Regular mechanism of parity and time invariance nonconserving effects enhancement in neutron capture and scattering near p-wave compound resonances

V. V. Flambaum
Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder, Colorado 80302;
National Institute of Standards and Technology, Boulder, Colorado 80309;
and Institute of Nuclear Physics, 630090 Novosibirsk, U.S.S.R.
(Received 20 August 1991)

Recent measurements of parity nonconserving (PNC) effects in ^{238}U and ^{232}Th contradict the results of random matrix theory for nuclear compound states. In this work the value of the PNC effect is expressed in terms of a wave function at the nuclear surface where the wave function of the compound state is not "random" due to boundary conditions. A mechanism is suggested which can explain the permanent sign and large value of these effects. The correlations between compound-state components are considered. The T- and P-odd effects can be expressed in terms of observed P-odd effects. The "dynamical enhancement" of small interactions in other reactions and other systems is also discussed.

PACS number(s): 24.60.Dr, 25.40.Dn, 25.80.Dj

I. INTRODUCTION

The present paper has been written in connection with recent measurements of the parity nonconservation (PNC) effect in neutron capture to p-wave compound resonances of ^{238}U and ^{232}Th [1,2]. The values of the effect (dependence of cross section on neutron helicity) have the same sign for 90% of p-wave resonances where the observed effect is larger than two standard deviations from zero. This result seems to contradict the random matrix theory which has been applied for a description of the compound state for many years.

As is known the relative magnitude of parity violation in nuclear forces is very small:

$$F \sim Gm_\pi^2 = 2 \times 10^{-7} . \tag{1}$$

This magnitude of the PNC effect has been observed, e.g., in p-p or p-α scattering. In Ref. [3] (see also Refs. [4–13]) it was shown that near p-wave compound-resonance PNC effects are five orders of magnitude larger. There are two reasons for the enhancement: (1) The small distance between opposite parity levels (s- and p-wave resonances) in the compound state of the nucleus; and (2) the admixed s-wave amplitude is 2–3 orders of magnitude larger than the basic p-wave amplitude.

For example, in the simplest two-resonance approximation the relative difference in p-wave resonance cross sections for positive and negative helicity of neutrons is [3]

$$P = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = 2\alpha\sqrt{\frac{\Gamma_s^n}{\Gamma_{p_{1/2}}^n}} , \tag{2}$$

$$i\alpha \approx \frac{\langle s|W|p\rangle}{E_p - E_s} . \tag{3}$$

Here $i\alpha$ is the coefficient of mixing by weak interaction between compound states of opposite parity (p and s resonances); neutron widths Γ_s^n and Γ_n^p should be evaluated at p-wave resonance energy. In the general case it is necessary to sum over the nearest s resonances in a PNC amplitude.

The ratio of s-wave to p-wave capture amplitudes for neutron energy 1–100 eV is

$$\frac{T_s}{T_{p_{1/2}}} = \sqrt{\frac{\Gamma_s^n}{\Gamma_{p_{1/2}}^n}} \sim \frac{1}{kR} \sim 10^3 - 10^2 . \tag{4}$$

Here κ is the neutron momentum, and R is the radius of the nucleus. Due to the closeness of opposite parity levels in the compound nucleus, the mixing coefficient α in Eq. (3) is much larger than estimate (1). A first attempt to estimate α was made in Ref. [14] in the spirit of random matrix theory (see also Refs. [15–20,3,4,12,29]). Experiments on neutron radiative capture [21] and fission [22] confirmed the existence of this enhancement. The "experimental" value

$$\alpha \sim 10^{-4} \tag{5}$$

is 2–3 orders of magnitude larger than estimate (1). This enhancement is called a "dynamical enhancement." Using this result and estimate (4), we predicted [3]

$$P \sim 10^{-2} . \tag{6}$$

This effect was first observed in Dubna [23] (see also Refs. [24–26]). Observations of the "tail" of the p-resonance effect for thermal neutrons were reported in Refs. [27,28].

The magnitudes of all observed effects were in agreement with theoretical estimates. However, in the estimations of weak matrix element in Refs. [14,3,4,17,12,29], the supposition was used that the compound state has a random structure (the expansion coefficients of the compound state in terms of simple basic states and matrix elements are random). This supposition contradicts recent experiments [1,2].

The present work is an attempt to explain this puzzle and to attract attention to other interesting related problems.

II. TRANSFORMATION OF WEAK INTERACTION HAMILTONIAN AND VALENCE MECHANISM

The Hamiltonian of a weak interaction of nucleon with nucleus is

$$\hat{W} = \frac{Gg}{2\sqrt{2}m}\{\boldsymbol{\sigma}\cdot\mathbf{p}\rho + \rho\boldsymbol{\sigma}\cdot\mathbf{p}\}\ , \tag{7}$$

where ρ is nuclear density, and g is a dimensionless constant. For a neutron $g \sim 1$; for a proton $g \approx 4$ (see, e.g., Ref. [30]). We can transform this Hamiltonian to a more convenient form. Replace momentum $\mathbf{p} = im[\hat{H}, \mathbf{r}]$, where H is the Hamiltonian describing a nucleon in the nucleus. If we neglect spin-dependent terms (e.g., spin-orbit interaction) in the Hamiltonian H, the interaction W can be transformed to the following form:

$$\begin{aligned}\hat{W} &= \tilde{W} + W_0\ ,\\ \tilde{W} &= -\frac{Gg}{4\sqrt{2}m}\{\mathbf{p}\cdot\mathbf{n}\rho'\boldsymbol{\sigma}\cdot\mathbf{r} + \rho'(\mathbf{n}\cdot\mathbf{p})(\boldsymbol{\sigma}\cdot\mathbf{r})\\ &\qquad + (\boldsymbol{\sigma}\cdot\mathbf{r})(\mathbf{p}\cdot\mathbf{n})\rho' + \boldsymbol{\sigma}\cdot\mathbf{r}\rho'\mathbf{n}\cdot\mathbf{p}\}\ ,\\ W_0 &= \frac{Ggi}{\sqrt{2}}[H, \rho\boldsymbol{\sigma}\cdot\mathbf{r}]\ .\end{aligned} \tag{8}$$

Here $\rho' = d\rho/dr$ (it appears from the commutator $[H, \rho]$), $\mathbf{n} = \mathbf{r}/r$. For simplicity we consider here a spinless spherical target nucleus. The interaction W_0 does not contribute to the parity nonconserving effects in neutron scattering. Actually, the parity nonconserving part of the scattering amplitude is

$$f_{\rm PNC} = -\frac{m}{2\pi\hbar^2}\langle\Psi_f^*|\hat{W}|\Psi_i\rangle\ . \tag{9}$$

Here Ψ_f and Ψ_i are wave functions of the system which at large neutron-nucleus distance are scattering waves. These wave functions correspond to the same energy. Therefore, the matrix element of the commutator with Hamiltonian ($W_0 \sim [H, \rho\boldsymbol{\sigma}\cdot\mathbf{r}]$) is equal to zero. [It is easy to check by substitution into the Schrödinger equation that W_0 gives only the phase for the compound-nucleus wave function: $\Psi \to e^{-i\varphi}\Psi$, $\varphi = \sum_n \varphi_n$, $\varphi_n = (Gg_n/\sqrt{2})\rho\sigma_n r_n$, the summation carried out over nucleons.]

