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POSSIBLE DOUBLET MECHANISM FOR A REGULAR COMPONENT OF PARITY VIOLATION IN NEUTRON SCATTERING

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Abstract

A nucleus with octupole deformation of the mean field reveals rotational doublets with the same angular momentum and opposite parity. Mediated by the Coriolis-type interaction, the doublet structure leads to a strong regular component in the parity violation caused by weak interaction. This can explain sign correlations observed in polarized neutron scattering by ^{232}Th.

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Large effects of parity nonconservation (PNC) in compound nuclear states [1-3] are observed in experiments with polarized neutrons. Now it is widely accepted that the mechanism of statistical (sometimes called "dynamical") enhancement of weak interactions due to the high level density in compound nuclei [4–9] is responsible for the large magnitude of the effects. Roughly speaking, the enhancement in comparison to the parity mixing between single-particle states is proportional to $\sqrt{N}$ where $N \sim 10^5 - 10^6$ is a number of simple shell model configurations in a generic complicated compound wave function. Matrix elements of the weak interaction H_W between such states of opposite parity are suppressed by a factor $\sim 1/\sqrt{N}$ with respect to single-particle estimates but the level spacing in the denominator is diminished by factor $\sim N$. It results in statistical enhancement $\sim \sqrt{N} \sim 10^3$.

Additional enhancement due to the interference of low-energy s-wave and p- wave neutron resonances mixed by weak interaction is provided [7] by the factor $(\Gamma_s^{(n)}/\Gamma_p^{(n)})^{1/2} \sim 1/kR \sim 10^2 - 10^3$ where k is neutron wave number, R is nuclear radius, $\Gamma_s^{(n)}$ and $\Gamma_p^{(n)}$ are neutron widths for the s- and p-waves, respectively. Acting together, those factors of statistical and kinematical enhancement lead to the longitudinal asymmetry (or analyzing power measuring the difference of total cross sections $\sigma_\pm$ for neutrons with positive and negative helicity)

$$P = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \tag{1}$$

which reaches in some cases the magnitude of about 10%.

Statistical nature of the enhancement implies randomness of matrix elements of weak interaction between complicated states of opposite parity. Therefore one would expect the random sign of asymmetry (1). Recent LAMPF experiments [3] show, contrary to this expectation, that neutron capture to p-wave compound resonances in ^{233}Th leads to the asymmetry of the same sign for all eight resonances where the effect is statistically significant. At the same time, other compound nuclei seem to be closer to the random distribution of the sign of asymmetry. In all cases the order of magnitude of the effect agrees with the predictions based on the abovementioned two factors. Therefore several attempts have been made [10–14] to find a mechanism which would be able to generate a regular (non-random) component of the PNC asymmetry. These attempts were unsuccessful in the sense that the desired magnitude of the weak matrix element was inconsistent with our knowledge on weak interactions in nuclei.

The experimental pattern for a target of ^{232}Th gives a hint that this nucleus, and consequently the compound nucleus ^{233}Th, might be a special case due to some pecularities of its structure as compared to "normal" deformed heavy nuclei like ^{238}U which apparently exhibit random asymmetry. Below we discuss the specific features of parity violation which could be related to structure of Th nuclei.

It is known that Th isotopes display strong octupole correlations [15–19]. The potential energy surface in the space of the quadrupole and octupole deformation parameters is quite complicated. As a function of quadrupole deformation it has triple-humped structure [20,21]. Due to the mass asymmetry of fission, on the top of the outer barrier the cold nucleus goes through the pear-shaped configurations (fission channels [15]) corresponding to large octupole deformation. We assume that static octupole deformation in Th is present already in the first (ground state) potential well. However, this assumption is not critical because at the excitation energies near neutron threshold, the nuclear wave function in the space of the deformation parameters certainly has a significant probability of large octupole deformation, $\beta_3 \simeq 0.35$ [22,23,21].

For sufficiently strong deformation, the adiabatic approximation is justified which allows one to write down [15] the wave functions as products of orientational D-functions and intrinsic functions $|\chi\rangle$. In the case of axial symmetry the projection $K = \mathbf{In}$ of the total angular momentum $\mathbf{I}$ on the intrinsic symmetry axis $\mathbf{n}$ is conserved and can be used to label the intrinsic wave function $|\chi\rangle = |a; K\rangle$. In neutron capture by a spinless target we are interested in states with $|K| = 1/2$. For a given intrinsic function with $K \neq 0$ presence of octupole deformation, or of any shape which is axially symmetric but has no symmetry with respect to reflection in the equatorial plane, leads [15] to rotational doublets with definite parity η,

$$|\Psi^I_{MK;\eta}\rangle = \sqrt{\frac{2I+1}{8\pi}}\{D^I_{MK}(\varphi,\theta,0)|a;K\rangle + \eta(-1)^{I+K}D^I_{M-K}(\varphi,\theta,0)|a;-K\rangle\}. \qquad (2)$$

Energy splitting of doublet states implies that there exist a physical interaction which can couple "right- and left- oriented" configurations $|a;\pm K\rangle$. One can imagine various specific mechanisms of coupling [24,7], for example tunneling of an excess cluster. In the case of $K = 1/2$ the Coriolis force acting in the first order can be sufficient to generate this coupling similar to the decoupling parameter in the normal spectra of odd-A deformed nuclei [15].

