SYMMETRIES AND SPIN-ANGULAR CORRELATIONS IN NEUTRON INDUCED REACTIONS: ELASTIC, RADIATIVE AND FISSION CHANNELS

Barabanov A.L.

Kurchatov Institute, Moscow 123182, Russia

Abstract

This is a review of the most important results and new proposals on study of spin-angular correlations in the interaction of slow neutrons with medium and heavy nuclei. Special attention is given to spin-angular correlations sensitive to violations of fundamental symmetries - spatial parity and time reversal invariance. Other nuclear characteristics that may be obtained in measurements of spin-angular correlations are also discussed.

1. Introduction

Spin-angular correlations in neutron induced reactions arise due to interference of partial waves (carriers of definite angular momenta) and are sensitive to any mechanisms influencing these waves. Therefore from the beginning of 1950th years spin-angular correlations are actively used as a tool of studying those terms in Hamiltonians of strong, weak and electromagnetic interactions which depend on angular momenta (spins). In particular, forces breaking fundamental symmetries, spatial parity (P) and time reversal invariance (T), are of this type.

However, each of reactions, (n,n), (n,γ) and (n,f), initiated by neutrons, has special features. The purpose of the report is to present the current situation with measurement of different spin-angular correlations in neutron reactions and to discuss their importance.

The report is devoted mainly to the interaction of slow neutrons (s-, p- and d-waves) with medium and heavy nuclei. Thus there are three types of processes in the interaction of slow neutrons with nuclei: elastic scattering, capture with emission of γ quantum (radiative capture) and fission (if target nuclei are heavy enough). Besides it is possible to study a total cross section by neutron transmission through the target. According to the optical theorem the total cross section is determined by the amplitude of elastic scattering on the zero angle. Therefore all the effects connected with transmission are actually determined by the elastic channel.

All four possible channels of neutron-nucleus interaction are listed in Figure 1.

2. What there is spin-angular correlation?

Let us address to Figure 1 to explain what spin-angular correlation means. In an entrance channel of nuclear reaction there are two colliding particles (for example, a neutron and a nucleus), each of which, generally speaking, has a spin - **s** and **I**. The momentum **k** the incident particle is represented also.

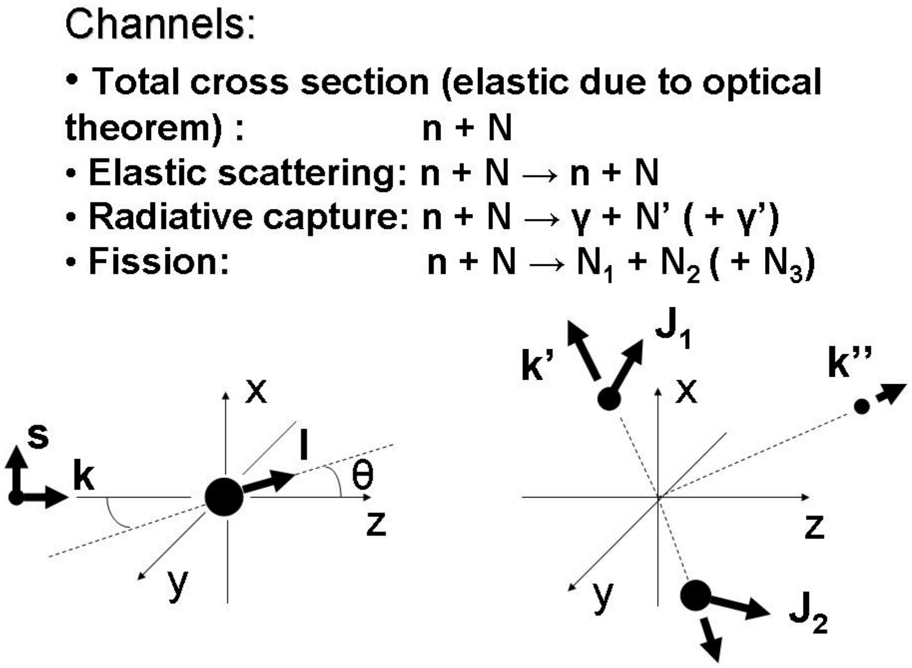
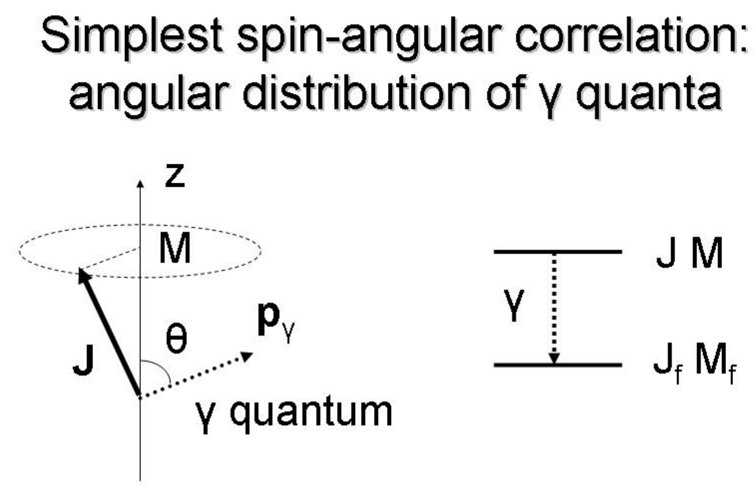


