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One-body, collective contributions to parity mixing in compound nuclear states

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One-body contributions to parity mixing in compound nuclear states are discussed, with reference to the recent polarized neutron transmission experiments. The role of the $J=0^-$ giant spin-dipole resonance as a mediator of parity mixing in complex nuclear states is pointed out, and an expression of the parity violating spreading width derived. The collective nature of the mixing mechanism is stressed, and an analogy with isospin mixing in nuclei is drawn.

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Recently, there has been renewed interest in the subject of parity violation in nuclei [1]. This rise of interest is a result of a new class of parity violation experiments [2,3] in nuclei. We refer here to measurements of parity violation effects in the compound nucleus. These experiments were proposed [2] and some were performed about eight years ago. The basic premise of these experiments is based on the idea that due to a high density of states, parity mixing will be enhanced in the compound nucleus. The small separation of s- and p-wave resonances in the compound nucleus leads to a large enhancement sometimes by a factor of 10^3 in the parity mixing observables. Indeed, the first neutron-scattering experiments [2] as well as the recently reported ones [3] produce parity mixing effects of the order of 10%, confirming the idea of enhancement.

In these measurements one scatters polarized neutrons from a complex nucleus and measures the helicity dependence of the total cross section. The longitudinal asymmetry coefficient is

$$\epsilon=\frac{\sigma_+-\sigma_-}{\sigma_++\sigma_-}, \tag{1}$$

where σ_+,σ_- denote the total cross sections for neutrons when the initial neutron beams have first positive and then negative helicities. The asymmetry ϵ is proportional to the parity violating matrix element and, therefore, by measuring the asymmetry one obtains information about the parity violating component of the nucleon-nucleon force in nuclei [1].

The parity mixed states excited in these epithermal experiments lie in the domain where the spacings between the admixed levels are typically of the order of 10–100 eV. The asymmetry ϵ is *linearly dependent* on the amplitude of the parity admixed component and therefore one should expect an enhancement in ϵ when the density of the states is high [2,4].

The theoretical description and analysis of these experiments are given in terms of the statistical theory of nuclear spectra [4–6]. It is argued that the density of states is so large and the complexity of the compound nucleus wave functions so high that such an approach should be most suited. In these theories the random nature of two-body matrix elements of the nuclear Hamiltonian is emphasized.

It is useful to introduce the notion of a *spreading width.* For example, in the case of parity violation effects in the compound nucleus the spreading width is given by

$$\Gamma_{PV}=2\pi\overline{M}^2_{PV}/\overline{D}\,, \tag{2}$$

where $\overline{M}^2_{PV}$ is a parity violating matrix element squared averaged over a certain energy region and $\overline{D}$ is the average level spacing. This quantity is not very sensitive to the excitation energy and density of states. The reason is that both $\overline{D}$, the spacing, and the matrix elements *squared* are inversely proportional to the density of states n. One can also easily see how an enhancement in ϵ will appear when states in the compound nucleus are excited. It was shown that [1,4]

$$\bar{\epsilon}^2\sim\overline{M}^2_{PV}/\overline{D}^2 \tag{3}$$

expressed in terms of Γ_{PV}:

$$(\bar{\epsilon}^2)^{1/2}\sim(\Gamma_{PV}/2\pi\overline{D})^{1/2}\,. \tag{4}$$

Since Γ_{PV} is weakly energy dependent and $\overline{D}$ is inversely proportional to the density of states n, one finds that

$$(\bar{\epsilon}^2)^{1/2}\sim\sqrt{n} \tag{5}$$

and thus there should be an enhancement in the asymmetry measurements when the density of nuclear states is high.

In the present paper we will approach differently the question of parity violation in the compound nucleus. We will not emphasize the chaotic nature of the compound nuclear domain, but rather we will concentrate on the more collective aspects of the physics and therefore will also concentrate on the one-body aspects of parity violation effects in the compound nucleus.

It is quite useful to recall some of the physics that is connected to the question of isospin mixing [7,8] in the compound nucleus and draw analogies to the present case of parity mixing. In medium- and heavy-mass nuclei the isobaric analog state (IAS) is shifted by the Coulomb interaction (basically by its one-body part) into the region of the compound nucleus. There the IAS which has isospin T is surrounded by a dense spectrum of nuclear states

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of isospin $T-1$. The Coulomb interaction admixes these compound states into the IAS giving rise to an isospin violating spreading widths Γ_{IV}. The Coulomb interaction is of long range and therefore the dominant component is its one-body part [7,8]. The direct mixing between the relatively simple one-particle-one-hole (1p-1h) IAS and the complicated multiparticle-multihole $T-1$ states is small. The dominant mechanism of mixing is the following. The isovector one-body part of the Coulomb interaction finds itself a state (or resonance) that admixes strongly with the IAS. Since the operative part of the interaction is a one-body isovector monopole, the mixing occurs with the $T-1$ component of the isovector monopole state [7-9] (IVM) ($J=0^+$, $T=1$). The result is an isospin admixed IAS:

$$|\mathrm{IAS}\rangle_{\mathrm{adm}}=|\mathrm{IAS}\rangle_T+\alpha|\mathrm{IVM}\rangle_{T-1}\,. \tag{6}$$

