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PARITY VIOLATION IN NEUTRON INDUCED REACTIONS

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ABSTRACT

The theory of parity violation in neutron induced reactions is discussed. Special attention is paid to the energy dependence and enhancement factors for the various types of nuclear reactions and the information which might be obtained from P-violating effects in nuclei.

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1. INTRODUCTION

As is well known, in a parity conserving interaction the amplitude of any process is a scalar quantity, i.e. only the even correlations of the initial and final state vectors (or pseudo vectors) are present. If there is an additional P-violating interaction, the amplitude for the same process can be written as

$$f = f_{PC} + f_{PNC}, \tag{1.1}$$

where f_{PC} and f_{PNC} are the P-even (scalar) and P-odd (pseudo scalar) terms, respectively. Consequently, the probability of the process is

$$w \sim \mid f_{PC} + f_{PNC} \mid^2 = \mid f_{PC} \mid^2 + 2Re(f_{PC} f^*_{PNC}) + \mid f_{PNC} \mid^2 . \tag{1.2}$$

In eq.(1.2), the first term is connected with the parity conserving process (or parity allowed transition), the third one corresponds to the parity forbidden transition and the second one corresponds to the interference between P-odd and P-even processes. The third term is proportional to the second power of the weak coupling constant, and therefore will be neglected. Thus, the ratio of the P-violating to P-conserving probabilities is

$$\alpha \sim \frac{Re(f_{PC} f^*_{PNC})}{\mid f_{PC} \mid^2} \sim \frac{\mid f_{PNC} \mid}{\mid f_{PC} \mid}. \tag{1.3}$$

A simple estimate for this ratio for a nuclear decay (reaction) is

$$\alpha \sim G m_\pi^2 \sim 2 \cdot 10^{-7}, \tag{1.4}$$

where G is the weak coupling Fermi constant; m_π is the π -meson mass, which is the characteristic scale of the nucleon interaction. But it is well known that typical values for the different P-odd effects in neutron-induced reactions (see, *e.g.*refs.[1-6]) are about $\alpha \sim 10^{-4} - 10^{-1}$. This means that there are general nuclear enhancement factors for parity-violating effects in nuclear reactions.

It should be noted that two enhancement factors were predicted[7–10]: the most important one is the small level spacing between the compound states (*dynamical enhancement*), while the second one arises from the possible increase in the ratio of parity- forbidden to parity-allowed transition matrix elements caused by the nuclear structure of the states involved (*structural enhancement*).

The first experiment on the P- violating nuclear interaction[1], namely a measurement of a γ -ray asymmetry in a polarized neutron capture reaction (at thermal neutron energy) confirmed these predictions: the effect turned out to be quite large ($\sim 10^{-4}$). Since the investigations were performed for thermal neutron energy region, nobody bothered at that time about the specific features of the reaction theory involved (energy dependence of the effect, the role of the entrance channel, etc.). The first theoretical paper[11] mentioning the possible enhancement of the effect of γ -ray circular polarization in the vicinity of a compound nucleus resonance remained unnoticed.

Quite independently, theoretical investigations were carried out (see e.g. refs.[12,13]) on the parity-violating effects in neutron elastic scattering reactions (rotation of the polarization plane and the appearance of longitudinal polarization for neutron beams). These investigations were concerned only with potential scattering models and predicted the possible enhancement of the effects by the presence of the potential p-resonances (see refs.[14,15]). But all the experimentally known p-resonances in neutron-induced reactions are of complicated compound-nucleus origin. The compound p-resonance enhancement was theoretically considered for parity-violating effects in refs.[16–19]).

The first experimental observations of P-odd quantities were done for thermal neutrons[20,21]. And later, in agreement with the prediction of ref.[16], the abnormally large effects ($\sim 10^{-1} - 10^{-3}$) were observed in the vicinity of p-wave compound nuclear resonances[22] (see also refs.[2 ,3 ,4 ,23]). From that time, the intensive investigation of parity-violation in neutron induced reactions was initiated.

Parallel to these investigations, unexpected large effects were observed for fission fragment asymmetry from the $(n, fission)$ reactions[24]. (The detailed discussion of these effects is in Sec.7.)

Let us define now some P-odd quantities which were frequently measured. One of the most "popular" P-odd effects is the asymmetry of the products in the final channel f for (n,f) reaction

$$\alpha_{nf} = \left(\frac{d\sigma_\uparrow}{d\Omega} - \frac{d\sigma_\downarrow}{d\Omega}\right) \Big/ \left(\frac{d\sigma_\uparrow}{d\Omega} + \frac{d\sigma_\downarrow}{d\Omega}\right) = \Delta_{nf} \Big/ \left(\frac{d\sigma_\uparrow}{d\Omega} + \frac{d\sigma_\downarrow}{d\Omega}\right), \tag{1.5}$$

which is connected to the $(\sigma \mathbf{k}_f)$ correlation. Here $d\sigma_{\uparrow(\downarrow)}/d\Omega$ is the differential cross section for the parallel (antiparallel) direction of the final particle momentum $\mathbf{k}_f$ and the neutron spin σ. Omitting for simplicity the trivial statistical spin factor[19] we can write the expression for the numerator of eq.(1.5):

$$\Delta_{nf} \simeq \frac{16\pi^3}{k^2} \sum_{l_i,l_f} Re\{\langle l_f\beta_f|\,T\,|l_i\beta_i\rangle \, \langle l_f+1\beta_f|\,T\,|l_i\beta_i\rangle^* \,(-1)^{l_i}\}. \tag{1.6}$$

Here T is a reaction matrix which is related to the S-matrix by $2\pi i\hat{T} = \hat{1} - \hat{S}$ and to the reaction amplitude f by $\hat{f} = -(2\pi)^2(k_i k_f)^{-1/2}\hat{T}$, k is the momentum of the initial neutron, $l_{i,f}$ and $\beta_{i,f}$ are the orbital momentum and the additional quantum number defining the initial or final channel.

For the neutron transmission through the target one can consider two P-odd values[12,13] which are related to the $(\sigma \mathbf{k})$ correlation : the total cross section $(\sigma_\pm)$ difference for opposite neutron helicities

$$\Delta_{tot} = \sigma_- - \sigma_+ = \frac{4\pi}{k} Im(f_- - f_+) \tag{1.7}$$

and the neutron spin rotation angle around the axis $\mathbf{k}$

$$\frac{d\Phi}{dz} = \frac{2\pi N}{k} Re(f_- - f_+). \tag{1.8}$$

Here $f_\pm$ are the amplitudes for the forward scattering of neutrons with positive and negative helicities, N is the density of target nuclei in the sample and z is the length of the target sample. Usually, instead of the Δ_{tot} value, the following ratio (the normalized value) is used

$$P = \frac{\Delta_{tot}}{\sigma_- + \sigma_+} = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+}. \tag{1.9}$$

From eq. (1.6)one can see that P-odd asymmetry of the reaction product in the final channel is proportional to the the P-odd and P-even reaction matrixes (or amplitudes). The P-violating effects in the transmission of polarized neutrons through a target (eqs.(1.7) and (1.8)) are proportional to the P-odd part of the elastic scattering amplitude.

2. THE THEORY OF PARITY VIOLATING EFFECTS

The general formalism for calculating P-violating amplitudes is described in refs.[18,19]. Following these papers one can obtain the P-violating part of the reaction matrix (distorted-wave Born approximation in weak interaction) as

$$T_{PNC} = \left\langle \Psi_f^- \middle| W \middle| \Psi_i^+ \right\rangle, \tag{2.1}$$

where W is the weak interaction operator. According to the microscopic theory of nuclear reactions[27], the initial and final wave functions are

$$\Psi_{i,f}^{\pm} = \sum_k a_{k(i,f)}^{\pm}(E)\, \phi_k + \sum_m \int b_{m(i,f)}^{\pm}(E, E')\, \chi_m^{\pm}(E')\, dE'. \tag{2.2}$$

Here ϕ_k and χ_m are the wave functions of the k-th nuclear compound resonance and the potential scattering in the channel m. The first coefficient in eq.(2.2) is

$$a_{k(i,f)}^{\pm}(E) = \frac{\exp(\pm i\delta_{i,f})}{(2\pi)^{\frac{1}{2}}} \frac{(\Gamma_k^{i,f})^{\frac{1}{2}}}{E - E_k \pm \frac{i}{2}\Gamma_k}, \tag{2.3}$$

where E_k, Γ_k and Γ_k^i are the energy, total width and partial width in the i channel of the k^{th} nuclear compound resonance, E is the neutron energy and δ_i is the potential scattering phase.

$$(\Gamma_k^i)^{\frac{1}{2}} = (2\pi)^{\frac{1}{2}} \langle \chi_i(E)| V |\phi_k\rangle , \tag{2.4}$$

where V is a residual interaction operator.

$$b_{m,\alpha}^{\pm} = \exp(\pm i\delta_\alpha)\delta(E-E')\delta_{m,\alpha} + a_{k,\alpha}^{\pm}\frac{\langle\phi_k| V |\chi_m(E')\rangle}{(E-E'\pm i\varepsilon)}. \tag{2.5}$$

The first term in eq.(2.5) corresponds to the potential scattering. In order to estimate the second term, one can use the factorization procedure for the potential scattering wave function inside the range of the nuclear potential[28]. According to such approximation, this wave function is

$$\chi_E^{\pm}(r) \simeq \left(\frac{\Gamma_0}{2\pi}\right)\frac{\exp(i\delta)}{E-E_0\pm\frac{1}{2}i\Gamma_0}u(r), \tag{2.6}$$

where E_0 and Γ_0 are the energy and width of the potential resonance and $u(r)$ is the function normalized to unity within the volume of the nuclear potential. Then, substituting the second term of eq.(2.5) into eq.(2.2), one can obtain the following part of the total wave function

$$\Psi_\alpha^V = \frac{1}{2}\frac{\Gamma_k^\alpha}{E-E_k+\frac{1}{2}i\Gamma_k}\left[\frac{2(E-E_0)}{\Gamma_0} - i\right]\chi_m(E). \tag{2.7}$$

Here we used the approximation $E_0 \gg \Gamma_0$. The function (2.7) corresponds to the so-called valence nucleon model, which may be of some importance in the vicinity of the single-particle resonance.