Figure 1

In an exit channel there are at least two particles (**k**' is their relative momentum) which fly away from one another. For example, it can be the elastic scattered neutron and recoil nucleus. Or the γ quantum and recoil nucleus; the nucleus, being in an excited state, can emit a second γ quantum represented in the Figure 1 as a third particle in the exit channel (with the momentum **k**"). Two particles in the exit channel can be also two fragments from nuclear fission, while the third particle can be α particle in ternary fission, or γ quantum emitted by one of the fragments. Besides the momenta, the particles in the exit channel possess, generally speaking, the spins - $\mathbf{J}_1$ and $\mathbf{J}_2$ (the spin of the third particle is not represented to simplify the Figure).

Thus, it is possible to put the question, what is the probability of the process at which spins and momenta of colliding and formed particles have the certain directions. Calculation of such probability is calculation of the spin-angular correlation.

One should note, however, that the arrows representing momenta of the particles in the Figure 1, really are showing the momenta, because the momentum direction can be fixed exactly. At the same time the direction of a particle spin cannot be fixed, because only one projection of the spin (on an axis of quantization) is defined. Therefore the arrows representing the spins, in fact are showing the axes of orientation of particle spins. For simplicity, however, we will name the directions of axes of spin orientation the spin directions.



$$d\,w\,(\theta) \sim \sum_{M_f} |\langle J_f M_f\,|\hat{V}\,|\,J\;M\rangle|^2 \sim a + b\cos^2\theta + \ldots$$

Figure 2

As an example of the simplest spin-angular correlation, let us consider the angular distribution of γ quanta that are emitted by a quantum system (by atom or nucleus) in a transition $|J\rangle \rightarrow |J_f\rangle$ (see Figure 2). Orientation of spin J with respect to an axis z is determined by a distribution over projections M of the spin on the axis. Let the initial projection M be fixed, while a final projection M_f is out of interest. Then, as shown in Figure 2, summation over M_f should be performed at the calculation of the angular distribution $dw(\theta)$. Generally, the additional summation over M is needed with the weights describing the initial distribution over M. In any case the angle θ is the angle between the momentum $\mathbf{p}_\gamma$ of γ quantum and the axis z of spin orientation.

If parity is conserved, only even degrees of $\cos\theta$ enter into the angular distribution (as shown in Figure 2). Parity violation was just found in 1957 as a contribution of linear term (~ cos θ) into the angular distribution of electrons with respect to polarized spins of β decaying nuclei ^{60}Co [1].

Thus, the orientation of spin J of a particle with respect to the fixed axis z is determined by the distribution over projection M of the spin on the axis. Two typical situations are shown in Figure 3: polarization and alignment. Ensemble of particles is named polarized along the axis z if the population n_M of substate with the projection M of the spin on this axis monotonously grows with an increase of M. On the other hand, pure alignment takes place when there is the equality: $n_M=n_{-M}$. The parameters describing polarization, $p_1(J)$, and alignment, $p_2(J)$, are expressed via the first and second moments, $\langle M\rangle$ and $\langle M^2\rangle$, of the distribution n_M, as shown in Figure 3. Higher moments, as a rule, have no practical value.