The derivative $\rho' = d\rho/dr$ is large only on the surface of the nucleus. In the simplest model of constant nuclear density at $r < R$ (R is the nuclear radius),

$$\begin{aligned}&\rho = \rho_0\theta(r-R)\ ,\quad \rho' = -\rho_0\delta(r-R)\ ,\\ &\rho_0 = (\tfrac{4}{3}\pi r_0^3)^{-1}\ ,\quad r_0 = 1.15\ \text{fm}\end{aligned} \tag{10}$$

is the internucleon distance. Thus, the main contribution to parity nonconservation effects comes from the surface of the nucleus. The wave function outside the nucleus (scattered neutron wave) for the energy close to $P_{1/2}$-wave compound resonance is of the form (we consider the region near the nucleus, $\kappa r \ll 1$):

$$\begin{aligned}\varphi &= e^{ikz}\chi_\pm + \varphi_{\rm scatt}\\ &\longrightarrow \left[1 + \frac{f_0}{r} + \frac{i}{\kappa r^2}f_{1/2}(\bar{\boldsymbol{\sigma}}\cdot\bar{\mathbf{n}})(\bar{\boldsymbol{\sigma}}\cdot\bar{\mathbf{n}}_\kappa)\right]\chi\ .\end{aligned} \tag{11}$$

Here χ is a spinor corresponding to right or left helicity of neutron, $\bar{\boldsymbol{\sigma}}\cdot\bar{\mathbf{n}}_\kappa\chi = \pm\chi, \mathbf{n}_\kappa = \boldsymbol{\kappa}/\kappa$:

$$f_0 = -a - \frac{1}{2\kappa}\frac{\Gamma_{ns}}{E - E_s + i\Gamma_s/2}\ , \tag{12}$$

$$f_{1/2} = -\frac{1}{2\kappa}\frac{\Gamma_{np}}{E - E_p + i\Gamma_p/2}\ , \tag{13}$$

f_0 s-wave and $f_{1/2} - p_{1/2}$ -wave scattering amplitudes, a is the scattering length (for ^{232}Th $a \approx 10$ fm).

Using formulas (8)–(11) it is easy to calculate the "valence" contribution of wave (11) to parity nonconserving (PNC) effects (the valence mechanism was first discussed in Refs. [11] and [13]). If we "forget" about other components of the compound state and calculate the matrix element between neutron states (11), we obtain

$$f^V_{\rm PNC}(0) = \pm f_{1/2}\frac{4}{\kappa}\frac{Gg_n}{\sqrt{2}}\rho_0\left(1 + \frac{f_0}{2R}\right)\ , \tag{14}$$

$$\begin{aligned}\sigma &= \frac{4\pi}{\kappa}{\rm Im}f(0) = \frac{4\pi}{\kappa}{\rm Im}(f_{1/2} + f_{\rm PNC})\ ,\\ P^v &= \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{4}{\kappa}\frac{Gg_n}{\sqrt{2}}\rho_0\left(1 + \frac{{\rm Re}(f_0)}{2R}\right)\\ &= 0.9\times10^{-3}g_n\left(1 + \frac{{\rm Re}(f_0)}{2R}\right)\sqrt{\frac{1\ \text{eV}}{E}}\ .\end{aligned} \tag{15}$$

Here E is the neutron energy, and $\sigma_\pm$ is the resonance neutron capture cross section for neutron helicity + or −. Far from s-wave resonances $[1 + {\rm Re}(f_0)/2R] \sim 1$. Therefore, for $g_n \sim 1$, estimates of the valent mechanism are 1 to 2 orders of magnitude smaller than observed effects in Sn, La, Cd, Br, Th, and U isotopes ($P \sim 10^{-2}$–10^{-1} for $E \sim 1 - 100$ eV).

III. THE SOURCE OF ENHANCEMENT

As is known, the wave function of a compound state is very complicated. It can be represented as a sum of simple components Φ_α (Φ_α is a product of particle, hole, vibration, and rotation states)

$$\Psi_c = \sum b_\alpha\Phi_\alpha\ . \tag{16}$$

The number of "principal" components in Ψ_c (i.e., the components which provide the main contribution to normalization) is equal to (see, e.g., Ref. [31])

$$N \sim \frac{\Gamma_{spr}}{\mathcal{D}} \sim 10^4 - 10^6\ . \tag{17}$$

Here $\mathcal{D}$ is the average distance between the compound levels with the same angular momentum and parity ($\mathcal{D} \sim 1 - 100$ eV), and $\Gamma_{spr} \sim$ MeV is the fragmentation width of the state φ_α to the levels of the compound nucleus (in other words, it is the scale of residual nucleon-nucleon interaction that mixes simple states). By virtue of the normalization condition ($\sum b_\alpha^2 = 1$) $b_\alpha \sim 1/\sqrt{N}$.

In a calculation of the "valence" mechanism contribution we take into account only one single-particle component in the compound-state wave function: $\varphi\psi_t$, where ψ_t is the target nucleus state, φ is the neutron wave (11). The weight of this component is proportional to $1/N$, i.e., very small. It is useful to explain this point in detail. In perturbation theory formula (9) we have the total wave function of the system:

$$\Psi_i = \varphi\Psi_t + \sum_s \sqrt{\frac{\pi\Gamma_n^s}{mk}} \frac{1}{E - E_s + i\Gamma_s/2} \Psi_c^s + i\sqrt{\frac{\pi\Gamma_n^p}{mk}} \frac{1}{E - E_p + i\Gamma_p/2} \Psi_e^p . \tag{18}$$

We include to the total wave function Ψ_i "valence" component $\varphi\Psi_t$ from Eq. (11), s-wave compound-resonance states Ψ_c^s, and p-wave compound-resonance states Ψ_c^p. The coefficient before Ψ_c can be found from a comparison of formula (9) with the compound-state contribution to $f_{\rm PNC}$ (see Refs. [3,4,10,29]):

$$f_{\rm PNC}^e = -\frac{1}{k} \frac{i\sqrt{\Gamma_n^s}\langle\Psi_c^s|W|\Psi_c^p\rangle\sqrt{\Gamma_n^p}}{(E - E_s + i\Gamma_s/2)(E - E_p + i\Gamma_p/2)} . \tag{19}$$

Here Γ and Γ_n are the total and neutron widths of the resonance.

Using formula (18) we can compare probabilities of single-neutron (unexcited target) state and many-particle states. It is enough to calculate normalization integral $\int |\psi_i|^2$ over the nucleus. The weights of single-particle (valence) states are

$$W_v^s \sim \left(1 + \frac{f_0}{R}\right)^2 \frac{4}{3}\pi R^3 , \tag{20}$$

$$W_v^p \sim \left(\frac{f_{1/2}}{kR^2}\right)^2 \frac{4}{3}\pi R^3 \sim \frac{\pi}{\kappa^4 R} \frac{(\Gamma_n^p/2)^2}{(E - E_p)^2 + \Gamma_p^2/4} . \tag{21}$$

The weights of many-particle (compound-state) components are

$$W_c^s \sim \left(\frac{\pi\Gamma_n^s}{m\kappa}\right) \frac{1}{(E - E_s)^2 + \Gamma_s^2/4} , \tag{22}$$

$$W_c^p \sim \left(\frac{\pi\Gamma_n^p}{m\kappa}\right) \frac{1}{(E - E_p)^2 + \Gamma_p^2/4} . \tag{23}$$

Resonance parameters can be found in Ref. [33]. For example, at the energy $E = 8.3$ eV in ^{232}Th where the p-wave resonance is located, we obtain

$$\frac{W_c^s}{W_v^s} \sim 10^4 \sim N_s \frac{f_0^{\rm res}}{f_0 + R} \sim 0.1 N_s , \tag{24}$$

$$\frac{W_c^p}{W_v^p} \sim 10^6 \sim N_p . \tag{25}$$

Parameter N in this case can be defined as the "experimental" value (inverse spectroscopic factor of the resonance):

$$N \sim \frac{\Gamma_{\rm single}^n}{\Gamma^n} \sim 10^6 , \quad \Gamma_{\rm single}^n \sim (\kappa R)^{2\ell+1} \frac{1}{mR^2} \tag{26}$$

is the width of a "single-particle" resonance, ℓ is the orbital momentum. In s-wave the ratio W_c^s/W_v^s is smaller because the resonance cross section at that point is much smaller than the potential scattering contribution.