Taking into account, for simplicity, only two compound resonances, we can express the P-violating matrix (2.1) by a sum of terms corresponding to the various P-violating mechanisms

$$\begin{aligned}\langle f| T |i\rangle =& a_{i,\alpha}^{+}a_{f,\beta}^{+}\langle\phi_\beta| W |\phi_\alpha\rangle + a_{i,\alpha}^{+}\exp i\delta_\beta\langle\chi_\beta| W |\phi_\alpha\rangle + \\ & a_{f,\beta}^{+}\exp i\delta_\alpha\langle\phi_\beta| W |\chi_\alpha\rangle + \exp i(\delta_\alpha+\delta_\beta)\langle\chi_\beta| W |\chi_\alpha\rangle + \dots\end{aligned} \tag{2.8}$$

This sum of terms can be represented by means of corresponding diagrams (see Fig.1). The first term in (2.8) (Fig.1a) describes the parity mixing of the compound nucleus states. The second and third terms describe the P-violating decay

(Fig.1b) and capture (Fig.1c) of a compound resonance, respectively. The fourth term (Fig.1d) corresponds to the direct (potential scattering) process caused by the weak P-odd interaction (see, e.g. refs.[13,14]). The expression is more complicated for the valence mechanism of P-violation[29] (see also refs.[30,31]), its diagram is shown in Fig.1e.

Let us consider the low energy neutron induced reactions. For this case one can easily find that the second and third terms in eq.(2.8) might contribute only when the energy difference between the neighboring s- and p-wave resonances exceeds $1keV$ in medium and heavy nuclei. Using square-well wave functions for a crude estimate, one can see that the fourth term is of importance only when the level spacing $D \gtrsim 0.1keV$. As a result, the first term is dominant for the majority of medium and heavy nuclei. Therefore, we obtain the parity-violating amplitudes

$$\langle l'+1, f|\,T\,|s\rangle = -\frac{1}{2\pi}\frac{v(\Gamma_s^n\Gamma_p^f)^{\frac{1}{2}}}{[s^+][p^+]}e^{i(\delta_s^n+\delta_{l'+1}^f)}, \tag{2.9}$$

$$\langle l', f|\,T\,|p\rangle = -\frac{1}{2\pi}\frac{v(\Gamma_p^n\Gamma_s^f)^{\frac{1}{2}}}{[s^+][p^+]}e^{i(\delta_p^n+\delta_{l'}^f)}. \tag{2.10}$$

Here $[s^\pm, p^\pm] = (E - E_{s,p}) \pm i\Gamma_{s,p}/2$, $v = -\int \phi_s W \phi_p d\tau$ is real for T-invariant interactions, $l', (l'+1)$ are the orbital momenta in a final channel.

In the corresponding approximation, the parity-conserving amplitudes are

$$\langle l', f|\,T\,|s\rangle = \frac{1}{2\pi}\frac{(\Gamma_s^n\Gamma_s^f)^{\frac{1}{2}}}{[s^+]}e^{i(\delta_s^n+\delta_{l'}^f)} - \frac{\delta_{f,n}}{\pi}e^{i\delta_s^n}\sin\delta_s^n, \tag{2.11}$$

$$\langle l'+1, f|\,T\,|p\rangle = \frac{1}{2\pi}\frac{(\Gamma_p^n\Gamma_p^f)^{\frac{1}{2}}}{[p^+]}e^{i(\delta_p^n+\delta_{l'+1}^f)} - \frac{\delta_{f,n}}{\pi}e^{i\delta_p^n}\sin\delta_p^n. \tag{2.12}$$

Here $\delta_{n,f}$ is the Kronecker symbol. The phase shifts for the slow neutrons $\delta_l^n \sim (kR)^{2l+1}$ are negligibly small (R is a nuclear radius) and therefore we will omit them in the compound-resonance terms of the amplitude. For simplicity the spin dependence of the partial widths is omitted also (for the complete expressions, see e.g. refs.[18,19,25, 26,32,33]).

Using these results one can obtain, in the two resonance approximation, the expressions for the P-violating effects of eqs.(1.5)-(1.8) are

$$\Delta_{nf} = \frac{2\pi}{k^2}\frac{v(\Gamma_s^f\Gamma_p^f)^{\frac{1}{2}}}{[s][p]} Re\{[p^-]\Gamma_s^n \exp\imath(\delta_{l'}^f - \delta_{l'+1}^f) - [s^-]\Gamma_p^n \exp\imath(\delta_{l'+1}^f - \delta_{l'}^f)\}, \tag{2.13}$$

$$\Delta_{tot} = -\frac{2\pi}{k^2}\frac{v(\Gamma_s^n\Gamma_p^n)^{\frac{1}{2}}}{[s][p]}[(E-E_s)\Gamma_p + (E-E_p)\Gamma_s], \tag{2.14}$$

$$\frac{d\Phi}{dz} = \frac{4\pi N}{k^2}\frac{v(\Gamma_s^n\Gamma_p^n)^{\frac{1}{2}}}{[s][p]}[(E-E_s)(E-E_p) - \frac{1}{4}\Gamma_s\Gamma_p], \tag{2.15}$$

where $[s,p] = (E-E_{s,p})^2 + \Gamma_{s,p}^2/4$.

It may be worth noting that the P-odd asymmetry value is practically independent of the p-wave neutron width, but the difference of the total cross sections is proportional to this width. The reason for the difference between these P-odd effects is connected with the nature of the various P-odd correlations. In the case of Δ_{tot} (the correlation of $(\sigma\mathbf{k})$), it is necessary to have the neutron p-wave resonance for the initial channel interference. But for Δ_{nf} (the correlation of $(\sigma\mathbf{k}_f)$), one should have the final channel interference and therefore it is enough to have the s-wave neutron resonance and a level with opposite parity. This level has no excitation through the neutron channel. One of the consequence of these different dependence on the p-wave neutron width is the essentially different values of P-odd effects in the thermal region of the neutron energy. For example, the typical magnitude of the asymmetry $\alpha_{n,\gamma}$ in $n-\gamma$ correlation is about $10^{-3}-10^{-4}$, but the relative difference of total cross section P is about $10^{-6}-10^{-7}$ (see detailed discussions in the following sections).

To obtain the expressions for α_{nf} and P, we should calculate the denominators of eqs (1.5)and (1.9) (see, e.g. ref.[19]). However, it is preferable to use the experimental values for these quantities because the contributions from other resonances are more important for denominators than for numerators in the general case (see detailed discussion in Sec.6).

3. THE ENHANCEMENT FACTORS

Let us consider the difference between the total cross sections, which is related to the P-odd correlation $(\sigma \mathbf{k})$, in the transmission of neutrons with opposite helicities through the unpolarized target. According to eq.(1.7) one can rewrite the difference (2.14) as

$$\Delta_{tot} = \sigma_- - \sigma_+ \simeq \frac{4\pi}{k^2} Im \frac{(\Gamma_s^n)^{1/2} v (\Gamma_p^n)^{1/2}}{(E - E_s + i\frac{\Gamma_s}{2})(E - E_p + i\frac{\Gamma_p}{2})}. \tag{3.1}$$

The diagram corresponding to this amplitude is given at Fig.2. The quantity Δ_{tot} displays resonance jumps (see Fig.2) near both s- and p-wave resonances increasing its value by a factor of $(D/\Gamma)^2$ with respect to the point between the resonances ($D =\mid E_s - E_p \mid$). These jumps are caused by the resonance enhancement of the wave function amplitude in the region of the interaction. The physical meaning of the resonance enhancement is quite obvious from the estimates of the compound-system life-time (see, e.g., refs.[34,35]). In the resonance state, the particle remains within the nucleus for a longer time of the order of the resonance life time $\sim (1/\Gamma)$. Therefore, it is natural to expect an enhancement of symmetry violation proportional to the ratio of the resonance lifetime $(1/\Gamma)$ to the lifetime of compound- nucleus away from the resonance (Γ/D^2), that is to (D/Γ). The denominator of the relative value P contains the total cross section σ_{tot} which consists of the s-resonance contribution

$$\sigma_s \simeq \frac{\pi}{k^2} \frac{\Gamma_s^n \Gamma_s}{(E - E_s)^2 + \Gamma_s^2/4}, \tag{3.2}$$

p-resonance contribution

$$\sigma_p \simeq \frac{\pi}{k^2} \frac{\Gamma_p^n \Gamma_p}{(E - E_p)^2 + \Gamma_p^2/4} \tag{3.3}$$

and the potential scattering

$$\sigma_{pot} \sim \frac{\pi}{k^2}(kR)^2. \tag{3.4}$$

The quantity σ_{tot} also displays a marked resonance jump in the vicinity of the s -wave resonance, which compensates completely for the corresponding jump in the numerator P. Therefore, the effect P is not enhanced in the vicinity of the s-wave resonance and remains approximately on the same level as the value between the resonances:

$$P(E_s) \simeq 4\frac{v}{D}\sqrt{\frac{\Gamma_p^n}{\Gamma_s^n}}\left[1+\frac{\sigma_{pot}}{\sigma_s}\right]^{-1}. \tag{3.5}$$

The presence of the penetration factor $\sqrt{\Gamma_p^n/\Gamma_s^n} \sim (kR)$ is characteristic of all correlations observed in low energy nuclear reactions which arise due to initial state interference and, consequently, are proportional to the neutron momentum (the correlation $(\sigma\mathbf{k})$ in the case considered).

In general, σ_{tot} is dominated by the smooth background of σ_s and σ_{pot} in the vicinity of the p-wave resonance, since $(kR) \ll 1$. Therefore, the resonance jump of Δ_{tot} near $E = E_p$ is retained in the effect P, which is enhanced here by a factor of $(D/\Gamma)^2$

$$P(E_p) \simeq 8\frac{v}{D}\sqrt{\frac{\Gamma_p^n}{\Gamma_s^n}}\frac{D^2}{\Gamma_s\Gamma_p}\left[1+\frac{\sigma_p+\sigma_{pot}}{\sigma_s}\right]^{-1}. \tag{3.6}$$

Now the interesting point is to see which choice of the s- and p-resonances provides the maximal value of the ratio P (see ref.[36]). To simplify the picture, we shall neglect the smooth potential scattering background σ_{pot} for a moment. Then, using eqs.(1.9) and (3.1), one can write P as follows

$$P \sim \frac{v}{\sqrt{\Gamma_s\Gamma_p}}\left\{\frac{2Im F_s F_p^*}{|F_s|^2+|F_p|^2}\right\}, \tag{3.7}$$

where

$$F_s = \frac{\sqrt{\Gamma_s^n \Gamma_s}}{(E - E_s + i\Gamma_s/2)} \qquad F_p = \frac{\sqrt{\Gamma_p^n \Gamma_p}}{(E - E_p + i\Gamma_p/2)}.$$

Here, $v/\sqrt{\Gamma_s \Gamma_p}$ is almost constant, since the total widths are practically energy independent for $(kR) \ll 1$. It is well known that the ratio of the interference term for the two F amplitudes over the sum of their squares is maximal when $| F_s |=| F_p |$, as in the usual interference phenomena. In our p-resonance case, this condition is

$$\sigma_p(E_p) = \sigma_s(E_p) \tag{3.8}$$

or

$$\Gamma_s^n/\Gamma_p^n = 4D^2/\Gamma^2 \tag{3.9}$$

if $\Gamma_s \simeq \Gamma_p \simeq \Gamma$. One can derive conditions (3.8) and (3.9) by direct parameter variation in eq.(1.9). Thus, we get from (3.6)

$$P_{max} \simeq \frac{v}{D}\frac{D}{\Gamma} = \frac{v}{\Gamma}. \tag{3.10}$$

Two conclusions follow from eq.(3.10) concerning the possibilities to find maximal values of P. First of all, one should search for strong p-wave resonances in the cross section. From this aspect, it is preferable to choose larger kR values (higher neutron energies E), since for larger E the probability to find the strong p-resonance and to satisfy eq.(3.8) is greater. Secondly, it is better to observe the radiative capture $P_{n\gamma}$ and not P in the total cross section. (For $P_{n\gamma}$, one should replace the total cross sections $\sigma_\pm$ in eq.(1.9) by the radiative capture cross sections $\sigma_\pm^{n\gamma}$). In this case, the potential scattering term drops out of the denominator in eq.(1.9) causing the enhancement of $P_{n\gamma}$ by a factor $\sim \sigma_{tot}/(\sigma_s + \sigma_p)$.