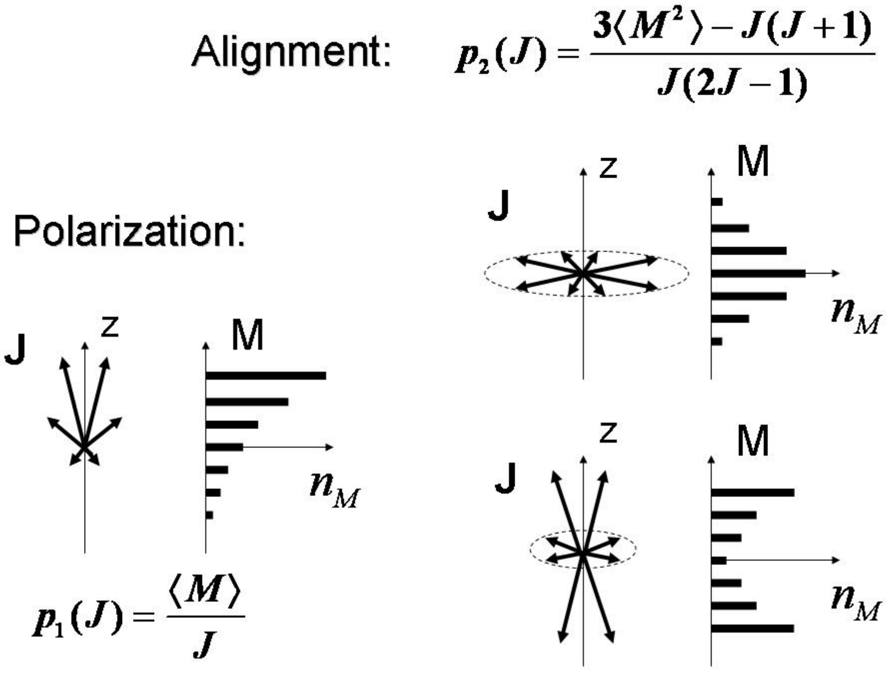


Figure 3

Of course, in the real experiment it is difficult to fix at once directions of many vectors. As a rule, the directions of only two vectors are fixed (herewith explicit or implicit summation over directions of all other vectors is performed). If one of these vectors is the momentum of a particle in the exit channel (with respect to some other vector) one says not about spin-angular correlation but, simply, about angular distribution. Correlations of three vectors are studied in the most advanced experiments.

Combination of these vectors may be rather unexpected. For example, last decade a T odd correlation of three vectors in ternary fission was actively discussed. These vectors are spin of the incident neutron, momentum of the light fragment and momentum of the α particle (or, generally, third particle in the fission). This correlation will be discussed in the end of the report.

3. Fundamental symmetries and spin-angular correlations

Let us pass now to the main question - why studying of spin-angular correlations is of interest? Let us address to Figure 4. Obviously, the spin-angular correlations is a natural tool of studying of any characteristics related to spins. The simplest point is measurement of spins and parities of quantum levels or spin dependence of level density. Some similar things will be discussed later. The other clear point is study of spin dependent forces, such as spin-spin, spin-orbital and tensor interactions. So, in particular, the model explaining the T odd correlation in ternary fission by specific spin-orbital forces in the exit channel is described in Section 8.

Goal: spin-angular correlations is a tool of studying of any characteristics related to spins

- **Spins and parities of levels, level density...**
- **Interactions: spin-spin, spin-orbit, tensor...**
- **Fundamental symmetries: P (after 1956) and T (mainly after 1964):**

Parity Violating (PV), ~σp, π-, ρ-, ω-mesons
Time Violating Parity Violating (TVPV), ~σr, π-mesons
Time Violating Parity Conserving (TVPC), ~rp, ρ-mesons

Figure 4

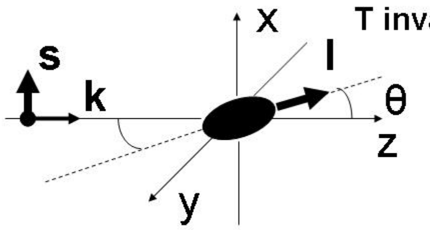
However, the sensitivity of spin-angular correlations to violation of fundamental symmetries – spatial parity (P) and time reversal invariance (T) - are of principal interest. The existence of such sensitivity is clear because the forces breaking fundamental symmetries depend somehow on spins (on angular momenta).

In fact, as it was told above, P invariance violation has been established in 1957 just by means of the elementary P odd correlation of spin and momentum in β decay. After 1964, when CP violation was found [2], searches of T non-invariant spin-angular correlations in nuclear reactions and decays have begun. These searches had no success till now, probably, simply because accuracy of the experiments was not sufficiently high.