Since the energy separation within the doublet is supposedly of the order of several keV one can expect that mixing of the doublet states of opposite parity by weak interaction is much more favorable than mixing of the single-particle orbitals separated by MeV. However, the direct mixing of states (2) with the same intrinsic structure and opposite η is possible only if the weak perturbation H_W violates time reversal symmetry along with space inversion symmetry [24] (see also [15,7]). Indeed, the mixing matrix element can be expressed in terms of intrinsic expectation values of weak interaction,

$$\langle\Psi^I_{MK;-\eta}|H_W|\Psi^I_{MK;\eta}\rangle = \frac{1}{2}\{\langle a;K|H_W|a;K\rangle - \langle a;-K|H_W|a;-K\rangle\}. \qquad (3)$$

Since H_W is a pseudoscalar, the intrinsic matrix element $\langle a;K|H_W|a;K\rangle$ should be proportional to the intrinsic pseudoscalar K. On the other hand, it means that this quantity, together with K, changes sign under time reversal which contradicts to T-invariance of H_W. Actually, one can see from (3) that only T-odd interaction leading to the opposite sign of the two matrix elements in curly brackets can result in the direct mixing of the doublet states.

Note that for a P- *and* T-odd interaction direct mixing within the doublet is not forbidden which can be of some interest for the problem of search for $T-$ and P-violating nuclear forces. In this respect the situation is similar to that in the problem of the electric dipole moment of a particle [25].

To clarify the situation we can refer to the simple model where the mixing of single-particle s- and p-orbitals is caused by an electric field through the dipole interaction $-\mathcal{E}z$ as for an electron in a dipole molecule. The mixed orbitals $|\pm 1/2\rangle$ with the projection

$j_z = m = \pm(1/2)$ of the particle angular momentum onto the field axis are

$$|\pm 1/2\rangle = \sqrt{1-\xi_{\pm}^2}|s_{1/2},\pm\rangle + \xi_{\pm}|p_{1/2},\pm\rangle \tag{4}$$

where the polarizability coefficients $\xi_{\pm}$ differ merely by sign, $\xi_{\pm} = \pm\xi$. Indeed, the spin-angular structure of the $p_{1/2}$ wave function is $\sim (\vec{\sigma}\mathbf{r})|s_{1/2}\rangle$. Therefore the polarizability is proportional to the diagonal matrix element $\langle s_{1/2}|z(\vec{\sigma}\mathbf{r})|s_{1/2}\rangle$ which, in turn, is proportional to the matrix element of j_z and changes its sign for $m \to -m$. Now, the expectation value

$$\langle \pm 1/2|H_W| \pm 1/2\rangle = \pm 2\xi\sqrt{1-\xi^2}\mathrm{Re}\langle s_{1/2},\pm|H_W|p_{1/2},\pm\rangle \tag{5}$$

vanishes for the standard parity-nonconserving weak interaction when the amplitude $\langle s|H_W|p\rangle$ is an imaginary pseudoscalar. Contrary to that, the similar amplitude for a hypothetical P- and T-violating hamiltonian H_{PT} would be a real pseudoscalar so that eq.(5) would give non-zero expectation values of the same magnitude but of the opposite sign for the projections $\pm 1/2$.

Going back to our original problem we see that the mixing of the doublet states by the P-odd but T-even interaction should be mediated by another ("normal", P- and T-even) interaction H' leading to the non-adiabatic admixtures of different configurations $|b;K'\rangle$. In particular, it can (but does not have to) be the same interaction which was already mentioned as inducing the energy splitting *within the doublet*. The interaction H' in the first order influences PNC via matrix elements $\langle a;-K|H'|b;K\rangle$ which appear in the P-conserving mixing matrix element

$$\langle \Psi^{aI}_{MK;\eta}|H'|\Psi^{bI}_{MK;\eta}\rangle = \eta A_{IK}\langle a;-K|H'|b;K\rangle \tag{6}$$

with the amplitude A_{IK} depending on the nature of interaction H'. As a result of the joint action of H' and H_W the total rotational function (1) acquires an admixture of opposite parity,

$$|\Psi^{aI}_{MK;\eta}\rangle \to |\tilde{\Psi}^{aI}_{MK;\eta}\rangle = |\Psi^{aI}_{MK;\eta}\rangle + \beta|\Psi^{aI}_{MK;-\eta}\rangle, \tag{7}$$

where the mixing amplitude β is

$$\beta = -2\eta \frac{A_{IK}}{E - E_{-\eta}} \sum_b \frac{\langle a; -K|H'|b; K\rangle\langle b; K|H_W|a; K\rangle}{E - E_b}. \quad (8)$$