Now we consider the so called "dynamic" enhancement factor, which is connected with the ratio v/D (see refs.[7,9,10]). For a crude estimate of this ratio, one can expand the compound resonance wave function ϕ in terms of simple-configuration wave functions ψ_i which are admixed to compound resonances by strong interactions:

$$\phi = \sum_{i=1}^{N} c_i \psi_i. \tag{3.11}$$

Using the normalization condition for the coefficients c_i and the statistical random-phase hypothesis for matrix elements $\langle\psi_i| W |\psi_k\rangle$ we obtain

$$v = \langle\phi_s| W |\phi_p\rangle = \overline{\langle\psi_i| W |\psi_k\rangle} N^{-1/2}. \tag{3.12}$$

Here $\overline{\langle\psi_i| W |\psi_k\rangle}$ is the average value of the matrix elements between simple configurations. In the black nucleus statistical model, the number of components (N) is estimated in terms of the average spacing $\overline{D}$ of compound resonances and the average spacing $\overline{D}_0$ of single-particle states:

$$N \approx \overline{D}_0/\overline{D}. \tag{3.13}$$

One can estimate N from experimental data on neutron strength functions, since in the statistical model of heavy nuclei the neutron strength function is proportional to the N^{-1} (see, e.g., ref.[37]). The value N is about 10^6. Hence

$$\frac{v}{D} \simeq \frac{\overline{\langle\psi_i| W |\psi_k\rangle}}{\overline{D}_0} \sqrt{N}, \tag{3.14}$$

where the ratio of the "simple" weak matrix element to the single particle level distance is about 10^{-7} (or the usual scale of the nucleon weak interaction). The enhancement factor $\sqrt{N}$ occurs as a result of the small level distance between nuclear compound resonances ($D \sim N^{-1}$) and the random-phase averaging procedure ($\sim N^{-1/2}$).

For calculation of the P-odd effects, we shall use the phenomenological formula[19]

$$v \simeq 2 \cdot 10^{-4} \sqrt{\overline{D}(eV)}. \tag{3.15}$$

(The theoretical estimate of this quantity was carried out in ref.[38], where the resemblance of weak interaction matrix elements to the partial widths of electromagnetic transitions ($M0$ giant resonance) between compound states was used.) Taking this expression for v, one can see that the maximal possible P effect might be

$$P_{max} \sim 10^{-4} \sqrt{\overline{D}(eV)}/\Gamma \leq 10\%. \tag{3.16}$$

We have taken into account that for medium and heavy nuclei the usual values are $\overline{D} \in (1 - 10^3) eV$, $\Gamma \in (0.05 - 0.2) eV$. Naturally, the fluctuations of v and Γ may somewhat increase this estimate.

It should be noted that the ratio $\sqrt{\Gamma_p^n/\Gamma_s^n}$ is due to the amplitude interference in the entrance channel. In the exit channel interference (e.g. $(\sigma \mathbf{k}_f)$ correlation) this ratio will be replaced by a structure enhancement factor[9,10]. This enhancement factor for electromagnetic transitions in low excitation nuclear or atomic decays is

$$\sqrt{\frac{\Gamma_p^f}{\Gamma_s^f}} = \frac{\langle f|\, E1\, |i\rangle}{\langle f|\, M1\, |i\rangle}. \tag{3.17}$$

As we will see later, for P-odd correlations of nuclear fission the enhancement factor is proportional to $\sim \sqrt{\mathcal{P}_p/\mathcal{P}_s}$, where $\mathcal{P}_{s,p}$ are the fission barrier penetrabilities of the transition states with opposite parities.

4. THE WEAK INTERACTION AND P-ODD EFFECTS IN NUCLEI

At the beginning of the investigation of the parity violation in nuclei, there was a hope of obtaining information about the weak hadron neutral current properties. From P-odd nucleon interaction we can study the non-leptonic weak process without a change of the strange quantum number. It is not possible from non -leptonic decays of hyperons. Nowadays, careful and numerous investigations of the standard electro-weak model are carried out up to the radiative correction level of accuracy. Therefore, in order to test the standard model in nuclear physics, one should obtain the proper parameters of the model with the same accuracy from experimental data. However, it is not possible to compute the nuclear quantities with the required accuracy.

To clear up this point, let us compare the value for the Weinberg angle which was obtained from high energy experimental data[39] $\sin^2\theta_W = 0.2259 \pm 0.0046$ with the same one obtained from the experimental data for parity-violating effects of nuclei with simple structure and low excitation energy[40]: $\sin^2\theta_W = 0.0 \pm 0.4$. Obviously, the problem of the theoretical description for the compound nuclear reactions is more complicated, and therefore the calculated quantities are expected to be more uncertain.

In spite of this, there are some significant arguments for the investigation of parity-violating effects in complicated nuclei. First, these effects are an additional and, in some cases, very sensitive method to study nuclear properties. For example, detailed information about neutron p-wave resonances may be obtained from the magnitude of parity-violating effects. Parity violation in the compound nuclear stage can be used for the verification of the statistical approach to nuclear theory (see, e.g. refs.[41,30,42]). The study of parity-violation in the fission of nuclei can give additional information about the nature of the transition states and the ternary fission properties (see Sec.7).

Second, different mechanisms of parity-violation (from the mixing on the compound nuclear stage) may be observed. Unfortunately, all the existing experimental data on the P-violation in the different neutron induced reactions are described in the framework of parity mixing in the compound nuclear stage. One of the way to observe the other mechanisms is the measurement of the P-odd effects with broad energy resolution. In this case, the contribution from the mixing in the compound stage would decrease as $n^{-1/2}$ (where n is the number of nuclear compound resonances at the interval of the energy resolution) because of the random signs for contributions from different resonances.

What could be a more significant point is the investigation of nuclear enhancement factors and the selection of the optimal experimental conditions to test the CP-violation effects in neutron elastic scattering, e.g. choosing the most appropriate nucleus, p-resonance energy and so on (see, e.g.[43]).

To clarify the points mentioned above, concerning nuclear properties, some specific reactions will be considered in the following sections.

5. PARITY VIOLATION IN THE (n,γ) REACTION

The neutron radiative capture process is one of the simplest for the theoretical investigation of the P-odd effects in nuclear reactions. We will discuss here only some essential features of $n-\gamma$ correlations (a detailed description of the different P-odd and P-even correlations in this reaction may be found in ref.[26]). Let us consider the $(\sigma \mathbf{k}_\gamma)$ correlation which corresponds to the asymmetry $\alpha_{n\gamma}$ of photon emission relative to the direction of the spin of the incident polarized neutrons. In this case eq.(2.13) for the parity-violating differential cross-section difference can be written as

$$\Delta_{n\gamma} = \frac{2\pi}{k^2}\frac{v(\Gamma_s^\gamma \Gamma_p^\gamma)^{\frac{1}{2}}}{[s][p]} Re[(E-E_p)\Gamma_s^n - (E-E_s)\Gamma_p^n], \qquad (5.1)$$

Taking into account that, for the low energy region, the radiative capture cross section is almost determined by s-resonance contributions, one can obtain

$$\alpha_{n\gamma} \simeq \frac{2v}{[p]}\sqrt{\frac{\Gamma_p^\gamma}{\Gamma_s^\gamma}}(E - E_p) \tag{5.2}$$

and in the p-wave resonance vicinity

$$\alpha_{n\gamma} \simeq \frac{2v}{D}\left(\frac{D}{\Gamma}\right)\sqrt{\frac{\Gamma_p^\gamma}{\Gamma_s^\gamma}}. \tag{5.3}$$

The last expression is the direct product of the three enhancement factors which were discussed in Sec.3. The characteristic behavior of these P-odd quantities is presented in fig. 3 The difference in the energy behavior for $\Delta_{n\gamma}$ in the vicinities of s- and p-resonances is connected with the essentially different scale of the corresponding neutron widths for low energy neutrons ($\Gamma_p^n \ll \Gamma_s^n$). (See, also, the discussion after eq.(2.13)). Comparing eqs. (5.1) and (2.14), we can see that $\alpha_{n\gamma}$ and P have similar magnitudes in the p-wave resonance vicinity. However, outside of the p-wave resonance, the magnitude of $\alpha_{n\gamma}$ is larger than that for P because the small penetrability factor is absent for the $\alpha_{n\gamma}$ asymmetry.

There will be a more complicated picture for the case of the "integral" (n,γ) reactions[44,45](see the detailed investigation in refs.[41,26,30]), where γ-quanta of various energies are detected . In these experiments, the magnitudes of the γ-quanta asymmetry $\alpha_{n\gamma}^{\Sigma}$ and circular polarization are about $10^{-5} - 10^{-6}$ for different nuclei at the thermal neutron energy point. These values are in agreement with the rough statistical estimate using the factor $\sim n^{-1/2}$ which arises due to summing the n partial γ-ray transitions with random phases. A careful calculation[41,30] gives the following value for this factor

$$m = \sqrt{\frac{\Gamma_p^\gamma}{\Gamma_s^\gamma}}\frac{\sum_{f'}[(I_{pf'}I_{sf'})^{1/2}E_\gamma^{sf'}F(E_\gamma^{sf'})\varepsilon(E_\gamma^{sf'})\{spinfactor\}]}{\bar{\varepsilon}\sum_{ff'}(POP_{f'}I_{ff'}E_\gamma^{ff'})}, \tag{5.4}$$

where $I_{ff'}(E_\gamma^{ff'})$ is the intensity of the γ transition $f \to f'$ with energy $E_\gamma^{ff'}$, POP_f is the population of the decaying state f with total radiative width $\Gamma_{\gamma f} =$

$\sum_{f'} \Gamma_\gamma^{ff'}$, and $POP_i = 1$ for the capture state i. The presence of the factors $\varepsilon(E_\gamma)$, $F(E_\gamma)$ and E_γ in eq.(5.4) is related to the experimental method of refs.[44,45].