Thus, nothing definite is known so far about forces breaking T invariance. Therefore two possibilities should be considered. If T non-invariant forces violate parity, they are TVPV interactions (T Violating P Violating). Or, on the contrary, they keep parity, and their name is TVPC interactions (T Violating P Conserving).

4. Spin-angular correlations in the total cross section

We address to the amplitude of elastic scattering of neutron by nucleus on the zero angle – f(0). There are only three vectors in our disposal - spin **s** and momentum **k** of the incident neutron and spin **I** of the target nucleus. Assuming, that velocities are small (thus, only s- and p-waves participate), and that the neutrons are polarized, while the nuclei are both polarized and aligned, we receive the required amplitude presented in Figure 5.



T invariance: $S_J(lj \to l'j') = S_J(l'j' \to lj)$

	s1/2	p1/2	p3/2
s1/2		PV	PV
p1/2	PV		
p3/2	PV		

$$\vec{\mathbf{s}} + \vec{\mathbf{I}} = \vec{\mathbf{j}}, \quad \vec{\mathbf{j}} + \vec{\mathbf{I}} = \vec{\mathbf{J}}$$

$$f(0) = a_0 + a_1 p_1(I)(\vec{\sigma}\vec{\mathbf{I}}) + a_2 p_1(I)(3(\vec{\sigma}\vec{\mathbf{k}})(\vec{\mathbf{I}}\vec{\mathbf{k}}) - (\vec{\sigma}\vec{\mathbf{I}})) +$$

Spin – spin effects

$$+ a_3 p_2(I)(3(\vec{\mathbf{k}}\vec{\mathbf{I}})^2 - 1) +$$

Deformation effect

$$+ b_1(\vec{\sigma}\vec{\mathbf{k}}) + b_2 p_1(I)(\vec{\mathbf{I}}\vec{\mathbf{k}}) +$$

P odd effects

$$+ b_3 p_2(I)(3(\vec{\sigma}\vec{\mathbf{I}})(\vec{\mathbf{k}}\vec{\mathbf{I}}) - (\vec{\sigma}\vec{\mathbf{k}})) +$$

$$+ c_1 p_1(I)(\vec{\sigma}[\vec{\mathbf{k}}\vec{\mathbf{I}}]) + c_2 p_2(I)(\vec{\sigma}[\vec{\mathbf{k}}\vec{\mathbf{I}}])(\vec{\mathbf{k}}\vec{\mathbf{I}})$$

T odd effects

Figure 5

I shall note at once, that the full structure (eight spin-angular correlations) has been written out only in the middle of 1980th years (see, e.g., [3, 4] and references therein). I shall notice, that the terms with factors “a” are caused by spin-spin and tensor forces, terms with factors “b” are due to parity violating (PV) forces whereas two last terms with factors “c” - 3-fold and 5-fold correlations - are non-zero, only if there is a violation of S matrix symmetry with respect to the main diagonal, that means the T violation.

I'd like to draw the attention to the fact that up to now from the specified eight correlations only two were investigated in the interaction of slow neutrons with nuclei. They are, first, spin-spin correlation, (**sI**), that is of great practical importance (it is used for polarization of neutrons by their transmission through polarized targets - see, e.g., [5]) and, secondly, the simplest P odd correlation of neutron spin and momentum, (**sk**). Discovery [6] of this P odd correlation in the beginning of 1980th years or, more accurately, the fact of its large enhancement, have stimulated revealing of all other terms in the amplitude of elastic scattering on the zero angle.