Although the IVM is many MeV above the IAS [7-10], the fact that it can be connected through a one-body potential to the IAS prevails. The state in Eq. (6) containing $T-1$ components is now mixed with the surrounding $T-1$ compound nuclear states via the strong interaction force. The latter leads to the isospin violating spreading width of the IAS [7-9]. One derives the following expression for this width [7-9]:

$$\Gamma_{IV}=\frac{|\langle \mathrm{IAS}|V_c|\mathrm{IVM}\rangle|^2}{(E_M-E_{\mathrm{IAS}})^2+\Gamma_M^2/4}\Gamma_M\,, \tag{7}$$

where E_M and E_{IAS} are the energies of the IVM and IAS and Γ_M is the strong interaction spreading width of the IVM. One should mention that strictly Γ_M should be evaluated at the energy of the IAS, but as remarked the energy dependence of a spreading width is weak.

We will now use the above considerations to draw analogies between isospin and parity violation in nuclei. The parity violating part of the nucleon-nucleon force was studied quite extensively in the past. Among the various theories studied, the role of a single-particle parity violating (PV) force was first considered by Michel [11]. Of course, such a one-body PV force results from the convolution of a two-body PV force with the single-particle nuclear density. Since the one-body potential has to be a pseudoscalar, even under time reversal, the possibilities of simple forms for such a potential are limited. The simplest of these [11,12] is

$$V_{\mathrm{PV}}=g(r)\boldsymbol{\sigma}\cdot\mathbf{p}\,, \tag{8}$$

where $g(r)$ is a function of the radial coordinate only, and $\boldsymbol{\sigma}$ and $\mathbf{p}$ are the spin and momentum of the nucleon. The PV potential might be an isoscalar as well as isovector and therefore

$$g(r)=g_0(r)+g_1(r)\tau_z\,, \tag{9}$$

where τ_z is the third component of the nucleon isospin operator $\boldsymbol{\tau}$. For a zero-range PV nucleon-nucleon force the functions $g_0(r)$ and $g_1(r)$ should be proportional to the isoscalar and isovector nuclear densities. Taking $g_1=\kappa(N-Z)g_0/A$ and a square-well nuclear density one arrives at the expression

$$V_{\mathrm{PV}}=g_0\left[1+\kappa\frac{N-Z}{A}\tau_z\right]\boldsymbol{\sigma}\cdot\mathbf{p}\,, \tag{10}$$

where g_0 is a combined constant, also containing the weak interaction coupling constant, and κ is a constant that represents the possibility that the isoscalar and isovector PV interactions have different strengths. Consider a single-particle nuclear Hamiltonian:

$$H=\sum_{i=1}^{A}\left[\frac{p_i^2}{2M}+U(r_i)\right]+\sum_{i=1}^{A}g_i\boldsymbol{\sigma}_i\cdot\mathbf{p}_i \equiv H_0+\sum_i g_i\boldsymbol{\sigma}_i\cdot\mathbf{p}_i\,, \tag{11}$$

where

$$g_i=\left[1+\kappa\frac{N-Z}{A}\tau_z(i)\right]g_0\,. \tag{12}$$

The one-body nuclear potential $U(r)$ is assumed to be velocity independent. In this case a solution to order g_0^2 of the Schrödinger equation with H can be obtained by making the transformation [11,12]

$$H=e^{iS}H_0e^{-iS} \tag{13}$$

and finding the eigenfunction of H to be

$$\Psi=e^{iS}|\Phi\rangle\,, \tag{14}$$

where

$$S=M\sum_i g_i\boldsymbol{\sigma}_i\cdot\mathbf{r}_i \tag{15}$$

and

$$H_0|\Phi\rangle=E|\Phi\rangle\,. \tag{16}$$

To first order in g_0,

$$|\Psi\rangle=\left[1+iM\sum_i g_i\boldsymbol{\sigma}_i\cdot\mathbf{r}_i\right]|\Phi\rangle\,. \tag{17}$$

The second term in the wave function is the parity violating component. We note that

$$\frac{1}{\sqrt{3}}\sum_i(\boldsymbol{\sigma}_i\cdot\mathbf{r}_i)=\sum_i r_i[\boldsymbol{\sigma}_i\otimes Y_1(\hat{\mathbf{r}}_i)]^{0^-}\,, \tag{18}$$

where the expression on the right-hand side (rhs) of this equation denotes the coupling of the spin operator $\boldsymbol{\sigma}$ viewed as a tensor of rank 1, to the spherical harmonics of rank 1, to form a tensor of rank 0, i.e., a pseudoscalar. This is of course the $J=0^-$ component of the spin-dipole operator. This operator when acting on $|\Phi\rangle$ will produce particle-hole excitations of the spin-dipole type ($S=1$, $L=1$). Multiplying this operator by g_i will produce isoscalar and isovector spin-dipole configurations.