If the amplitudes of the partial γ widths are unknown, the numerator in eq.(5.4) can be estimated only through its standard deviation. These values for different nuclei were calculated in refs.[41,30] from a joint description of the total radiative widths and γ spectra of the reaction (n, γ) with a phenomenological parametrization of the energy dependence of the excited state density and the positions of the discrete low-lying levels. Some experimental data[44,45] and averaging factors[30] m are presented in Table 1. From this table, one can see that weak matrix elements obtained from "integral" and "differential" (see refs.[2,46,47]) experimental data have similar magnitudes. The ratio of m_{coh} and m gives illustration of the randomness of the signs of amplitude for partial γ-transitions. If there were coherence in the signs of the amplitudes, the theoretical estimates of the $\alpha_{n\gamma}^{\Sigma}$ values would be greater than the experimental ones by the factor of m_{coh}/m.

6. P-EVEN CORRELATIONS

The discussion presented above shows that the investigation of P-violating effects provides us with essential information about nuclear properties. From this point of view, it is important to study P-even correlations since these quantities contain the same nuclear information as P-odd ones without the "weak interaction contamination". The various P-even correlations were discussed in refs.[19,26,48,33]. Here we consider only two quantities: the right-left asymmetry α_{rl} which arises from the $\sigma[\mathbf{k} \times \mathbf{k}_\gamma]$ correlation ($\mathbf{k}_\gamma$ is the γ-quantum momentum) and the forward-back asymmetry α_{fb} which arises from the $(\mathbf{k}\mathbf{k}_\gamma)$ correlation.

$$\alpha_{rl} = \left(\frac{d\sigma_r}{d\Omega} - \frac{d\sigma_l}{d\Omega}\right) \Big/ \left(\frac{d\sigma_r}{d\Omega} + \frac{d\sigma_l}{d\Omega}\right) = \Delta_{rl} \Big/ \left(\frac{d\sigma_r}{d\Omega} + \frac{d\sigma_l}{d\Omega}\right), \qquad (6.1)$$

where $d\sigma_{r(l)}/d\Omega$ is the differential cross section for the neutron spin direction along (opposite to) the $[\mathbf{k} \times \mathbf{k}_\gamma]$ axis;

$$\alpha_{fb} = \left(\frac{d\sigma_f}{d\Omega} - \frac{d\sigma_b}{d\Omega}\right) \Big/ \left(\frac{d\sigma_f}{d\Omega} + \frac{d\sigma_b}{d\Omega}\right) = \Delta_{fb} \Big/ \left(\frac{d\sigma_f}{d\Omega} + \frac{d\sigma_b}{d\Omega}\right), \qquad (6.2)$$

where $d\sigma_{f(b)}/d\Omega$ is a differential cross section for γ -quantum direction along (opposite to) $\mathbf{k}$. These two correlations are proportional to the imaginary and real parts of the production of s- and p-wave P-even amplitudes ,respectively, because they arise from the interference of the final channels with opposite parities. As is well known, in general, any correlation depends on the spin dependent parts of the p-wave neutron width amplitude $(\Gamma_p^n(j))^{\frac{1}{2}}$ (or with dimensionless parameters $x = (\Gamma_p^n(1/2))^{1/2}/(\Gamma_p^n)^{1/2}$ and $y = (\Gamma_p^n(3/2))^{1/2}/(\Gamma_p^n)^{1/2}$). Here $j = 1 \pm 1/2$ is the total neutron spin and $\Gamma_p^n = \Gamma_p^n(1/2) + \Gamma_p^n(3/2)$ is the neutron p-wave width (in the total neutron spin representation). Due to this, the (n, γ) correlation measurement is one of the methods used to obtain the x and y values. In the spin-channel representation, the correlation values are dependent on the corresponding parameters $x_s = (\Gamma_p^n(I - 1/2))^{1/2}/(\Gamma_p^n)^{1/2}$ and $y_s = (\Gamma_p^n(I + 1/2))^{1/2}/(\Gamma_p^n)^{1/2}$), where I is the spin of the target nucleus and $s = I \pm 1/2$ is the channel spin. These two representations are connected with each other through an unitary transformation[37,33]

$$\begin{aligned} x_s &= \frac{1}{\sqrt{3}}x + \sqrt{\frac{2}{3}}y \\ y_s &= -\sqrt{\frac{2}{3}}x + \frac{1}{\sqrt{3}}y. \end{aligned} \qquad (6.3)$$

Using the previously discussed approach[19] (see Sec.2), one can obtain the following expressions for the corresponding differences of the differential cross sections[49]

$$\Delta_{rl} = \frac{\pi}{k^2} \sum_{i,j} (x_j + y_j/2^{\frac{3}{2}}) \frac{(\Gamma_{si}^n \Gamma_{pj}^n \Gamma_{si}^\gamma \Gamma_{pj}^\gamma)^{\frac{1}{2}}}{[s_i][p_j]} [(E - E_{si})\Gamma_{pj} - (E - E_{pj})\Gamma_{si}], \quad (6.4)$$

$$\Delta_{fb} = \frac{2\pi}{k^2} \sum_{i,j} (-x_j + y_j/2^{\frac{1}{2}}) \frac{(\Gamma_{si}^n \Gamma_{pj}^n \Gamma_{si}^\gamma \Gamma_{pj}^\gamma)^{\frac{1}{2}}}{[s_i][p_j]} [(E - E_{si})(E - E_{pj}) + \frac{1}{4}\Gamma_{pj}\Gamma_{si}], \quad (6.5)$$

Here we have omitted the trivial spin multipliers[26,48]. For comparison, we also present the multi resonance expression for the P-odd total cross section difference

$$\Delta_{tot} = -\frac{2\pi}{k^2}\sum_{i,j} x_j \frac{v_{ij}(\Gamma^n_{si}\Gamma^n_{pj})^{\frac{1}{2}}}{[s_i][p_j]}[(E-E_{si})\Gamma_{pj}+(E-E_{pj})\Gamma_{si}], \qquad (6.6)$$

where $v_{ij} = -\langle\phi_i|W|\phi_j\rangle$ is a weak matrix element for the i- and j-compound resonances. In this approximation, the total (n,γ) cross section is

$$\sigma_\gamma = \frac{\pi}{k^2}\sum_{i,j}\left(\frac{\Gamma^n_{si}\Gamma^\gamma_{si}}{[s_i]}+\frac{\Gamma^n_{pj}\Gamma^\gamma_{pj}}{[p_j]}\right). \qquad (6.7)$$

From eqs.(6.4)-(6.7) one can see that, in the vicinity of a p-wave resonance, the contribution from the i-th s-wave resonance is proportional to d_i^{-1} for the Δ_{tot} ,Δ_{rl} and Δ_{fb} values, whereas for the σ_γ it is proportional to d_i^{-2} ($d_i = |E-E_i|$ is a distance between some interesting energy point and i-th s-wave resonance position). For the case far from the p-resonance, the corresponding contributions are proportional to d_i^{-3} for the Δ_{tot} and Δ_{rl} values, and to d_i^{-2} for the Δ_{fb} and σ_γ values.

In other words, when the neutron energy is far from the p-wave resonance, the two resonance approximation is more accurate for the Δ_{tot} and Δ_{rl} values than for Δ_{fb} and σ_γ ones (because of less influence from other resonances). But, in the vicinity of the p-wave resonance, this approximation is essentially worse for the P-odd and P-even correlations than for the (n,γ) cross section. Therefore, one should make sure that the two resonance approximation for these correlations is valid even if it is good enough for the cross section description[49]. Therefore, to obtain the x and y values (or the spin dependent parts of the neutron width amplitudes), one should measure the different correlations with the same energy dependence[49,26]. On the other hand one is faced with the problem of the theoretical multi resonance description which is complicated by the absence any information about "negative" neutron resonances[50–52]. In any case, these correlations give unambiguous information about the position of the p-wave resonances and a rough estimate of these neutron and γ-decay widths.

It should be noted that the P-even correlations have a resonance enhancement factor which can lead to a correlation value up to unity (or 100% effect) in the vicinity of p-wave compound resonances[19]. (The characteristic behavior, e.g., the α_{rl} asymmetry is presented in fig. 4 .) Moreover, these P-even values increase with the neutron energy value as $\sim \sqrt{E}$. Due to these properties the P-even correlations are quite observable.

7. PARITY VIOLATION IN THE NUCLEAR FISSION

7.1 BINARY FISSION

Let us consider the P-violating effects in more complicated reaction: the neutron-induced fission. One of the surprising points in nuclear parity violation was the observation of the quite large ($\sim 10^{-4}$) P-odd asymmetry $\alpha_{n,fis} \sim (\sigma \mathbf{k}_f)$ (where $\mathbf{k}_f$ is a momentum of the light fragment) in the nuclear fission reaction induced by thermal neutrons[53]. The most interesting feature was the absence of the decreasing factor due to final state averaging, when the final channels were resolved only in a very crude manner (see, e.g. refs.[5,54,55]). That the number of final states for nuclear fission ($N_f \sim 10^{10}$) is far larger than for the (n,γ) reaction ($N_\gamma \sim 10^4$), which leads to the inhibition factor in $\alpha^{\Sigma}_{n\gamma}$ asymmetry in the "integral" γ-decay of about $N_\gamma^{-1/2} \sim 10^{-2}$ (see Sec.5).

The investigation of parity violation in the nuclear fission was initiated about thirty years ago following the suggestion to measure P-odd correlations for spontaneous fission[56]. In that paper, the pear-like shape of the nuclei on the fission stage was considered for the estimate of P-violating quantities. According to this approach[56], the nuclear wave function in the first power of the weak interaction coupling constant can be represented as a sum of wave functions with opposite parities (this is connected with the pear-like nuclei orientation along the direction of the nuclear spin):

$$\Psi = \Psi_+ + F\Psi_-. \tag{7.1}$$

According to perturbation theory

$$F = \frac{\langle \Psi_- | W | \Psi_+ \rangle}{E_+ - E_-}, \tag{7.2}$$

where $E_\pm$ are the energy for $\Psi\pm$ states. (The energy difference in eq.(7.2) may be small because of the quasi generated parity doubled structure of the rotation spectrum[56].) The estimated magnitude of the P-odd effect α was (see refs.[56,57])

$$\alpha \sim F\sqrt{\mathcal{P}_-/\mathcal{P}_+}. \tag{7.3}$$

A possible enhancement factor is caused by the ratio of barrier penetrabilities ($\mathcal{P}_\pm$) for the opposite parity states. The generalization of this enhancement mechanism for neutron induced fission was given in ref.[57]. In this paper the sub-barrier energy region of the two-humped nuclear fission barrier was considered.