Note that there is no close s-wave resonance in this region and neutron scattering looks like pure potential scattering. Nevertheless, inside the nucleus we have a compound-nucleus state rather than a simple neutron state. The relative weight of the valence component is 10^{-4} only.

This picture obviously shows that the compound-nucleus contribution cannot be neglected. Moreover, this contribution is the source of the enhancement of PNC effects.

We need to find matrix elements of the weak interaction between compound states of opposite parity

$$\langle\psi_s|W|\psi_p\rangle = \left\langle \sum b_\alpha \Phi_\alpha^+ |W| \sum c_\beta \Phi_\beta^- \right\rangle = \sum_{\alpha,\beta} b_\alpha^* c_\beta^* \langle\Phi_\alpha^+|W|\Phi_\beta^-\rangle . \tag{27}$$

What matrix elements are nonzero in this sum? W is the single-particle operator, i.e., it can change the state of only one particle. This means that multiparticle wave functions Φ_α^+ and Φ_β^- differ only by the state of one particle: $\Phi_\alpha^+ = \psi_1\varphi_\mu^+$, $\Phi_\beta^- = \psi_1\varphi_\nu^-$. In a spherical nucleus nucleon bound states of opposite parity and the same angular momentum belong to different shells, i.e., the distance between them is about

$$\Delta E = E_+ - E_- \sim 5 - 10 \text{ MeV} . \tag{28}$$

But the energy of the principal components of compound states should satisfy the conditions $|E - E_\alpha| \lesssim \Gamma_{spr}$ and $|E - E_\beta| \lesssim \Gamma_{spr}$; i.e., the energies of single-particle states should satisfy the condition $|E_\nu - E_\mu| \lesssim \Gamma_{spr} \sim 1$ MeV which contradicts condition (28). (This argument for the absence of principal component contribution was considered in Refs. [11,12,29].) Therefore, if we consider only principal components of compound states, at least one of the orbitals (φ_μ^+ or φ_ν^-) should belong to the continuous spectrum. We have appropriate continuous spectrum states: s-wave and p-wave parts of the scattered neutron wave function, and doorway neutron states φ_s and φ_p [see Eq. (11)]. We have four possibilities:

(1) $\varphi_\mu^+ = \varphi_s , \quad \varphi_\nu^- = \varphi_{p_{1/2}}$,

(2) $\varphi_\mu^+ = \varphi_s , \quad \varphi_\nu^- = \theta_{p_{1/2}}$,

(3) $\varphi_\mu^+ = \theta_{s_{1/2}} , \quad \varphi_\nu^- = \varphi_{p_{1/2}}$,

(4) $\varphi_\nu^- = \varphi_{p_{3/2}} , \quad \varphi_\mu^+ = \theta_{d_{3/2}}$.

Here θ is the wave function of the neutron bound state near the threshold (if it exists), $E_\theta \gtrsim -\Gamma_{spr}$. Note that in practice cases (1)–(3) coincide. Actually, the bound state and the continuous spectrum states with $E \approx 0$ are proportional to each other inside the nucleus since $|E| \ll |U|$, $|U|$ is a strong potential depth. Therefore, there is no need to include in the basis set of the orbitals both states φ_ℓ and θ_ℓ. In other words, bound state (or single-particle resonance) near the threshold leads only to enhancement of the corresponding scattering wave and gives the maximum of the neutron strength function.

Since the neutron state has an energy near the threshold ($\Gamma_{spr} \gtrsim E_{\nu,\mu} \gtrsim -\Gamma_{spr}$), the target nucleus state ψ_1 can have only a small excitation energy $E_1 \lesssim \Gamma_{spr}$ to satisfy the principal component condition $|E_{\mu,\nu} + E_1 - E| \lesssim \Gamma_{spr}$. These lowest target nucleus states are relatively simple: ground state (valence mechanism), one excited nucleon state, vibrational or rotational excitation (in deformed nucleus). Note that these states belong to "doorway" states which determine the spread width of the neutron state in the nucleus (the processes are 1 particle $\longrightarrow$ 2 particle + 1 hole, 1 particle + phonon, 1 particle + rotation). After averaging over the compound resonances there is structure corresponding to the position of these states. Therefore, the "doorway" part of the compound-state wave function is, roughly speaking, similar in every compound resonance (expansion coefficients are proportional to neutron capture amplitude $T = \sqrt{\Gamma^n}$ and can be described approximately by perturbation theory in a residual nucleon-nucleon interaction). Consequently, this part of the compound-state wave function gives a regular contribution to the PNC effect. Moreover, there is a coherent definite sign contribution (see Sec. IV "quasielastic" contribution).

Thus, we have shown that in a spherical nucleus the principal components of a compound-state wave function give regular contribution to the PNC effect.

In a deformed nucleus there can be low-lying opposite parity levels with small energy intervals ($|E_+ - E_-| \lesssim \Gamma_{spr}$). However, there can be only a few such levels with the same angular momentum. Matrix elements of the weak interaction between these states are not large because bound-state wave functions are smaller at the surface due to the boundary condition [remember that $\tilde{W} \sim \delta(r-R)$]. They also have different angular parts of wave functions (see Nilsson coefficients, e.g., in Ref. [31]) which suppress weak mixing. In other words, the states in the deformed nucleus "remember" their spherical origin and the distance between "well-mixed" states is still large. In this case, the above discussion is applicable to deformed nuclei also. However, I should also present an argument in favor of the possible importance of low-lying opposite parity states.

Due to the small energy of the excitation, the rest of the neutron capture energy can be used for excitation of several more particles. The number of possible states increases exponentially with the number of excited particles. In other words, there are many principal components in the compound-state wave functions ψ_s and ψ_p which have the structure like $\psi_1|+\rangle$ and $\psi_1|-\rangle$, where $|+\rangle$ and $|-\rangle$ are low-lying simple opposite parity states with the same angular momentum. All of them contribute to the PNC effect which is proportional to $\langle+|\tilde{W}|-\rangle$. However, there are no reliable arguments that this contribution has the same sign for different compound resonances since many-particle components of the wave function have very complicated structure and coefficients $b^*_\alpha c_\beta$ for these components are probably random (one could try to consider correlations between these components—see next section).

One can also consider the contribution of "small" components of the compound-state wave function which do not satisfy the "principal component condition": $|E_\alpha - E| \lesssim \Gamma_{spr}$. In the simple model of constant level density the coefficients before small components decrease like (see, e.g., Ref. [31])

$$c_\alpha \sim \frac{1}{\sqrt{N}} \frac{\frac{1}{2}\Gamma_{spr}}{\sqrt{(E_\alpha - E)^2 + \frac{1}{4}\Gamma^2_{spr}}} \sim \frac{1}{\sqrt{N}} \frac{\Gamma_{spr}/2}{E_\alpha - E}, \tag{29}$$

i.e., we have a suppression factor for the small component contribution $\sim \Gamma_{spr}/2(E - E_\alpha)$. Opposite parity single-particle levels in a spherical nucleus are separated by the interval $\Delta E \sim 8$ MeV. If one component, say, $|\psi_1\rangle|\varphi^+_\mu\rangle$, is principal, another component $|\psi_1\rangle|\varphi^-_\nu\rangle$ is suppressed by the factor $\Gamma_{spr}/2\Delta E \lesssim 1/10$ (see Refs. [11,12,29]). States φ^+_μ and φ^-_ν are bound states, so they are not large at the nuclear surface and hence the matrix element $\langle+|\tilde{w}|-\rangle$ is not large. The contribution of small components to weak matrix elements between compound states is probably random since ψ_1 is, generally speaking, a excited many-particle wave function.