We now generalize this idea by postulating that in the case when the strong interaction nuclear Hamiltonian is more complete and contains two-body parts, then also the one-body parity violating potential in Eq. (8) and the $J=0^-$ spin-dipole state are responsible for parity violation in compound nuclear states. We will now refer to the case when H_0 in Eq. (11) is replaced by

$$\tilde{H}_0=H_0+\sum_{i>j}V_{ij}\,. \tag{19}$$

Of course, when the two-body nuclear V_{ij} potential contains spin operators and is velocity dependent it will not commute with S in Eq. (15), and the admixed state in Eq. (17) will not be an eigenstate of the full Hamiltonian. Still, we should expect that the $J=0^-$ spin-dipole configurations will serve as doorways for parity mixing. Moreover, two-body parts in the nuclear Hamiltonian $\tilde{H}_0$ will correlate the 1p-1h states and produce collective, giant spin-dipole states or resonances. We will use the following definitions of "ideal" giant $J=0^-$ spin-dipole (SD) states.

The isoscalar is

$$|\mathrm{SD};0^-\rangle_0=\frac{1}{N_0}\sum_i r_i[\sigma_i\otimes Y_1(\hat{\mathbf{r}}_i)]^{0^-}|\tilde{\Phi}\rangle \tag{20a}$$

and the isovector is

$$|\mathrm{SD};0^-\rangle_1=\frac{1}{N_1}\sum_i r_i[\sigma_i\otimes Y_1(\hat{\mathbf{r}}_i)]^{0^-}\tau_z(i)|\tilde{\Phi}\rangle\,, \tag{20b}$$

where $|\tilde{\Phi}\rangle$ is an eigenstate of $\tilde{H}_0$ and N_0,N_1 are appropriate normalization factors equal to the square root of the total $J=0^-$ isoscalar and isovector $L=1$, $S=1$ strength. As already remarked, the above states are not eigenstates of $\tilde{H}_0$. The two-body parts of $\tilde{H}_0$ will couple these ideal states to more complicated nuclear configurations giving rise to a width. The one-body PV potential will couple $|\tilde{\Phi}\rangle$ and states in Eq. (20) to produce

$$|\Psi\rangle=|\tilde{\Phi}\rangle+\alpha_0|\mathrm{SD};0^-\rangle_0+\alpha_1|\mathrm{SD};0^-\rangle_1\,. \tag{21}$$

The mixing coefficients α_k $(k=0,1)$ can be calculated, for example, in perturbation theory:

$$\alpha_k=\frac{\langle\tilde{\Phi}|\sum_i g_i\sigma_i\cdot\mathbf{p}_i|\mathrm{SD};0^-\rangle_k}{\hbar\omega_k-E}\,, \tag{22}$$

where $\hbar\omega_k$ are the energies of the spin-dipole giant resonances built on the state $|\tilde{\Phi}\rangle$ and E is the energy of the state $|\tilde{\Phi}\rangle$. (Note that g_i contains the isoscalar and isovector parts of the PV operator, and these will couple to $k=0$ and $k=1$, respectively.)

Once we identified the doorway states (in this case two states) which are responsible for parity violation we may now proceed and complete the analogy with isospin violation. The parity admixed state $|\Psi\rangle$ in Eq. (21) couples via the strong, parity conserving force with the opposite parity compound nucleus states $|\psi_c\rangle$, surrounding $|\tilde{\Phi}\rangle$, giving rise to the parity violating spreading width. (Of course, one may also say that the parity conserving force mixes the spin dipole with the compound states surrounding $|\tilde{\Phi}\rangle$ and then the PV force couples these to $|\tilde{\Phi}\rangle$. These are equivalent pictures.) The expression for this width is now

$$\Gamma_{\mathrm{PV}}=\frac{|\langle\tilde{\Phi}|V_{\mathrm{PV}}|\mathrm{SD}\rangle_0|^2}{(\hbar\omega_0-E)^2+\Gamma^2_{\mathrm{SD},0}/4}\Gamma_{\mathrm{SD},0}+\frac{|\langle\tilde{\Phi}|V_{\mathrm{PV}}|\mathrm{SD}\rangle_1|^2}{(\hbar\omega_1-E)^2+\Gamma^2_{\mathrm{SD},1}/4}\Gamma_{\mathrm{SD},1}\,, \tag{23}$$

where $\Gamma_{\mathrm{SD},0}$ and $\Gamma_{\mathrm{SD},1}$ are the spreading widths of isospin $T=0$ and $T=1$, $L=1$, $S=1$, $J=0^-$ giant resonances evaluated at the energy of $|\tilde{\Phi}\rangle$.