The first measurements of the P-odd correlation in the nuclear fission were performed above the fission barrier. The qualitative explanations of these large observed effects due to the important role of the nuclear compound states were given in refs.[58,59]. A model for the explanation of the P-odd effect in the neutron induced nuclear fission was suggested in refs.[60,61,62,25]. Following this approach, one should consider the pear-like shape of the nuclei at the fission stage and the P-odd mixing in the compound nuclear stage. These papers give the estimate of the P-odd correlation $\alpha_{n,fis}$ between the neutron spin and the fission fragment momentum as

$$\alpha_{n,fis} \simeq 2Re\left\{\sqrt{\frac{\Gamma_{\overline{\eta}}}{\Gamma_\eta}}\frac{v}{E - E_{\overline{\eta}} + \imath\Gamma_{\overline{\eta}}/2}\exp\imath(\phi_\eta - \phi_{\overline{\eta}})\right\}, \tag{7.4}$$

where $\Gamma_{\eta,\overline{\eta}}$ are the fission widths and $\phi_{\eta,\overline{\eta}}$ are " the phases of transition into the cold stage from the compound nucleus level " (see ref.[61]) for opposite parities.

In what follows, we will keep the approach suggested in refs.[19,63] which treat the fission channel on the same footing as any other inelastic channels in reaction throry. The main purpose of this approach is not to calculate the P-odd quantities, but to obtain information about fission process comparing the experimental data and theoretical predictions for these quantities. Let us consider the P-violating correlation between the incident neutron spin and the momentum of the light (or heavy) fission fragment. This correlation causes the asymmetry $\alpha_{n,fis}$ in the angular distribution of fission fragments with respect to the direction of the neutron spin(see eq.(1.5)). As was mentioned in Sec.2, the numerator $\Delta_{n,fis}$ of eq.(1.6) is proportional to the sum of the interference terms between the P-conserving and P-violating amplitudes

$$\Delta_{n,fis} \simeq Re \sum_{l,f} \{ f_{ss} f_{sp}^{*} + f_{pp} f_{ps}^{*} \}. \tag{7.5}$$

Here f_{ss} and f_{pp} are the parity-conserving amplitudes of neutron induced fission proceeding via the s and p resonances of the compound nucleus, respectively:

$$f_{ss} \sim (\Gamma_s^n)^{1/2} \exp(\imath\delta_s^n) \frac{1}{(E - E_s + \imath\Gamma_s/2)} (\Gamma_l^f)^{1/2} \exp(\imath\delta_l^f), \tag{7.6}$$

$$f_{pp} \sim (\Gamma_p^n)^{1/2} \exp(\imath\delta_p^n) \frac{1}{(E - E_p + \imath\Gamma_p/2)} (\Gamma_{l+1}^f)^{1/2} \exp(\imath\delta_{l+1}^f). \tag{7.7}$$

The parity-violating fission amplitudes f_{sp} and f_{ps} caused by the weak interaction that mixed the s- and p-compound resonances:

$$f_{sp} \sim (\Gamma_s^n)^{1/2} \exp(\imath\delta_s^n) \frac{-v}{(E - E_s + \imath\Gamma_s/2)(E - E_p + \imath\Gamma_p/2)} (\Gamma_{l+1}^f)^{1/2} \exp(\imath\delta_{l+1}^f), \tag{7.8}$$

$$f_{ps} \sim (\Gamma_p^n)^{1/2} \exp(\imath\delta_p^n) \frac{-v}{(E - E_p + \imath\Gamma_p/2)(E - E_s + \imath\Gamma_s/2)} (\Gamma_l^f)^{1/2} \exp(\imath\delta_l^f). \tag{7.9}$$

Here Γ_l^f is the partial width of the compound resonance of the decay into fragments in state f with relative angular momentum l, and δ_l^f is the potential phase shift in this exit channel.

Since Γ_p^n is very small in comparison with Γ_s^n for low energy neutrons, the term $f_{ss}f_{sp}^*$ is dominant in eq.(7.5). Then, omitting the spin factors, one obtain

$$\Delta_{n,fis} = \frac{2\pi}{k^2}\frac{v\Gamma_s^n}{[s][p]}\sum_{l,f}\{(\Gamma_l^f\Gamma_{l+1}^f)^{1/2} Re[(E-E_p-\frac{i}{2}\Gamma_p)\exp i(\delta_{l+1}^f-\delta_l^f)]\}. \quad (7.10)$$

For simplicity in the further discussion one can use the estimate of the phase difference in eq.(7.10) presented in ref.[19]: since the asymptotic energy of the fragments in thermal neutron-induced fission lies in the vicinity of their Coulomb barrier, the difference of the potential phase shifts for the consequent partial waves can be roughly estimated (see also ref.[64]) as $\delta_{l+1}^f - \delta_l^f \simeq 0$. Then

$$\Delta_{n,fis} \propto \sum_{l,f}(\Gamma_l^f\Gamma_{l+1}^f)^{1/2} \simeq \sum_f(\Gamma_s^f\Gamma_p^f)^{1/2}, \quad (7.11)$$

where $\Gamma_{s,p}^f = \Gamma_{l,(l+1)}^f$. One can represent[65,66] the fission width amplitude as a product of $b_{s,p}^t$ (the transition amplitude from the compound state into a certain transition state t) and γ_t^f (the decay amplitude of a state t into the final channel f):

$$(\Gamma_s^f)^{1/2} = \sum_t b_s^t\gamma_t^f, \qquad (\Gamma_p^f)^{1/2} = \sum_{t'} b_p^{t'}\gamma_{t'}^f. \quad (7.12)$$

Now eq.(7.11) can be written as

$$\sum_f(\Gamma_s^f\Gamma_p^f)^{1/2} = \sum_{t,t'}\{(b_s^t b_p^{t'})\sum_f(\gamma_t^f\gamma_{t'}^f)\}. \quad (7.13)$$

One can see from eq.(7.13) that, for a large number of transition states t, the sum over f is a sum of random quantities leading to a factor $(N_f)^{-1/2}$ ($N_f \sim 10^{10}$ is the number of final states f). If the process goes via only one transition state, the desired sign correlation of amplitudes results, with no randomness. But in our case, s and p states have opposite parities and the sign correlation means that they decay via the same transition state which does not require definite parity.

This is to a certain extent a generalization of Bohr's hypothesis of transition states in fission, which gives from eq.(7.11)

$$\Delta_{n,fis} \sim \sum_f (\Gamma_s^f \Gamma_p^f)^{1/2} \simeq (\Gamma_s^{fis} \Gamma_p^{fis})^{1/2}. \tag{7.14}$$

Here $\Gamma_{s,p}^{fis}$ is the total fission width of the s or p resonance. Then

$$\Delta_{n,fis} \simeq \frac{2\pi}{k^2} \frac{v(\Gamma_s^{fis}\Gamma_p^{fis})^{1/2}\Gamma_s^n(E-E_p)}{[(E-E_s)^2+\Gamma_s^2/4][(E-E_p)^2+\Gamma_p^2/4]}. \tag{7.15}$$

Therefore, for $\Gamma_p^n \ll \Gamma_s^n$

$$\alpha_{n,fis} \simeq \frac{2v}{(E-E_p)^2+\Gamma_p^2/4} \left(\frac{\Gamma_p^{fis}}{\Gamma_s^{fis}}\right)^{1/2} (E-E_p) \tag{7.16}$$

This gives for thermal neutron energies and $\Gamma_s^{fis} = \Gamma_p^{fis}$ the estimate

$$\alpha_{n,fis} \simeq 2v/E_p. \tag{7.17}$$

From the eqs.(7.15) and (7.16), one can see that, similar to the other P-odd asymmetries, the quantity $\alpha_{n,fis}$ has the dynamic enhancement factor and the resonance enhancement factor (see Sec.3). The structure enhancement factor in this case is proportional to the ratio of the fission width for opposite parities (or the corresponding barrier penetrabilities). It should be noted that this ratio may provide information on the transition state properties. First of all one might look at the case near the barrier when the fission barrier penetrability is large for Γ_p^{fis} and small for Γ_s^{fis}. This might enhance the previously observed quantities $\alpha_{n,fis}$ in a manner discussed in refs.[56,57] and give us additional information on fission barrier properties. The measurements of mass dependence for the P-odd asymmetry are also of importance since it might arise only through the different mass (M) dependence of $\Gamma_p^{fis}(M)$ and $\Gamma_s^{fis}(M)$. In any case, the discovery of such a dependence might indicate that the fission product mass distribution is formed at the saddle point. The statistical models (of the Fong type) state that the mass distribution is formed at the scission point. Therefore, they can hardly predict different mass distributions for neighboring resonances even if the fission barriers for opposite-parity states differ by $(0.5-1)MeV$. Thus one should not expect mass dependence of the asymmetry value if the statistical scission point models are applicable to fission. So far, the experimental evidence[54,55] show no dependence of $\alpha_{n,fis}$ within 10% accuracy.

Let us consider the physical consequences from the phase correlation hypothesis. One should stress that this hypothesis was introduced long ago[65–67] to explain the experimentally observed distribution law of resonance fission widths and the interference effects in total (integrated over the angles) fission cross sections. But, in those explanations, each transition state had fixed quantum numbers J (the compound nucleus spin), K (the projection of J on the nuclear symmetry axis) and parity π assigned to it. To explain the observed P-violating asymmetry (i.e. large values of eq.(7.13)), we are forced to remove the parity from the characteristics of the transition state. One possible explanation of this fact is as follows: the transition states are characterized by quantum numbers (including the energy) which describe the motion along internal variables (single-particle excitations, vibrations, etc.). The quantum number of the motion along the fission mode is not a characteristic of the transition state. This situation resembles charged particle motion in a homogeneous magnetic field[68]. For motion in a plane perpendicular to the magnetic field direction the energy is quantized, forming a set of the so-called Landau levels. For motion along the field there is a continuous energy spectrum. Therefore the transition states should be characterized by the intrinsic spin j (and not by the total spin J), intrinsic parity, etc. Let l be the angular momentum transferred along the fission variable (from the classical point of view this means that the fission fragments do not travel exactly along the symmetry axis). Since the motion along the fission variable is not quantized, the same energy can have different values of l and $l' \neq l$. Since the total spin J of the system should be conserved, this means

$$\mathbf{J} = \mathbf{j} + \mathbf{l} = \mathbf{j} + \mathbf{l}'. \qquad (7.18)$$

This indicates that the total spin J might differ from the quantum number j characterizing the transition state. The same is true for parities. Therefore one can observe the interference effects between the fission amplitudes for compound resonances with different total spins J, J' but decaying via the same transition state j. Note that we consider the interference effects in the differential cross sections (angular distributions) and not in the angle-integrated cross section which is usually treated in the theory of transition states[65,67]. Obviously the angle-integrated cross section can show only the interference between the resonances of the same spin (due to the orthogonality of spherical functions). The experimental ways to check the case $J \neq j$ were discussed in ref.[19]; namely, the measurement of the $\alpha_{n,fis}$-energy dependence in the vicinity of the compound s- resonance with $J = 0$. For an isolated $J = 0$ resonance the numerators in $\alpha_{n,fis}$ should be zero. This is understandable since one cannot polarize the compound system with $J = 0$. Therefore, in the absence of interference between $J = 0$ and $J = 1$ resonances, the experimental values of $\alpha_{n,fis}$ should display a gap in the region of a $J = 0$ resonance since this resonance contributes considerably to the cross section in the denominators of $\alpha_{n,fis}$ but does not contribute to the numerator (see Fig. 5).