The conclusion from this section is the following. The "quasielastic" components of a compound-state wave function (states of the type $\varphi\psi_1$ where φ is a doorway neutron state, and ψ_1 is low-lying excited target nucleus state) are the most probable candidates for the regular contribution to PNC effect. They are principal components of the compound-state wave function; doorway neutron wave functions φ_s and φ_p are large at the nuclear surface and have maximal weak matrix element $\langle\varphi_s|\tilde{w}|\varphi_p\rangle$; there is coherent definite sign contribution of such components (see next section).

The coherent contribution to the weak matrix element (27) is proportional to the number of coherent components N_c. It is necessary to compare this number with a random contribution. Similar to the well-known random-walk problem, the incoherent contribution is proportional to $\sqrt{N}$. The incoherent contribution is given mostly by a small component of the compound-state wave function; i.e., it contains the suppression factor $\Gamma_{spr}/\Delta E \sim 1/10$. Correspondingly, bound nucleon orbitals are not large at the nuclear surface and have a 3–10 times smaller matrix element of weak interaction than $\langle\varphi_s|\tilde{w}|\varphi_p\rangle$. In other words, due to boundary conditions the compound-state wave function at the nuclear surface is more "regular" than inside the nucleus.

To explain the results of experiments regular enhancement N_c should not be smaller than "random" enhancement

$$\sim \sqrt{N}\frac{\Delta E}{5\Gamma_{spr}} \sim \sqrt{N}/50 \quad \text{for} \quad N \sim 10^4 - 10^6\,. \tag{30}$$

Therefore, we need $N_c > 10$. This value of the enhancement factor is also necessary to explain the magnitude of the observed effect. The estimate of a "quasielastic" components number probably satisfies this condition.

IV. QUASIELASTIC MECHANISM, DOORWAY STATES, AND GIANT RESONANCES

We can write expansion (16) in another form:

$$\Psi_c^s = \varphi_s \psi_1^s + \varphi_p \psi_2^s + \quad \text{other components}\,, \tag{31}$$

$$\Psi_c^p = \varphi_p \psi_1^p + \varphi_p \psi_2^p + \quad \text{other components}\,. \tag{32}$$

Here we separate the "quasielastic scattering" contribution: φ_s and φ_p are s-wave and p-wave parts of the scattering neutron wave function [see Eq. (11)], and ψ_1 and ψ_2 are the sum of target nucleus states, ψ_1 containing the states of the same parity as the ground state:

$$\psi_1 = \psi_t + \sum c_i \psi_{it}\,, \tag{33}$$

ψ_{it} are the states with one, two, etc. excited nucleons, phonons, rotations. ψ_2 contain opposite parity states. (We use here a more extended definition of quasielastic states than in the preceding section.) "Other components" include the states of the compound nucleus with the initial neutron "fallen down" to a deeper bound state.

"Doorway" neutron states φ_s and φ_p can be considered simply as basis orbitals with $E \approx 0$ (part of complete basis set of orbitals). Actually, the asymptotic behavior of $E = 0$ orbitals outside the nucleus is $r^{-\ell}$, where ℓ is orbital angular momentum. We see that near the resonance φ_s and φ_p have such behavior [Eqs. (11), (12), and (13)]. Now consider the PNC amplitude (9), (19). It is proportional to matrix element of the PNC interaction (8):

$$\langle \Psi_s|\tilde{w}|\Psi_p\rangle = \langle \varphi_s|\tilde{w}|\varphi_p\rangle\langle \psi_1^s|\psi_1^p\rangle + \langle \varphi_p|\tilde{w}|\varphi_s\rangle\langle \psi_2^s|\psi_2^p\rangle$$
$$+\text{other component contribution.} \tag{34}$$

If one considers only the ground state of the target nucleus ψ_t in ψ_1^s and ψ_1^p [see Eq. (33)], the overlapping $\langle \psi_1^s|\psi_1^p\rangle$ is proportional to the weight of this component $1/N$ (valence contribution). However, the overlapping $\langle \psi_2^s|\psi_2^p\rangle$ is really much larger. The point is that the states ψ_2^s and ψ_2^p are excited from the target nucleus by the same strong field $\langle \varphi_s|V_{\text{strong}}|\varphi_p\rangle$ of the scattered neutron (see diagrams in Fig. 1). In other words, corresponding diagrams for the parity nonconserving amplitude (Fig. 2) contain a vertex of strong interaction $\langle \varphi_s|V_{\text{strong}}|\varphi_p\rangle$ squared and have definite sign (strictly speaking, states ψ_2^s and ψ_2^p do not coincide exactly due to interaction with other parts of compound-state wave functions which are

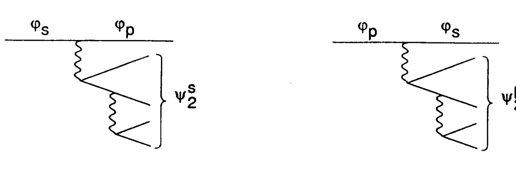

FIG. 1. Diagrams describing dipole "quasielastic" excitation of target nucleus by scattered neutron. The wavy line is the strong nucleon-nucleon interaction.

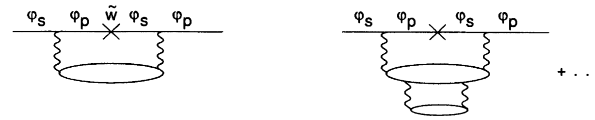

FIG. 2. Diagrams describing contribution of dipole "quasielastic" excitations to the parity nonconserving amplitude. Here in the intermediate state (cut of the loops) we have component of states ψ_2^s and ψ_2^p. Cross is the weak interaction.

different for s and p compound states). The states ψ_1^s and ψ_1^p in Eqs. (31) and (32) are excited by different fields $\langle \varphi_s|V_{\text{strong}}|\varphi_s\rangle$ and $\langle \varphi_p|V_{\text{strong}}|\varphi_p\rangle$ (see Fig. 3). However, both of these neutron states give a monopole field ($\sim \varphi_s^2$ or φ_p^2), and probably there is some coherent contribution too.

The contribution of the "quasielastic" part of the compound state (Figs. 1, 2, and 3) contains practically the same matrix element of weak interaction $\langle \varphi_s|\tilde{w}|\varphi_p\rangle$ as the "elastic" valence contribution (14) and (15). Therefore, we can write

$$P \sim P^v Q\,. \tag{35}$$

The enhancement factor Q is of the order of the number of "quasielastic" components N_q in the full compound-state wave function (16).

We can give a rough upper estimate of this number. One can write down the compound state ψ_c in the following form: $\psi_c = \sum_n \varphi_n \psi_n$. Here φ_n is a captured neutron state, and ψ_n is a sum over the possible target nucleus states. The total number of single-particle empty discrete states of the neutron is $\sim 10^2$. But the "quasielastic" contribution corresponds to the φ_s and φ_p states only. If all excited neutron states have equal probability, $N_q/N \sim 10^{-2}$ or $N_q \sim 10^3 - 10^4$.

It is easy to argue that in this estimate the value of N_q is overestimated. First, the residual nucleon-nucleon interaction most effectively admixes states φ_α in Eq. (16) within the simple state spread width (principal components, $|E_\alpha - E| \lesssim \Gamma_{spr} \sim 1$ MeV). The neutron components φ_s and φ_p in the "quasielastic" state have energy E. Therefore, target nucleus wave functions $\psi_1^{s,p}$ and $\psi_2^{s,p}$ include effectively only the lowest states with excitation energy $E_1 \lesssim \Gamma_{spr} \sim 1$ MeV. The density of states in this region is small, i.e., the number of "principal" components in the wave function Ψ_c, which contain φ_s and φ_p, is not large ($\sim$ 10). The residual nucleon-nucleon interaction also can admix higher states with energy $E_1 > \Gamma_{spr}$. The density of these states is much higher but their "weight"

FIG. 3. Monopole "quasielastic" excitation of target nucleus.