The spin-dipole resonance in particular of the isovector $(T=1)$ type was studied in the past both experimentally [13,14] and theoretically [15,16]. Theory indicates [16] that the average energy of the $J=0^-$ is several MeV higher than that of $J=1^-$ and 2^-. Usually more than $\frac{1}{3}$ of the total $L=1$, $S=1$ $(T=1)$ strength is contained in the $J=0^-$ component. As for the isoscalar $(T=0)$ spin dipole, there is only scarce experimental information [17]. One should expect $S=1$, $L=1$ $(T=0)$ strength to be found around $1\hbar\omega$.

It has become clear in the past decade that the Axel-Brink postulate [18], which states that every state has its giant dipole built on it, is well satisfied. The mechanism of parity mixing we discuss here should be viewed as an application of this postulate. The doorways for parity mixing in ground *as well as excited* states are the spin-dipole giant resonances built on these states. The mixing of p and s resonances discussed in the literature [2-4] is an example of this. The single-particle p (or s) resonance in an odd-even nucleus which mixes with the s (or p) is part of a spin dipole built on the latter. The full $S=1$, $L=1$, strength contains in addition p-h components of the core. Although we predict that most of the nuclear states will acquire similar PV spreading widths, one should not be deceived by this fact when considering the neutron polarization experiments. In these experiments only states having single-particle components in the n plus target ground-state compound system will be detected. Moreover, because of penetrability effects, only components of single-particle p states having admixtures of s states will be detected. The PV spreading width found in the recent ^{238}U experiment [3] is around $\Gamma_{\mathrm{PV}}=1\times10^{-7}$ eV. We use Eq. (23) to make a rough estimate for the parity mixing matrix element; replace the two doorways, the $T=0$ and $T=1$, by a single one located at an average energy of $1.5\hbar\omega$ which in a heavy nucleus is about 10 MeV. The widths of a dipole resonance is roughly of the order of $\Gamma_{\mathrm{SD}}\simeq5$ MeV in such a nucleus. These numbers give a PV matrix element of $\langle\Phi|V_{\mathrm{PV}}|\mathrm{SD}\rangle=\sqrt{2}$ eV for a state in heavy nucleus. This is not inconsistent with the size of the matrix element found in other parity violating experiments [1] at low excitation energies. Equation (23) suggests that the PV spreading width is quite state independent and that not only is it a smooth function of energy but also of mass number A. Neglecting the $N-Z$ dependence, the matrix element in the numerator of Eq. (22) can be shown by a direct calculation to have an $A^{1/2}$ dependence. On the other hand, the energy position of a dipole excitation in heavy nuclei scales approximately as $A^{-1/3}$. Using Eq. (23) we estimate

$$\Gamma_{\mathrm{PV}}\sim A^{5/3}\Gamma_{\mathrm{SD}}\,. \tag{24}$$

Spreading widths of giant resonances such as the dipole shrink as the mass increases. Based on these qualitative considerations, we should expect Γ_{PV} to increase as A^{δ} with $\delta\simeq1-1.3$.

One of the characteristic features of a doorway state approach is the occurrence of sign correlations among various matrix elements. This feature was extensively studied in the past [19]. For example, sign correlations lead to an asymmetric distribution of width in the fine structure of the IAS [7,19]. Remarkably, sign correlations in the ϵ were found in the ^{238}U and recently in the ^{232}Th experiments [3,20]. Our mechanism of doorway dominance leads to correlations between the coupling matrix element of the p-wave resonance to the positive parity compound states and between the decay amplitudes of these compound states. Both are proportional to the overlap of the compound states with the doorway. Using these properties and the fact that the doorway is far from the p resonances, one finds that there are indeed sign correlations in ϵ.

We have drawn the analogy between the cases of isospin mixing and parity mixing. The analogy is certainly not a complete one. The Coulomb force that is responsible for isospin mixing is of long range. Usually, therefore, only the one-body part is of importance, and strong mixing between states that differ in their composition by more than one particle is rare. In the case of parity mixing, the force responsible is of short range and therefore one should expect sometimes mixing induced also by the two-body parts of the PV interaction. Such "accidental" parity mixing is probably often encountered in lighter nuclei.

We should emphasize however, that the success of the shell model and mean-field approximation in nuclei where the underlying two-body nuclear force is of short range, suggests very strongly that also in the case of the parity violating interaction the one-body part will be the leading term. Therefore, as one proceeds to heavier nuclei the mechanism we suggest in this work is expected to dominate.

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