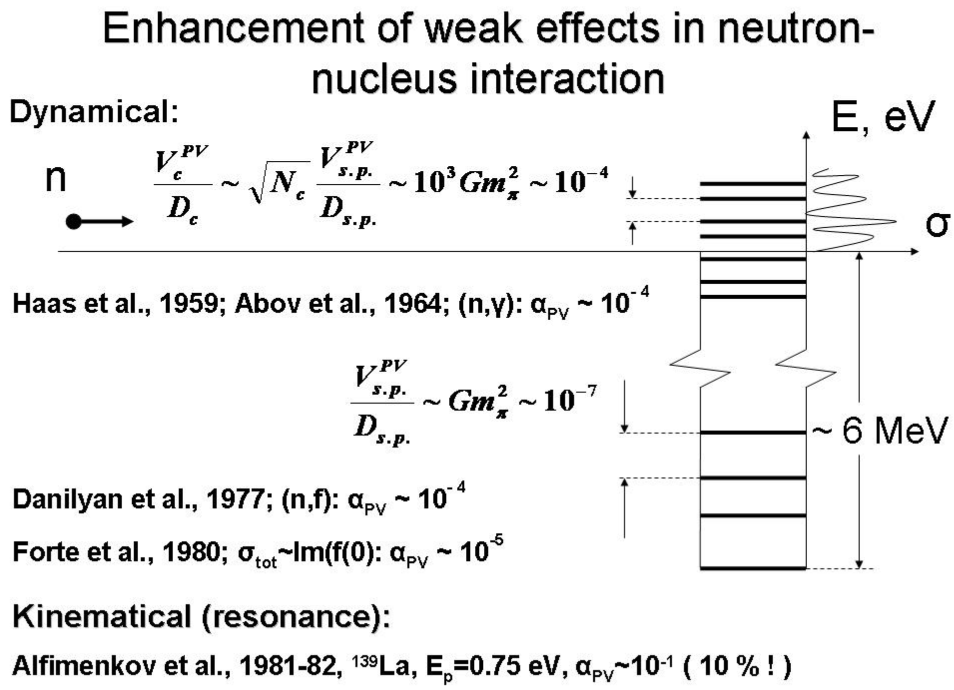


Figure 6

Let us stop in more detail on the enhancement. Some explanations are given in Figure 6. Neutron resonances are highly excited nuclear states. Distances between them are of the order of 10 eV that is much less than a typical distance (~ 1 MeV) between low lying states of nuclear spectrum. Therefore, if a mixing of the low lying states by PV forces is of the order of 10^{-7}, then the same mixing of neutron resonances may be much larger. Explicit expression for the corresponding enhancement factor of the scale of 10^3 that is named dynamical, is presented in Figure 6 (see, e.g., [7, 8]).

Dynamical enhancement has been predicted in [9], and then confirmed in the beginning of 1960th years in radiative capture of neutrons [10]. Later the similar enhancement was found for the P odd effects in nuclear fission [11] and in the elastic channel [6]. All these measurements were performed for thermal neutrons.

But in the same time, in the beginning of 1980th years, it has been realized [12, 13], that it is possible to receive an additional kinematical (or resonance) enhancement on 3 orders of magnitude in p-wave resonances. Then it has been checked up (and confirmed) in Dubna for ^{139}La nucleus [14]; in 1990th years the similar P odd effects at the level of 10 % have been found for ^{232}Th nucleus in Los Alamos [15].