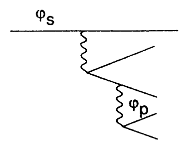

FIG. 4. Indirect excitation of the state $\varphi_p \psi_2^s$.

is suppressed by the factor $(\Gamma_{spr}/E_1)^2$ ("small" component weight).

The second argument is that there are other diagrams (see, e.g., Fig. 4) which show a similar contribution to the compound-state wave function $(\varphi_s \psi_1^s + \varphi_p \psi_2^p + \cdots)$ or the PNC amplitude. These diagrams correspond to interaction with "other components" in the wave functions (31) and (32), which are different for different compound resonances. Therefore, the "quasielastic" parts of the compound-state wave function (31) and (32) also provide some incoherent contribution.

We can look at this question in a more detailed way. After decay of a single-neutron state at the first step we have simple "doorway" states (2 particle + 1 hole, 1 particle + phonon, 1 particle + rotation). It is reasonable to suppose that the contribution of these states to the PNC effect is regular since they are similar in every compound resonance. (Remember that only some "doorway" states are "quasielastic" states which give a coherent contribution rather than simply a regular contribution.) One could suppose that after decay of these simple states to more complicated states (3 particle + 2 hole, etc.) there also could be a regular part of the compound-state wave function. During this decay process the number of possible states increases exponentially; i.e., one could obtain large regular enhancement. A natural question arises: At what step does the regular wave function transform into a "random" wave function of the compound state? The possible answer is: It depends on how many ways this component of the wave function can be created. The regular way corresponds to the creation of a state from the shortest chain of decays of the initial neutron state. However, there are also possibilities of this state creation after many steps, from more complicated states.

Let us try to develop a formalism to describe this process. Quasielastic contribution to the weak matrix element is equal to [see formulas (33), (34)]

$$\langle \Psi_s|\tilde{w}|\Psi_p\rangle = \langle \varphi_s|\tilde{w}|\varphi_p\rangle \left(\sum_\alpha c_\alpha^{1s} c_\alpha^{1p} - c_\alpha^{2s} c_\alpha^{2p}\right)$$

$$= \langle \varphi_s|\tilde{w}|\varphi_p\rangle (N_q^1 - N_q^2) \; ; \tag{36}$$

$$N_q = \sum_\alpha c_\alpha^s c_\alpha^p \tag{37}$$

is the effective number of coherent components, and c_α^s and c_α^p are the coefficients before the same states of target nucleus excited by the s-wave or p-wave neutron capture. Note that here we use normalization $c_0^s = c_0^p = 1$, c_0 is the coefficient before unexcited target state [see formula (33)]. Let us introduce classification of the target nucleus excited states. Let w_n be the effective number of states which appear at the nth step of single-captured-neutron state decay (nth order of perturbation theory in the residual nucleon-nucleon interaction). Then

$$N_q = \sum_n \langle c_n^s c_n^p \rangle W_n \; . \tag{38}$$

Here we introduce correlator (average value at fixed n) of the coefficients before similar target nucleus states in s-wave and p-wave compound states: $\langle c_n^s c_n^p \rangle$. Summation is carried out over decay steps n. The number of possible states increases with n exponentially.

Therefore, we can write down

$$W_n = g_n e^{-\langle E_n \rangle/T} \; , \quad g_n \approx e^{\alpha n} \tag{39}$$

is the "statistical weight" of the states which can appear at the nth step, T is the temperature of the target nucleus "heated" by captured neutron. Energy E_n can be estimated roughly as $E_n = nE_0$, E_0 is the average energy of excitation of one nucleon from the open shell or phonon, $E_0 \sim 1$ MeV. We assume that at every step one extra quasiparticle is excited. Thus, we have a simple exponential estimate for the effective number of quasielastic components at the nth step:

$$W_n = g_n e^{-E_0 n/T} = e^{(\alpha - E_0/T)n} \; . \tag{40}$$

Exponential ansatz also looks reasonable for the correlator of the coefficients:

$$\langle c_n^s c_n^p \rangle = e^{-\beta n} \; . \tag{41}$$

Really, correlations between component coefficients should rapidly decrease when the number of possible states increases. The hint for the law of this decrease can be obtained by means of perturbation theory consideration. We can suppose that in zero approximation there is no correlation between the coefficients of two states in compound-state wave function, say, c_α and c_β, which are not connected by the matrix element of the interaction H_{str}, i.e., $\langle c_\alpha c_\beta \rangle = 0$ (average at fixed n, n'). If we introduce the matrix element of the interaction between these states, the coefficients have to change according to perturbation theory:

$$\Delta c_\beta = \frac{\langle \psi_\beta | H_{str} | c_\alpha \psi_\alpha \rangle}{E - E_\beta} = c_\alpha \frac{\langle \beta | H_{str} | \alpha \rangle}{E - E_\beta} \; ,$$

$$\Delta c_\alpha = \frac{\langle \psi_\alpha | H_{str} | c_\beta \psi_\beta \rangle}{E - E_\alpha} = c_\beta \frac{\langle \alpha | H_{str} | \beta \rangle}{E - E_\alpha} \; , \tag{42}$$

$$\langle (c_\alpha + \Delta c_\alpha)(c_\beta + \Delta c_\beta) \rangle$$

$$= \left\langle |c_\alpha|^2 \frac{\langle \beta | H_{str} | \alpha \rangle}{E - E_\alpha} + |c_\beta|^2 \frac{\langle \alpha | H_{str} | \beta \rangle}{E - E_\beta} \right\rangle \; .$$

We see that mixing matrix elements provides nonzero correlator between coefficients. If there is no direct matrix element, correlator can appear in second, third, etc. order. Approximately, one can write

$$\langle c_n c_{n+2}\rangle = \frac{\langle c_n c_{n+1}\rangle\langle c_{n+1} c_{n+2}\rangle}{\langle c_{n+1}\rangle^2} \ . \tag{43}$$

In this situation exponential ansatz for correlator looks natural:

$$\langle c_n^s c_n^p\rangle = e^{-\beta n} \ . \tag{44}$$

Remember that $c_0^s = c_0^p = 1$ and we consider here correlator between the same states ψ_{it} in s and p compound resonances. Thus, we have

$$\begin{aligned} N_q &= \sum_{n=0}^{m} q^n = \frac{q^{m+1}-1}{q-1} \ , \\ q &= \langle c_n^s c_n^p\rangle w_n = e^{(\alpha - E_0/T - \beta)} \ . \end{aligned} \tag{45}$$

Here q is the effective parameter describing an increase of effective number of quasielastic states at every step of decay, m total number of steps. It is reasonable to suppose that at every step one extra nucleon or phonon is excited. The number of these excitations is limited by the maximal energy transfer to target nucleus and by the number of the nucleons in the unclosed shell. It is reasonable to suppose that $m \sim 5$. We used here normalization on valence component of compound resonances ($c_0 = 1$). Therefore, the value of PNC effect is equal to the resonance part of valence mechanism contribution times $N_q = N_q^1 - N_q^2$:

$$\begin{aligned} P &= \frac{2}{k}\frac{G q_n}{\sqrt{2}}\rho_0 \frac{\mathrm{Re}(f_0^{\mathrm{res}})}{R} N_q \\ &= 0.5 \times 10^{-3} g_n \sqrt{\frac{1\ \mathrm{eV}}{E}}\frac{\mathrm{Re}(f_0^{\mathrm{res}})}{R} N_q \ . \end{aligned} \tag{46}$$

If we compare this value, e.g., with experimental value of P for 8.3 eV ^{232}Th p-wave resonance we obtain $|g_n N_q| \approx 850$ or $q \approx 3.8$ for $m = 5$ (main s-wave resonance with $E = -9.38$ eV gives $f_0^{\mathrm{res}}/R = -1/9$). It means that at the first step about four quasielastic doorway states effectively "work." This number looks compatible with the number of low-lying target nucleus states with appropriate spin.