Here E is neutron energy and, up to our accuracy, in the denominator of the sum we neglect the rotational splitting of the doublet b. This admixture is directly related to the observed PNC asymmetry (1),

$$P = 2\sqrt{\frac{\Gamma_s^{(n)}}{\Gamma_p^{(n)}}}\beta. \quad (9)$$

If the splitting is due to the same interaction H' it also can be expressed in terms of the amplitude A_{IK},

$$E_\eta^{aI} - E_{-\eta}^{aI} = 2\eta A_{IK}\langle a; -K|H'|a; K\rangle. \quad (10)$$

In this case the resulting PNC admixture (8) at the resonance energy $E \approx E_\eta$ does not depend on A_{IK}.

Note that in the sum (8) the numerator contains two matrix elements and both of them are suppressed $\sim 1/\sqrt{N}$ for generic compound wave functions a and b. Therefore the contribution of the closest states with the energy difference of the order of the mean level spacing D in the compound nucleus is not statistically enhanced. Then one has take into account contributions of distant states b. If the product of matrix elements is peaked for the states b on the distance $E_b - E \simeq \omega$ from the resonance, the closure approximation gives

$$\beta = 2\eta \frac{A_{IK}\langle a; -K|H'H_W|a; K\rangle}{\omega(E - E_{-\eta})}, \quad (11)$$

and, in the case (10), at $E \approx E_\eta$ we come to a remarkably simple result

$$\beta = \frac{\langle a; -K|H'H_W|a; K\rangle}{\omega\langle a : -K|H'|a; K\rangle}. \quad (12)$$

Thus, in this scheme one can expect the admixture amplitude of the order $\beta \simeq (H_W)_{s-p}/\omega$ where $(H_W)_{s-p}$ is given by the typical single-particle matrix elements of weak interaction, $(H_W)_{s-p} \simeq 5$ eV. For the Coriolis force as H', the transition energy between deformed single-particle orbitals with $\Delta m = \pm 1$ is of the order of 100 keV which leads to the estimate $\beta \simeq 5 \times 10^{-5}$.

This can be compared with the mixing between compound states of opposite parity which can be estimated as the ratio of the typical corresponding matrix element to the level spacing, $\beta_{comp} \simeq \langle H_W \rangle_{comp}/D$. The experimental data [3] show that $\langle H_W \rangle_{comp} \approx 1.3 \times 10^{-3}$ eV. Mixing matrix elements of the same order are predicted by theoretical calculations [26] using the gas of thermally excited quasiparticles as a model for a compound nucleus. Such an approach gained a support in the recent detailed analysis [27] of chaotic shell model wave functions. Using this value and $D = 15$ eV, we obtain $\beta_{comp} \simeq 10^{-4}$.

As a result, the estimate of the regular component of the observable effect (9) gives $P \simeq 10^{-2}$. It means that the regular effect due to the doublet mechanism has to be seriously taken into consideration.

Our arguments are based on the assumption that the pear shape and related doublet structure persist at required excitation energies. If this is the case, the complicated intrinsic states are the superpositions

$$|a; \pm K\rangle = \sum_i C_i^a |\Phi_i; \pm K\rangle \tag{13}$$

of simple quasiparticle configurations $|\Phi_i; \pm K\rangle$ with amplitudes C_i^a independent of the sign of K. Therefore the matrix element in (13) contains a regular contribution

$$\langle a; -K|H'H_W|a; K\rangle \approx \sum_i (C_i^a)^2 \langle \Phi_i; -K|H'H_W|\Phi_i; K\rangle. \tag{14}$$

As mentioned above, such expressions (see also energy difference (10)) can be calculated explicitly if the excited nucleus is modeled by a gas of quasiparticles which, in the case under study, are moving in the pear-shaped field. Sums with the weights C_α^a are substituted in this approach by the expectation values for the thermal equilibrium ensemble [26,27].

Moreover, this approach is applicable regardless of the presence or lack of axial symmetry. In the general case the wave functions (2) are still similar combinations of the "right" and "left" states and we can view $\pm K$ in (13) as a general label necesssary to distinguish mutually reflected wave functions.

Different consideration of the regular contribution of the doublet states was independently started in [28].

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