7.2 TERNARY FISSION

Let us consider a ternary nuclear fission. Since there is a third particle in the exit channel (assume that it is an α particle with the momentum $\mathbf{k}_\alpha$), the number of correlations which can be studied in this process is clearly much larger. We shall consider the three P-violating correlations[63] which can be of major interest, namely $(\sigma \mathbf{k}_\alpha)$, $(\sigma \mathbf{k}_f)$ and $\mathbf{k}_\alpha[\mathbf{k} \times \mathbf{k}_f]$. The first correlation leads to the asymmetry $\alpha^T_{n\alpha}$ in the angular distribution of the α particle emitted from ternary fission when it travels parallel or antiparallel to the neutron spin direction. The second correlation causes asymmetry in ternary fission analogous to the $\alpha_{n,fis}$ asymmetry of binary fission. We shall call it $\alpha^T_{n,fis}$. The third correlation causes the difference in yields of α particles in the right and left hemispheres, which are separated by the plane containing the vectors $\mathbf{k}$ and $\mathbf{k}_f$. We shall call this asymmetry $\mathcal{A}$. Since ternary fission proceeds via the compound nucleus state, all the above asymmetries will be defined by the amplitudes analogous to eqs. (7.6)- (7.9). One should substitute the binary fission amplitudes and phase shifts $(\Gamma^f_l)^{1/2}\exp(\imath\delta^f_l)$ only by the ternary fission ones $(\Gamma^F_{\Lambda,l})^{1/2}\exp(\imath\delta^F_{\Lambda,l})$. Here Λ is the relative angular momentum of the fission fragments, l is the angular momentum of the α particle with respect to the center of mass of the fragments and $\delta^F_{\Lambda,l}$ is the phase shift in the final channel F. Contrary to the binary fission case, we cannot make any estimate for the differences of $\delta^F_{\Lambda,l}$ and should retain them as parameters. It seems reasonable to suppose that these differences should not depend strongly on the energy of incident neutrons and therefore should not cause additional sign randomness in the sum over the products of partial amplitudes analogous to eq.(7.11). Nevertheless, with a sum of terms analogous to eq.(7.11) $\Gamma^F_{s,p}$ might be some smaller than $\Gamma^f_{s,p}$. Indeed, for binary fission the orbital momentum l value was restricted by the centrifugal barrier $l \leq 10-30$ and the summation over l in eq.(7.11) could not considerably reduce the $\Gamma^f_{s,p}$ value with respect to the average value of $\Gamma^f_{l,(l+1)}$. For ternary fission, the centrifugal barrier does not suppress the possible values of Λ and l[69]. Therefore, one might expect a slight reduction of $\Gamma^F_{s,p}$ by a factor β with respect to the average values of $\Gamma^F_{\Lambda,l}$. However, one should not expect β to be smaller than 0.1, which would correspond to the total number of partial waves $\sim 10^2$. This result is in a good agreement with the existing experimental data[70].

Now we can write (omitting the spin factors) the expressions for the P-violating effects in the ternary fission $\alpha^T_{n\alpha}$, $\alpha^T_{n,fis}$ and $\mathcal{A}$. The corresponding numerators of these quantities are

$$\Delta^T_{n\alpha} \simeq Re \sum_{\Lambda,l,F} \left\{ f^T_{ss} f^{T*}_{sp} + f^T_{pp} f^{T*}_{ps} \right\}, \tag{7.19}$$

$$\Delta^T_{n,fis} \simeq Re \sum_{\Lambda,l,F} \left\{ f^T_{ss} f^{T*}_{sp} + f^T_{pp} f^{T*}_{ps} \right\}, \tag{7.20}$$

$$\Delta_A \simeq Im \sum_{\Lambda,l,F} \left\{ f^T_{ss} f^{T*}_{sp} + f^T_{pp} f^{T*}_{ps} \right\}. \tag{7.21}$$

Clearly $\alpha^T_{n\alpha}$ and$\alpha^T_{n,fis}$ are caused by the interference of opposite parity amplitudes in the exit channel, while $\mathcal{A}$ is caused by the interference in the entrance channel. Thus the possible additional small parameter β does not appear in the expression for $\mathcal{A}$.

Suppose now that the third particle of the ternary fission appears after the transition through the saddle point. One can apply all the considerations of binary fission to obtain the corresponding expressions for α and $\mathcal{A}$. Taking for simplicity only one s- and p-compound resonance and employing the fact that $\Gamma^n_p \ll \Gamma^n_s$ for the $\alpha^T_{n\alpha}$ and $\alpha^T_{n,fis}$ cases, we can obtain

$$\alpha^T_{n\alpha} \simeq \frac{2\beta v}{(E-E_p)^2 + \Gamma_p^2/4} \sqrt{\frac{\Gamma^T_p}{\Gamma^T_s}} Re \left\{ (E - E_p - \imath\Gamma_p/2) \exp(\imath\phi) \right\}, \tag{7.22}$$

$$\alpha^T_{n,fis} \simeq \frac{2\beta v}{(E-E_p)^2 + \Gamma_p^2/4} \sqrt{\frac{\Gamma^T_p}{\Gamma^T_s}} Re \left\{ (E - E_p - \imath\Gamma_p/2) \exp(\imath\phi) \right\}, \tag{7.23}$$

$$\mathcal{A} \sim 2v(\Gamma^n_s \Gamma^n_p)^{1/2} \frac{Im\{\Gamma^T_s[p-]\exp(\imath\delta) + \Gamma^T_p[s-]\exp(-\imath\delta)\}}{\Gamma^n_s\Gamma_s[p] + \Gamma^n_p\Gamma_p[s]}. \tag{7.24}$$

Here $\Gamma^T_{s,p}$ is the total ternary fission width of the corresponding resonances; $\phi = \delta^F_s - \delta^F_p$; $\delta = \delta^n_s - \delta^n_p$. Assuming $\sin\phi \sim \cos\phi \sim 1$, one gets the off-resonance estimates

$$\alpha^T_{n\alpha} \simeq \frac{2\beta v}{(E-E_p)}\sqrt{\frac{\Gamma^T_p}{\Gamma^T_s}}, \tag{7.25}$$

$$\alpha^T_{n,fis} \simeq \frac{2\beta v}{(E-E_p)}\sqrt{\frac{\Gamma^T_p}{\Gamma^T_s}}, \tag{7.26}$$

$$\mathcal{A} \sim \frac{2v}{(E-E_p)^2}\sqrt{\frac{\Gamma^n_p}{\Gamma^n_s}}\left[\Gamma_p + \Gamma_s\left(\frac{\Gamma^T_p}{\Gamma^T_s}\right)\right]. \tag{7.27}$$

Evidently all the quantities (7.22)-(7.24) contain the factors of dynamic and resonance enhancement. The expressions for $\alpha^T_{n,fis}$ and $\alpha^T_{n\alpha}$ also contain the possible structural enhancement factor $(\Gamma^T_p/\Gamma^T_s)^{1/2}$ similar to those appearing in binary fission. The expression for $\mathcal{A}$ contains the structural hindrance factor of the entrance channel $(\Gamma^n_p/\Gamma^n_s)^{1/2} \sim kR$ since both s- and p-neutron waves are needed for this correlation.

Thus, the estimates of P-violation in binary fission can be used[19] to obtain

$$\alpha^T_{n\alpha} \sim \alpha^T_{n,fis} \sim 10^{-4} - 10^{-5} \tag{7.28}$$

$$\mathcal{A} \sim 10^{-4}(kR) \sim 10^{-7} - 10^{-8} \tag{7.29}$$

for the same nuclei in the case of thermal neutron-induced ternary fission. All the effects might be enhanced by a factor of 1-1.5 orders of magnitude in the vicinity of p-wave resonance[19]. Additionally, $\mathcal{A}$ increases as $(E)^{1/2}$ with increasing neutron energy. The above results are valid if the ternary fission process proceeds with simultaneous formation of 3 particles. If the binary fission is followed by the emission of an α particle, then $\beta \sim 1$ and $\alpha^T_{n\alpha}$ is exactly 0 due to kinematical reasons. Indeed, for the two-step mechanism, the amplitude of the process $n + A \longrightarrow C + B + \alpha$ is factorized as a product of amplitudes $n + A \longrightarrow C + B'$ and $B' \longrightarrow B + \alpha$. Since, while measuring $\alpha^T_{n\alpha}$, the angles of emission for the fragments are not fixed, the information on the initial neutron spin is lost. This fact can be easily seen from the results of ref.[71] where the angular distribution of this correlation is obtained in the form

$$(\sigma \mathbf{k}_\alpha) \sim \cos\theta\cos\theta' + \sin\theta\sin\theta'\cos(\psi - \psi'). \qquad (7.30)$$

All the θ angles here are given with respect to the neutron spin direction, the non-primed variables indicate the direction of the B' emission, while the primed ones describe the motion of the α particle in the rest frame of B'. Clearly, eq.(7.30) becomes zero when integrated over $\sin\theta d\theta d\psi$. Of course, the experimental results even in this case should differ from zero because of the camouflaging effect caused by the correlation $(\sigma \mathbf{k}_f)$ since the α-evaporation probabilities are different for heavy and light fragments. Therefore the experimental result $\alpha^T_{n\alpha} \ll \alpha^T_{n,fis}$ should imply that the two-step process occurs, while $\alpha^T_{n\alpha} \sim \alpha^T_{n,fis}$ implies its absence.

One can point out that the $\mathcal{A}$ asymmetry does not contain the unknown quantity ϕ, contrary to $\alpha^T_{n\alpha}$ and $\alpha^T_{n,fis}$. Therefore, experimental studies of $\mathcal{A}$ might be the most unambiguous way to define the value of the weak matrix element and the p-resonance position. Comparing the observed values of $\mathcal{A}$ with those for $\alpha^T_{n\alpha}$ and $\alpha^T_{n,fis}$ in the case of subbarrier fission, one might also obtain information on the barrier penetrabilities for the resonance of different parities.

The $\mathcal{A}$ quantity is small in the thermal-neutron region but increases considerably for resonance neutrons. Since one does not need polarized neutron beams to measure it, one would measure it, e.g., in the (d,p) reactions. (See the detailed consideration of this reaction in ref.[72]).

