fragmented in this way.

The above pattern of fragmentation will be found whenever a doorway state has a spreading width $\Gamma^{\downarrow}$ of the order of only a few tens of inter-resonance spacings. The mechanism we have considered for ensuring such unusually small fragmentation entails tunneling through a barrier in the collective potential energy surface. Barriers of this kind are associated with phenomena involving large amplitude collective structural rearrangement like shape transitions and fission. The first barrier in double-humped fission barriers of certain actinide nuclei guarantees that the celebrated intermediate structure associated with states of the second well is not washed out. Conceivably, the barrier separating superdeformed states from states of normal deformation could for some isotopes imply that intermediate structure associated with the depopulation of a superdeformed band near its bandhead [27] is visible. Likewise, for nuclei with collective potential energy surfaces displaying some combination of spherical, oblate, and prolate minima with one of the secondary minima a couple of MeV below the neutron separation threshold, prolate-to-oblate or spherical-to-deformed shape fluctuations should give rise to some observable signature like the correlations among partial amplitudes discussed in this paper.

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