What could one conclude from this picture? Correlation between the coefficients of different compound states is really very small [$\sim \exp(-\beta n) <<< 1$]; i.e., the states look like "random" states. However, it does not mean that matrix element is random. Even very weak correlations (average degree of coherency $N_q/N \sim 10^{-3}$) due to very large number of correlating components give large definite sign contribution.

It is possible to estimate parameters α [number of states $\exp(\alpha n)$], E_0 (minimal excitation energy), and temperature of target nucleus T for different nuclei. Then one could extract correlator parameter β (roughly speaking, it is "correlation time" in units of nucleon free path time in compound nucleus). It is also interesting to carry out model numerical calculations for a few-nucleon system in the nucleus effective potential to determine β.

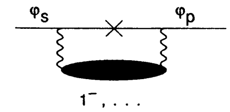

FIG. 6. Contribution of giant resonance excitation to PNC amplitude.

One can try to separate the coherent contribution among other "doorway" states (nonquasielastic) by separation of definite sign diagrams. However, in this case this separation is not as in the "quasielastic" mechanism where it was enough to separate symmetric diagrams for the PNC amplitude. Here the result depends on a strong interaction dynamic. For example, the strong fields $\langle s|V_{\mathrm{strong}}|a\rangle$ and $\langle b|V_{\mathrm{strong}}|p\rangle$ can have the same multipolarity (see diagram in Fig. 5), i.e., they excite the same states. Thus, one can suppose that decay of these states also could be similar, i.e., higher-order diagrams could have the same sign. However, as was shown in Sec. III this contribution is suppressed by the factor $\Gamma_{spr}/\Delta E \sim 1/10$, at least for a spherical nucleus.

Neutron strong (Fig. 6) or weak (Fig. 7) field can excite a giant resonance. In the first case we once more have a "quasielastic" or "doorway" contribution (cf. Fig. 2 or Fig. 5). The excitation by the weak field in Fig. 7 looks more attractive since the absorbed energy of neutron capture is enough to be close to the maximum of some resonances (e.g., 0^-). We should note, however, that this process changes the states of both the neutron and target nucleus, i.e., it is not described by a weak nuclear potential (7) and (8). These nondiagonal over target nucleus weak matrix elements are smaller than the matrix elements of the weak nuclear potential since in a potential target nucleons "work" coherently. Therefore, giant resonances probably do not explain enhancement of the regular effect.

Note that the contribution of weak 0^- giant resonance to PNC effects was first discussed in Ref. [12]. However, the mechanism considered in Ref. [12] gives a random sign for PNC effects.

There is one more possibility. One can consider a set of 0^- states (or 0^- giant resonance) admixed to the ground state of the nucleus by weak potential $\tilde{w}$ and scattering of neutrons on a mixed state $|0^+\rangle + \alpha|0^-\rangle$. However, in this case we have a large energy denominator between states $|0^+\rangle$ and $|0^-\rangle$ and a small mixing coefficient $\alpha \sim 10^{-6} - 10^{-7}$. This smallness compensates for the possible

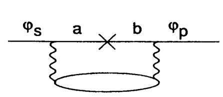

FIG. 5. Doorway state contribution to PNC amplitude.

FIG. 7. Excitation of giant resonance by weak field of neutron.

factor of coherence typical for giant resonances. There could be several times the enhancement in a deformed nucleus where the distance between opposite parity state and ground state is smaller. However, it is probably not enough to explain the effect.

The conclusion of this section is the following: "Quasielastic" components of a compound state (excitations of target nucleus open shells, phonons, and rotation) give a coherent contribution to PNC effects. There is also coherent contribution from simple "small" quasielastic components with excitation energy $\Delta E \gtrsim 5$ MeV (closed-shell excitations or giant resonances) and other doorway components. The number of these components is about $A^{2/3}$ or even more, but corresponding states are high states and their contribution is suppressed by the factor $\Gamma_{spr}/\Delta E \sim 1/10$.

V. EFFECTS OF TIME INVARIANCE VIOLATION

A T- and P-parity nonconserving nuclear potential has the following form:

$$W_{PT} = \frac{G}{2\sqrt{2}m}\eta\bar{\sigma}\cdot\bar{\nabla}\rho' \ , \qquad (47)$$

where η is a dimensionless constant characterizing the strength of T- and P-odd interactions. Similar to $\tilde{w}$ the operator w_{PT} is proportinal to ρ', i.e., the main contribution to the matrix element comes from the nuclear surface. In this situation we can hope that P- and T-odd effects will be approximately proportional to the observed P-odd effects in p-wave compound resonances.

A thorough discussion of T,P-odd effects can be found in Ref. [32]. The effect in neutron propagation is described by the amplitude

$$\hat{f}_{TP} = f_{TP}\frac{\boldsymbol{\kappa}}{\kappa}\left(\frac{\mathbf{s}}{s}\times\frac{\mathbf{I}}{I}\right) \ , \qquad (48)$$

where $\bar{\kappa}$, s are neutron momentum and spin, $\mathbf{I}$ is target nucleus spin. This amplitude describes rotation of the neutron spin s around the direction $\bar{\kappa}\times\bar{\mathbf{I}}$.

It is easy to calculate the ratio of T,P-violating amplitude $f_{T,P}$ to the parity nonconserving amplitude $\hat{f}_{\rm PNC} = f_{\rm PNC}\bar{s}\cdot\boldsymbol{\kappa}/s\kappa$ using wave function (11) and the expression for the amplitude (9) (valence mechanism):

$$\frac{f_{TP}}{f_{\rm PNC}} = \frac{\eta}{2g}\,\frac{(1+f_0/R)}{(1+2f_0/R)}C(J,I) \ , \qquad (49)$$

where $C(J,I)$ is a coefficient depending on spins of target nucleus (I) and compound resonance (J). For example, $C(J=0,I=\frac{1}{2})=1$, $C(1,\frac{1}{2})=-\frac{1}{3}$. The reader should note that the angle of neutron spin rotation is proportional to Re(f), difference of cross sections to Imf. For $f_{\rm PNC}$ the result is averaged over the target spin orientation.

When we consider the "quasielastic" mechanism, the ratio of the amplitudes will be close to estimate (49) since the factor of enhancement Q is the same. However, there is a reason to improve this estimate. The point is that all the components of compound state [except for "elastic" component (11)] have no exit to the continuous spectrum. Therefore, it is more correct to consider basis states φ_s and φ_p as bound neutron states with $E=0$. In this case outside the nucleus $\varphi_p \sim 1/r^2$, $\varphi_s \sim 1/r$; i.e., there is no constant term (unity) in the s-wave. In this case the ratio of "quasielastic" amplitudes and the ratio of T,P-odd and P-odd effects is

$$\frac{P_{TP}}{P_{\rm PNC}} = \frac{f_{TP}}{f_{\rm PNC}} = \frac{\eta}{g}C(J,I) \ . \qquad (50)$$

Actually, the difference between Eqs. (49) and (50) is within the accuracy of calculations which is not high due to "random" contributions of other compound-state components. However, we should note that this accuracy is good enough to extract the value of T,P-odd constant η from corresponding experiments since the accuracy of calculation of the constant η in the framework of different CP-violation models is even lower.

VI. DYNAMICAL ENHANCEMENT OF SMALL INTERACTIONS: BEHAVIOR UNDER AVERAGING, OTHER REACTIONS, AND OTHER SYSTEMS; INTERESTING EXPERIMENTS

From the point of view of perturbation theory, enhancement of a small perturbation in the quantum system with a dense spectrum looks natural. However, regular enhancement observed in neutron experiments [1,2] can essentially influence the conclusion. First, the factor of enhancement is probably better estimated as N_q (N_q is the number of coherently "working" components in compound-state wave function) rather than $\sqrt{N}$ (N is the total number of components). Second, the behavior under averaging over a large energy interval is completely different for regular enhancement and "random" enhancement. For "random" enhancement the effect disappears after averaging over the neutron energy; the factor of suppression is $1/\sqrt{N_r}$, N_r is a number of involved resonances. For regular enhancement we have no such suppression (there can be suppression due to the smallness of the p-wave resonance contribution to the average cross section; it disappears for high neutron energy).