7.3 P-EVEN CORRELATIONS

Let us consider P-even correlations for the neutron induced fission, e.g., $(\sigma[\mathbf{k}\times\mathbf{k}_f])$ and $(\mathbf{k}\mathbf{k}_f)$. Using the given in[19] approach, one can get values for the corresponding asymmetries (for simplicity, in the two level approximation with the estimation of the potential phase difference according to refs.[19,63]) as:

$$\alpha^{rl}_{n,fis} \sim (\Gamma^n_s\Gamma^n_p\Gamma^{fis}_s\Gamma^{fis}_p)^{1/2}\frac{(E-E_s)\Gamma_p-(E-E_p)\Gamma_s}{\Gamma^n_s\Gamma^{fis}_s[p]+\Gamma^n_p\Gamma^{fis}_p[s]}, \tag{7.31}$$

$$\alpha^{fb}_{n,fis} \sim 2(\Gamma^n_s\Gamma^n_p\Gamma^{fis}_s\Gamma^{fis}_p)^{1/2}\frac{(E-E_s)(E-E_p)+\frac{1}{4}\Gamma_s\Gamma_p}{\Gamma^n_s\Gamma^{fis}_s[p]+\Gamma^n_p\Gamma^{fis}_p[s]}. \tag{7.32}$$

From these equations, we can see that P-even correlations have the energy dependence similar to the ones for the (n,γ) case. Therefore, to obtain information about p-wave resonance properties and about properties of transition states in nuclear fission, P-even correlations might be more convenient than P-odd correlations (see discussion in Sec.6).

8. NEUTRON-INDUCED REACTIONS WITH CHARGED PARTICLES

The theoretical approach which was considered in Sec.2 is appropriate for any neutron-induced reaction and, with suitable modifications, to any low energy reaction. As example, from eqs.(1.5),(2.13), one can estimate the value of the P-odd asymmetry for the (n,p) reaction in the vicinity of the thermal neutron energy point

$$\alpha_{np} \simeq \frac{2v}{E_p}\sqrt{\frac{\Gamma^p_p}{\Gamma^p_s}}\left(\cos\phi+\frac{\Gamma_p}{2E_p}\sin\phi\right). \tag{8.1}$$

Here ϕ is the proton potential scattering phase difference for p- and s-wave neutron resonances, and $\Gamma^p_{s,p}$ is the proton decay width for the s- or p- resonance.

In eq.(8.1) , we omit the the spin factors (they may be find in ref.[19]). For the right-left P-even correlation in such an approximation one can obtain

$$\alpha_{np}^{rl} \simeq \sqrt{\frac{\Gamma_p^n \Gamma_p^p}{\Gamma_s^n \Gamma_s^p}} \left(\frac{E_p \Gamma_s - E_s \Gamma_p}{E_p^2} \cos\phi + \frac{2E_s}{E_p} \sin\phi \right) . \tag{8.2}$$

It should be noted that the estimates obtained from this expression are in good agreement with the experimental data[73] for the neutron-proton reaction on the ^{37}Cl.

9. SUMMARY

We have considered an unified theory of the parity-violating effects in neutron induced reactions. This theory includes the previously considered effects of potential-scattering mixing, valency nucleon model and direct-interaction contribution as particular limiting and simplified cases. Up to now, all existing experimental data confirm this theory to within the experimental accuracy. The theory allows us to classify the observed effects according to their respective magnitudes and to understand the physical sources of the differences of these magnitudes from each other.

We have seen that experimental values of P-violating effects provide us with information about nuclear structure. First of all, these effects seem to be the best way to obtain information on neutron p-resonance properties. Secondly, the asymmetry measurements in inelastic channels give us better insight into the properties of these channels. From this point of view, the measurement of P-even correlations for different neutron energies is more convenient since this quantity contains exactly the same nuclear information as P-odd ones without the "weak interaction contamination". And finally, one of the most significant purposes for studying P-violating effects in neutron-induced reactions is the search for the optimal conditions for T-violating measurements in neutron scattering.

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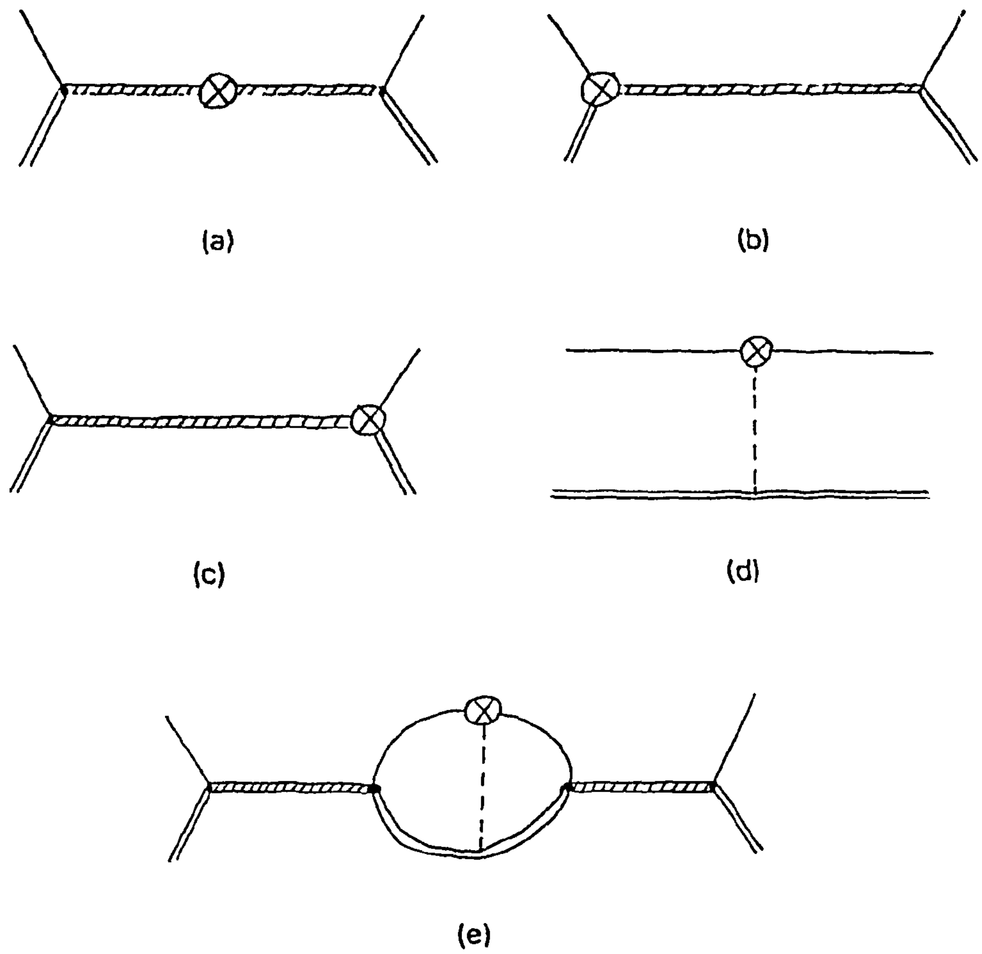