What experiments can clear up the nature of enhancement? First, it is interesting to measure the value of effects for many p-wave resonances in spherical nuclei where there are no low-lying opposite parity levels. (It can exclude some possibilities connected with such levels.) It would be interesting also to measure the nonresonance contribution to PNC effects (e.g., in thermal point). The valence model, for example, gives a more or less definite prediction for the ratio of resonance and nonresonance contributions. It is also natural to suppose that in any model predicting the permanent sign of the effects there could be a sizable contribution from distant resonances (which is in fact a nonresonance contribution).

An average over resonances effect could be observed in absorption of more energetic neutrons with an energy

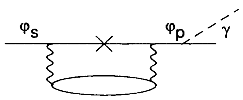

FIG. 8. "Quasielastic" mechanism for (n,γ) reaction.

$\sim 1-1000$ keV. In this case one will see only a regular contribution. It could be compared with the regular part of the effect which was observed in low-lying p-wave resonances. It is also interesting to estimate "energy correlation interval" by varying energy resolution.

It is even more interesting to measure PNC effects in many resonances for other reactions: neutron or proton radiative capture, fission, etc. Quasielastic mechanism of enhancement can work in the (n,γ) reaction if an electromagnetic transition goes to the ground or low state. In this case a single-particle component of the compound-state wave function (φ_s or φ_p) gives considerable contribution to the electromagnetic amplitude and the situation is similar to neutron scattering (see Fig. 8).

The case of γ transition to a high compound state or neutron fission is more complicated. There is an additional question: Is there a correlation between neutron capture amplitude and γ emission or fission amplitude? To obtain the answer experimentally one does not need to measure PNC effects. It is enough to measure the usual P-odd harmonics in an angular distribution ($\kappa_n\kappa_\gamma, \sigma_n(\kappa_n \times \kappa_\gamma)$; σ_n, κ_n are neutron spin and momentum, κ_γ is γ or light fragment momentum; see, e.g., Refs. [4,34,35,36]). In the (n,γ) reaction they are caused by interference of different parity capture and emission amplitudes: T_sM1 and T_pE1, etc.; in fission they are due to interference of opposite parity fission channels. Such measurements for many resonances or with low-energy resolution ($\Delta E \gg D$) could be very interesting tests of statistical theory of the compound state since they are sensitive to the relative signs of the amplitudes.

There is another way to pose the question: What is the dependence of the interference effects on the final state? In the case of fission the answer is known: The effect survives after averaging over final states (see experiment [22] and theory [4,17]). There have been experimental measurements of PNC effects in an integral γ-quantum spectrum. Probably the results do not contradict the random signs of radiation amplitudes [35,37]. However, it is now reasonable to carry out a more detailed investigation: to do measurements for different energy intervals of γ quanta, to measure parity conserving interference effects $\bar{\kappa}_n\bar{\mathbf{p}}_\gamma$ and $\bar{\kappa}_n(\bar{\sigma}_n \times \bar{\mathbf{p}}_\gamma)$.

The effects of dynamical enhancement of a small perturbation can also appear in other systems with dense spectra. The possibility of enhancement is especially important if the effect survives for poor energy resolution (averaging over some energy interval). I will simply list selected systems and possible interesting effects.

(1) Rare-earth and actinide atoms: search for T- and P-violating effects [38].

(2) Complex molecules: appearance of right-left asymmetry of biological molecules due to weak interaction influence on chemical reactions.

(3) Spin system (spin liquid and spin glass): Spin liquid state is probably realized in high-temperature superconductors. Possible effects: enhancement of interaction with admixture, interaction of localized spins with mobile hole or even enhancement of electron-electron interaction which leads to superconductivity. This question is the result of discussions with O. P. Sushkov.

(4) Atomic clusters and mesoscopic systems (quantum dots and rings in solids): transition from microscopic quantum system to macroscopic classical system, "violation" of quantum mechanics (e.g., disappearance of interference, superposition principle) due to enhancement of external noise or extra nonlinear term in the Schrödinger equation. This last question is also the result of discussion with O. P. Sushkov.

The experiment with rare-earth atoms is now in preparation [39]. As for questions (2)–(4) the existence of the effects here is at least not obvious. From one side, the distance between the energy levels $\mathcal{D}$ decreases exponentially with the number of particles. According to perturbation theory this could lead to very large enhancement of a small perturbation. From the other side, nobody has seen enhancement in macroscopic systems with infinitely dense spectra. There are several explanations for the "killing" of enhancement.

(1) Width of the states; effect is proportional to $(\mathcal{D}+i\Gamma)^{-1}$.

(2) Finite energy resolution ΔE; in the case of the random signs of the amplitudes the suppression of the effect $\sim 1/\sqrt{N_r} \sim \sqrt{\mathcal{D}/\Delta E}$, N_r is the number of levels within ΔE. Maximal enhancement in this case $\sim \sqrt{\Gamma_{spr}/\Delta E}$ instead of $\sqrt{\Gamma_{spr}/\mathcal{D}}$. However, in the case of the permanent sign amplitudes (as was observed in neutron capture) there is no such suppression.

(3) Conservation laws (momentum, angular momentum, etc.) which forbid greater part of matrix elements. However, they do not work well in the system with a "random" surface or "random" amixtures (remember the well-known example of a classical chaotic system: stadium with the balls). A realistic example of such a system is the "quantum dot" in a solid.

(4) And, of course, there is a trivial reason: Simple perturbation theory is not applicable if perturbation is larger than the distance between the levels.

Computer modeling of excited state systems of rare-earth atoms, molecules, clusters, and quantum dots probably could clear up these questions. And, of course, experimental investigation looks very interesting. For example, measurements of matrix elements between excited states of rare-earth atoms [39] (Stark shifts in excited states, electromagnetic amplitudes, PNC effects), angular and spin correlations which are due to interference of different electromagnetic amplitudes (e.g., $M1$, $E2$, and Stark amplitudes) or electron scattering amplitudes, spectra in more complicated systems (e.g., quantum dots), could be very useful.

VII. CONCLUSION

Transformation of a weak Hamiltonian expresses the value parity nonconserving effects in terms of a wave function at the nuclear surface. Due to boundary conditions, a wave function at the surface is not random even for very complicated compound nuclear states. This gives a possible qualitative explanation of "nonrandom" distribution of the values of measured PNC effects.

A mechanism that can explain both the permanent signs and large values of observed PNC effects is suggested. It is the contribution of the "quasielastic" part of the compound-state wave function (virtual excitation of target nucleus with no essential changes in the wave function of captured neutron). There are correlations among the coefficients before these "quasielastic" components in compound-state wave function. These correlations rapidly decrease during the "decay" process of doorway state. However, the coherent contribution due to these correlations is not small because of the very large number of components. Other doorway states and giant resonance contributions to PNC effects also can have permanent signs and are worth special consideration. However, these contributions are probably smaller than the "quasielastic" one.

The value of the T- and P-odd effects can be expressed in terms of measured PNC effects.

To clear up the nature of regular enhancement it is interesting to measure nonresonance background for the PNC effect, effects for many p-wave resonances in spherical nuclei, effects averaged over some energy interval for $1-1000$ keV neutrons, effects in other reactions: (n,γ), (p,γ), (n, fission).

The phenomenon of enhancement of small perturbations could exist in other systems: rare-earth and actinide atoms, complex molecules, atomic clusters, mesoscopic systems, spin liquid and spin glass.

And, finally, I would like to stress that the main purpose of this paper is to pose the questions and to attract attention to some ideas rather than to answer all the questions.