Fig. 1. The P-violating reaction matrix

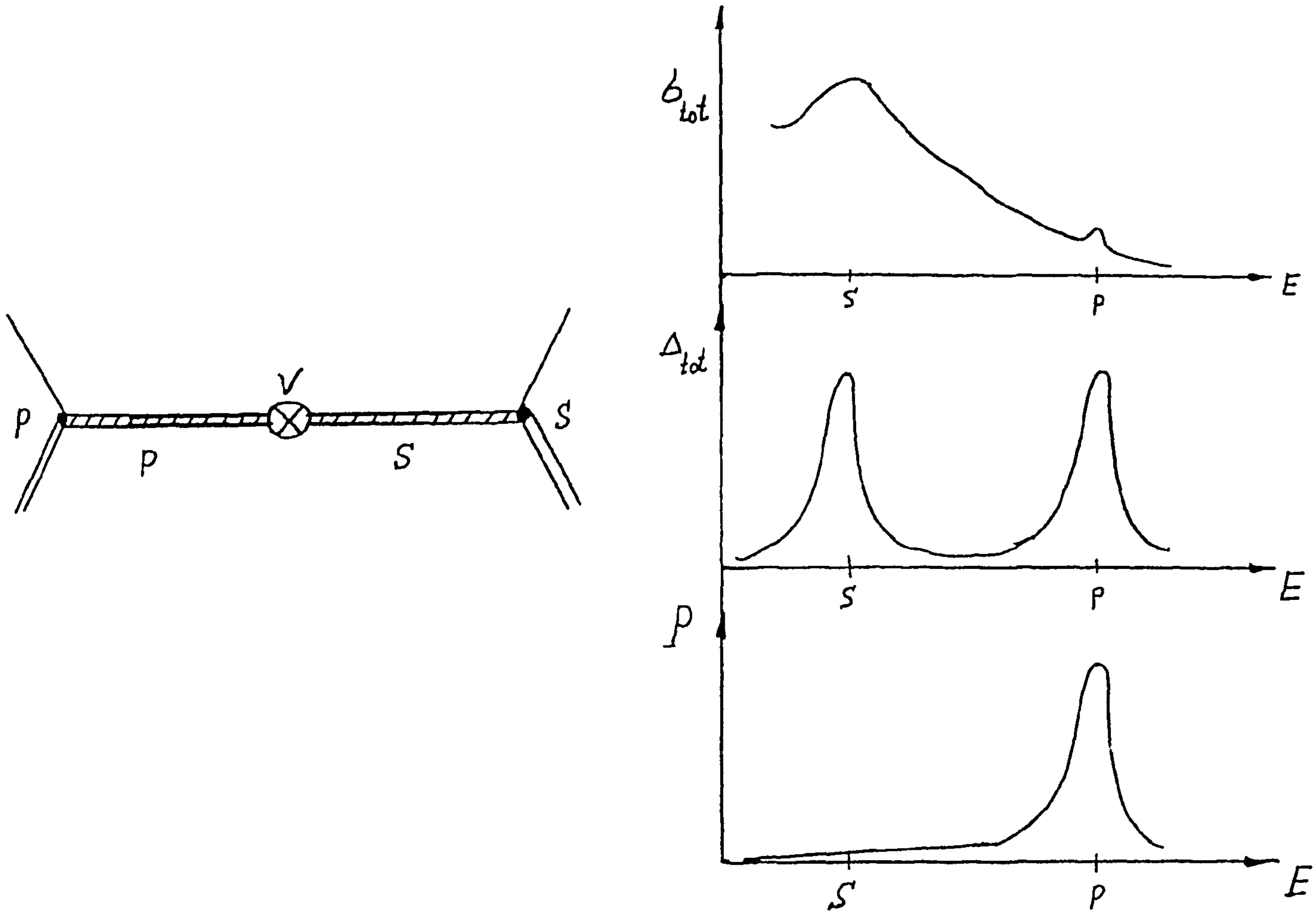

Fig. 2. The resonance enhancement of the total cross section difference

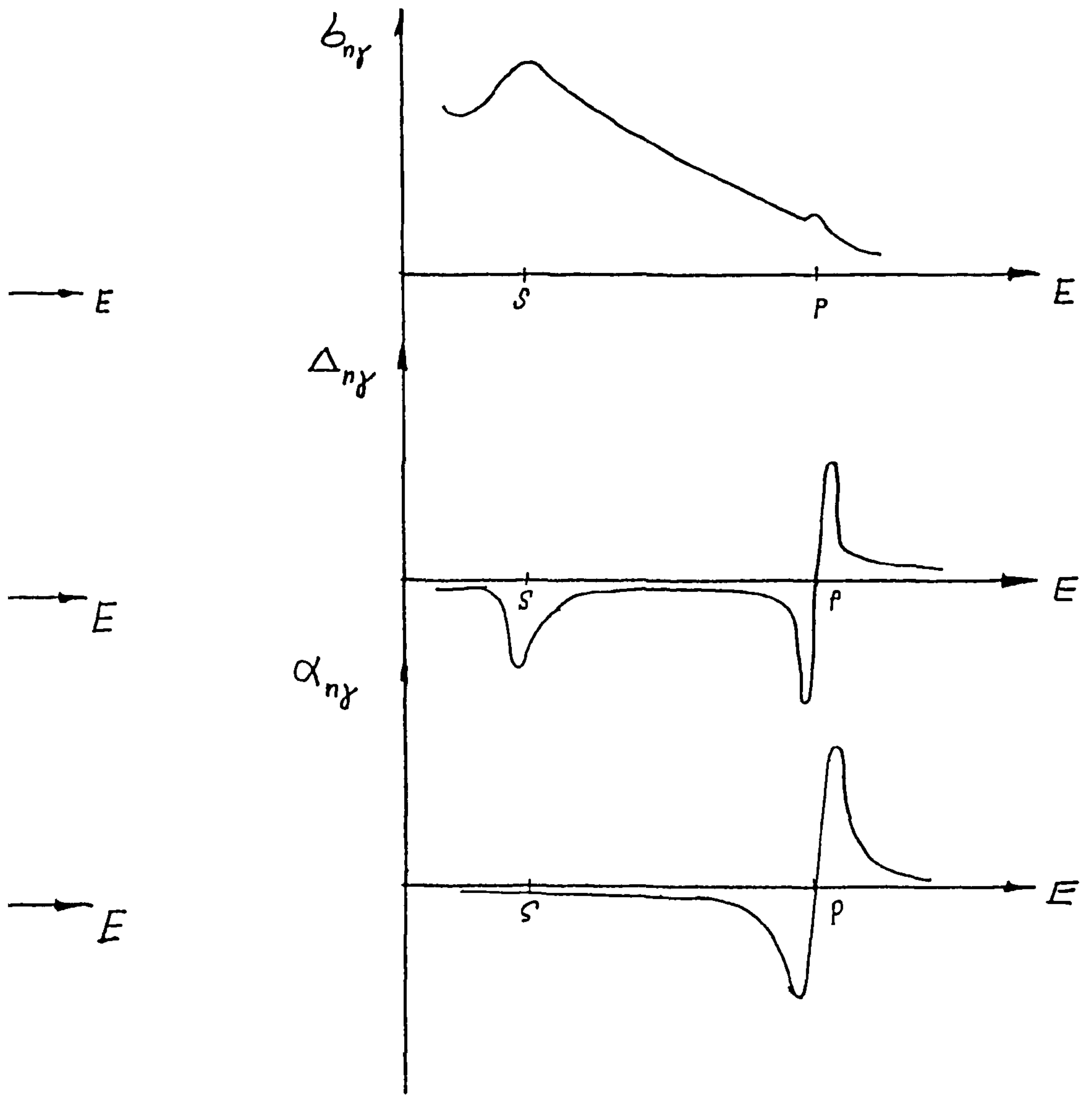

Fig. 3. The asymmetry in (n, γ) reaction

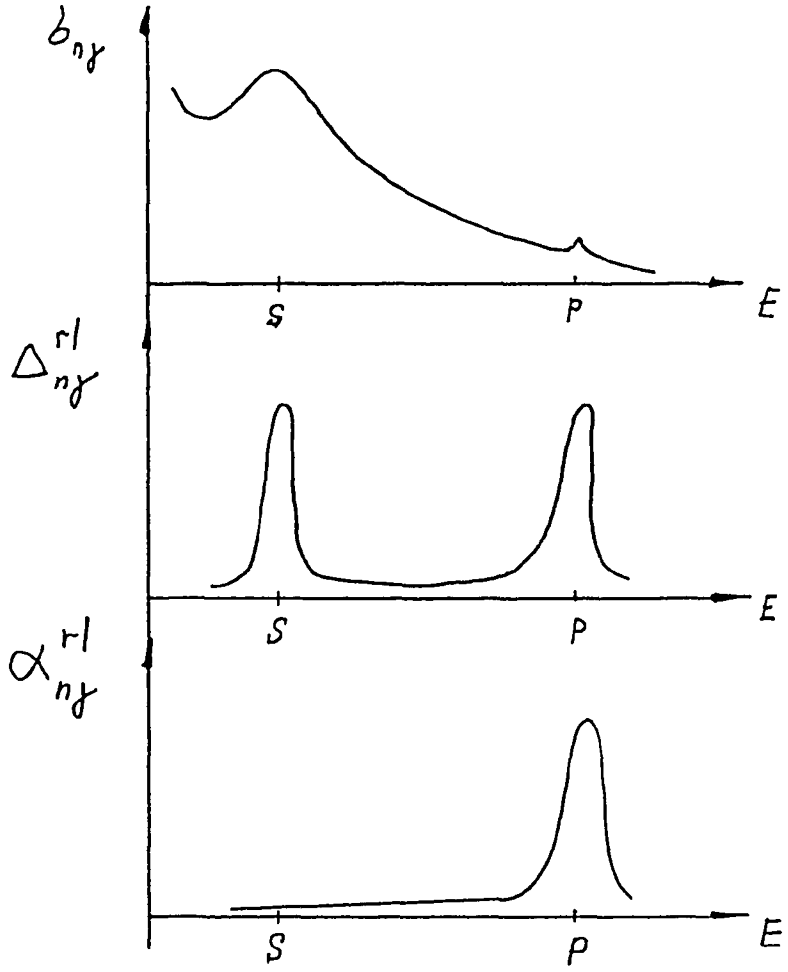

Fig. 4. The right- left asymmetry

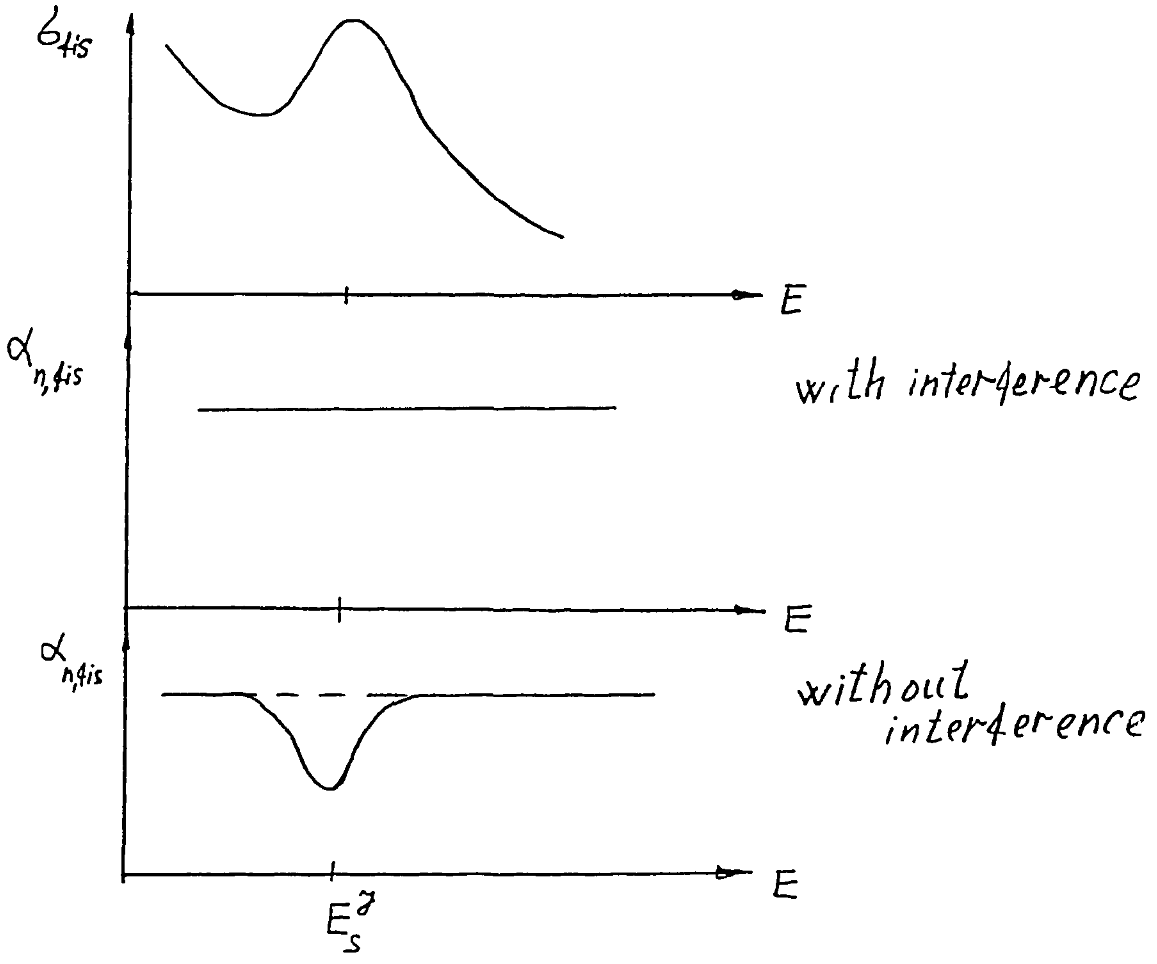

Fig. 5. The $\alpha_{n,fis}$ asymmetry in the vicinity of a s-wave resonance with zero spin.

Nucleus	$E_p(eV)$	$\alpha^{\Sigma}_{n\gamma}\times 10^6$	m	m_{coh}/m	$v(meV)$ integ	$v(meV)$ diff
^{82}Br	0.88	-19.5 ± 1.6	0.016	29.1	4.6 ± 0.4	3.0 ± 0.5
^{114}Cd	7.0	-1.3 ± 1.4	0.011	38	≤ 0.8	0.4 ± 0.1
^{118}Sn	1.33	2.4 ± 1.6	0.017	23.3	≤ 3.7	0.4 ± 0.1
^{140}La	0.75	-17.8 ± 2.2	0.043	10.4	0.96	1.3 ± 0.1

Table 1. The parity violation in the "integral" experiment