ACKNOWLEDGMENTS

The author is grateful to O. P. Sushkov and J. Price for useful discussions, and to D. Bowman, C. R. Gould, G. E. Mitchell, and N. R. Roberson for sharing their results (Ref. [2]) prior to publication. He thanks the staff of JILA Scientific Reports Office for their assistance in the preparation of this paper. This paper was supported in part by NSF Grant No. PHY89-04035.

[1] J. D. Bowman *et al.*, Phys. Rev. Lett. **65**, 1192 (1990).
[2] C. M. Frankle *et al.*, Phys. Rev. Lett. **67**, 564 (1991).
[3] O. P. Sushkov and V. V. Flambaum, Pis'ma Zh. Eksp. Teor. Fiz. **32**, 377 (1980) [JETP Lett. **32**, 353 (1980)]; INP Reports Nos. 80-148, 1980 and 81-37, 1981.
[4] O. P. Sushkov and V. V. Flambaum, Usp. Fiz. Nauk **136**, 3 (1982) [Sov. Phys. Usp. **25**, 1 (1982)]; 16th LINP Winter School Proceedings, p. 200 (Leningrad, 1981).
[5] V. A. Karmanov and G. A. Lobov, Pis'ma Zh. Eksp. Teor. Fiz. **10**, 332 (1969) [JETP Lett. **10**, 212 (1969)]; G. A. Lobov, Izv. Acad. Nauk SSSR (Ser. Phys.) **34**, 1141 (1970).
[6] M. Forte, in *Higher Energy Polarized Beams (Ann Arbor, 1977)*, Proceedings of the Workshop on Higher Energy Polarized Proton Beams, edited by A. D. Kirsch and A. J. Salthouse, AIP Conf. Proc. No. 42 (AIP, New York, 1978), Chap. 2, p. 86.
[7] L. Stodolsky, Phys. Lett. **50B**, 352 (1974); **96B**, 127 (1980).
[8] F. C. Michel, Phys. Rev. **329**, B133 (1964).
[9] G. Karl and D. Tadic, Phys. Rev. C **16**, 1726 (1977).
[10] V. E. Bunakov and V. P. Gudkov, Z. Phys. A **303**, 285 (1981); Nucl. Phys. **A401**, 93 (1983).
[11] D. F. Zaretsky and V. I. Sirotkin, Yad. Fiz. **37**, 607 (1983) [Sov. J. Nucl. Phys. **37**, 361 (1983)]; **45**, 1302 (1987) [**45**, 808 (1987)].
[12] S. G. Kadmensky, V. P. Markushev, and V. I. Furman, Yad. Fiz. **37**, 581 (1983) [Sov. J. Nucl. Phys. **37**, 345 (1983)].
[13] S. Noguera and B. Desplanques, Nucl. Phys. **A457**, 189 (1986).
[14] R. Haas, L. B. Leipuner, and R. K. Adair, Phys. Rev. **116**, 1221 (1959).
[15] R. J. Blin-Stoyle, Phys. Rev. **120**, 181 (1960).
[16] I. S. Shapiro, Usp. Fiz. Nauk **95**, 647 (1968) [Sov. Phys. Usp. **11**, 582 (1969)].
[17] O. P. Sushkov and V. V. Flambaum, Yad. Fiz. **33**, 59 (1981) [Sov. J. Nucl. Phys. **33**, 31 (1981)].
[18] J. B. French *et al.*, Ann. Phys. (N.Y.) **181**, 235 (1988); **181**, 198 (1988).
[19] O. Bohigas and H. A. Weidenmüller, Annu. Rev. Nucl. Part. Sci. **38**, 421 (1988).
[20] G. E. Mitchell *et al.*, Phys. Rev. Lett. **61**, 1473 (1988).
[21] Yu. G. Abov and P. R. Krupchitskii, Usp. Fiz. Nauk **118**, 141 (1976) [Sov. Phys. Usp. **19**, 75 (1976)], and references therein; G. V. Danilyan *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 380 (1976) [JETP Lett. **24**, 344 (1976)]; Benkoula *et al.*, Phys. Lett. **71B**, 287 (1977).
[22] G. V. Danilyan *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 197 (1977) [JETP Lett. **26**, 186 (1977)]; B. D. Vodennikov *et al.*, *ibid.* **27**, 68 (1978) [**27**, 62 (1978)]; V. N. Andreev *et al.*, *ibid.* **28**, 53 (1978) [**28**, 50 (1978)]; Petukhov *et al.*, *ibid.* **30**, 470 (1979) [**30**, 439 (1979)]; V. A. Vesna *et al.*, *ibid.* **31**, 704 (1980) [**31**, 663 (1980)], and references in Ref. [4].
[23] V. P. Alfimenkov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **34**, 308 (1981) [JETP Lett. **34**, 295 (1981)]; Nucl. Phys. **A398**, 93 (1983); Usp. Fiz. Nauk **144**, 361 (1984) [Sov. Phys. Usp. **27**, 797 (1984)].
[24] A. Biryukov *et al.*, Yad. Fiz. **45**, 1511 (1987) [Sov. J. Nucl. Phys. **45**, 937 (1987)].
[25] Y. Masuda *et al.*, Nucl. Phys. **A504**, 269 (1989).
[26] G. D. Bowman, J. D. Bowman, and V. W. Yand, Phys. Rev. C **39**, 1721 (1989).
[27] M. Forte *et al.*, Phys. Rev. Lett. **45**, 2088 (1980).
[28] E. A. Kolomensky *et al.*, Phys. Lett. **107B**, 272 (1981);

V. A. Vesna *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 351 (1982) [JETP Lett. **35**, 433 (1982)]; Yu. G. Abov *et al.*, Yad. Fiz. **40**, 1585 (1984) [Sov. J. Nucl. Phys. **40**, 1006 (1984)].
[29] V. V. Flambaum and O. P. Sushkov, Nucl. Phys. **A412**, 13 (1984).
[30] V. V. Flambaum, I. B. Khriplovich, and O. P. Sushkov, Phys. Lett. **146B**, 367 (1984).
[31] A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, New York, 1969), Vols. 1 and 2.
[32] *Tests of Time Reversal Invariance in Neutron Physics*, edited by N. R. Roberson, C. R. Gould, and J. D. Bowman (World Scientific, Singapore, 1987); P. K. Kabir, Phys. Rev. D **25**, 2013 (1982); L. Stodolsky, Nucl. Phys. **B197**, 213 (1982); V. E. Bunakov and V. P. Gudkov, Z. Phys. A **308**, 363 (1982).
[33] S. F. Mughabghab, M. Divadeenam, and N. E. Holden, *Neutron Cross Sections* (Academic, New York, 1981).
[34] O. P. Sushkov and V. V. Flambaum, Yad. Fiz. **33**, 629 (1981) [Sov. J. Nucl. Phys. **33**, 329 (1981)].
[35] V. V. Flambaum and O. P. Sushkov, Nucl. Phys. **A435**, 352 (1985).
[36] V. A. Vesna *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **36**, 169 (1982) [JETP Lett. **36**, 209 (1982)].
[37] V. E. Bunakov *et al.*, Yad. Fiz. **40**, 188 (1984) [Sov. J. Nucl. Phys. **40**, 119 (1984)].
[38] V. A. Dzuba, V. V. Flambaum, and I. B. Khriplovich, Z. Phys. D **1**, 243 (1986).
[39] L. M. Barkov, M. S. Zolotorev, and D. A. Melik-Pashaev, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 134 (1988) [JETP Lett. **48**, 145 (1988)]; D. Budker, E. D. Commins, D. DeMille, and M. Zolotorev, Talk at ICAP-1990, Ann Arbor (unpublished).

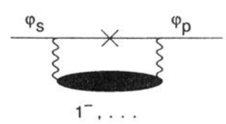

FIG. 6. Contribution of giant resonance excitation to PNC amplitude.

FIG. 7. Excitation of giant resonance by weak field of neutron.