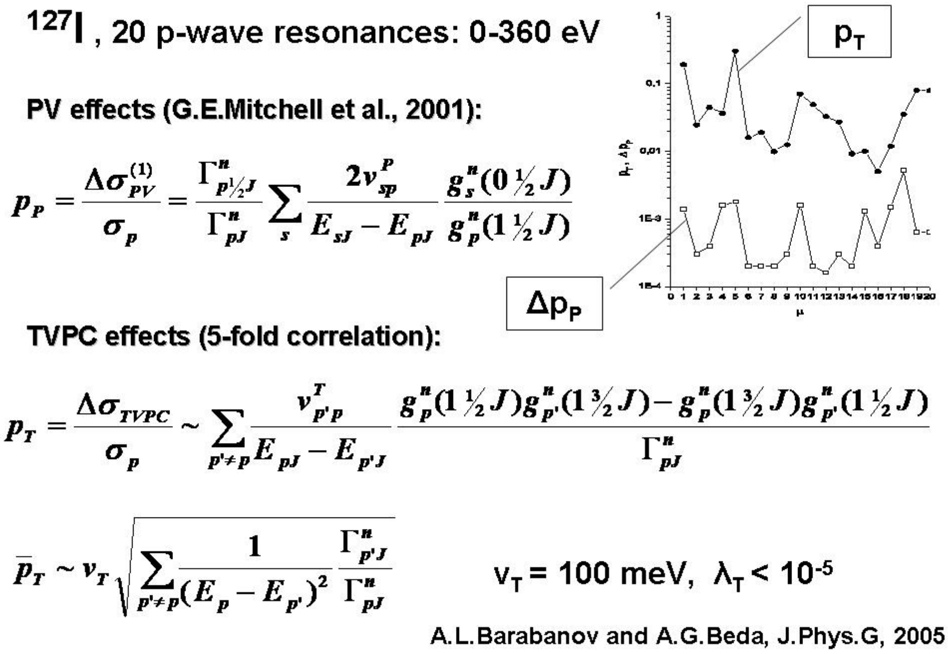


Figure 7

Later it has been shown [16, 17] that the same factors of enhancement - dynamical and kinematical (resonance) - should exist for T non-invariant effects in p-wave resonances. Thus, searching TV forces by means of measurement of 3-fold, (**s**[**kI**]), and 5-fold, (**s**[**kI**])(**kI**), correlations in the amplitude of elastic scattering on the zero angle is of great perspective. Notice that the 3-fold correlation is P odd, therefore it is sensitive to hypothetical TVPV forces. At the same time the 5-fold correlation is P even, thus its measurement is a way to search for TVPC interactions.

Recently we have pointed out [18] the new opportunities for searching TVPC forces in the interaction of polarized neutrons with aligned nuclei ^{127}I. In Figure 7 the expression is presented that defines the asymmetry p_T of the total cross section caused by 5-fold correlation. We have estimated this asymmetry in the assumption that the characteristic matrix element v_T of p-wave resonance mixing by hypothetical TVPC forces is equal to 100 meV that is approximately one order of magnitude lower than the current direct limit on this matrix element. In Figure 7 the results for p_T are presented for 20 p-wave resonances of ^{127}I nucleus found in Los Alamos at P odd effects study.

P odd effects p_P surpassing statistical errors Δp_P were found only in some of these p-wave resonances. However, due to similarity of proposed experiment (searching for TVPC effects) and performed experiment (investigation of PV effects), it is natural to expect that statistical errors of both measurements (proposed and performed) would be approximately identical in any p-wave resonance. Thus, comparison of the expected TVPC effects p_T and the measured statistical errors Δp_P is done in Figure 7. It is seen that the proposed experiment will allow to improve at least by one order of magnitude the existing limitation on TVPC forces (at the best it will allow to discover TVPC forces).

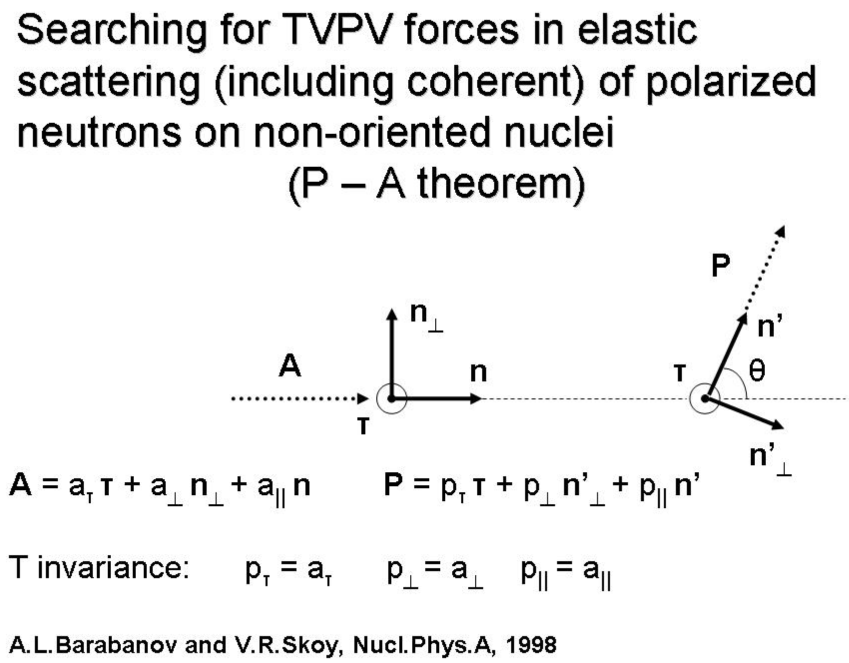


Figure 8

5. Spin-angular correlations in elastic scattering

One of the consequences of T invariance is the P-A theorem for elastic scattering that relates vectors of polarization **P** and asymmetry **A** (analyzing power). If T invariance holds, then the equalities exist between components of the specified vectors. These equalities are presented in Figure 8 (see, e.g., [19] and references therein). Thus, check of these relations is the test of T invariance.

One can show that the check of the equalities will testify the presence of TVPV forces if the components considered lay in a plane of reaction (in a plane of Figure). In this sense such test is similar to the search of 3-fold correlation in the total cross section. However, polarization of the target nuclei is needed for measurement of 3-fold correlation, while the check of the P-A theorem can be performed without nuclear polarization.

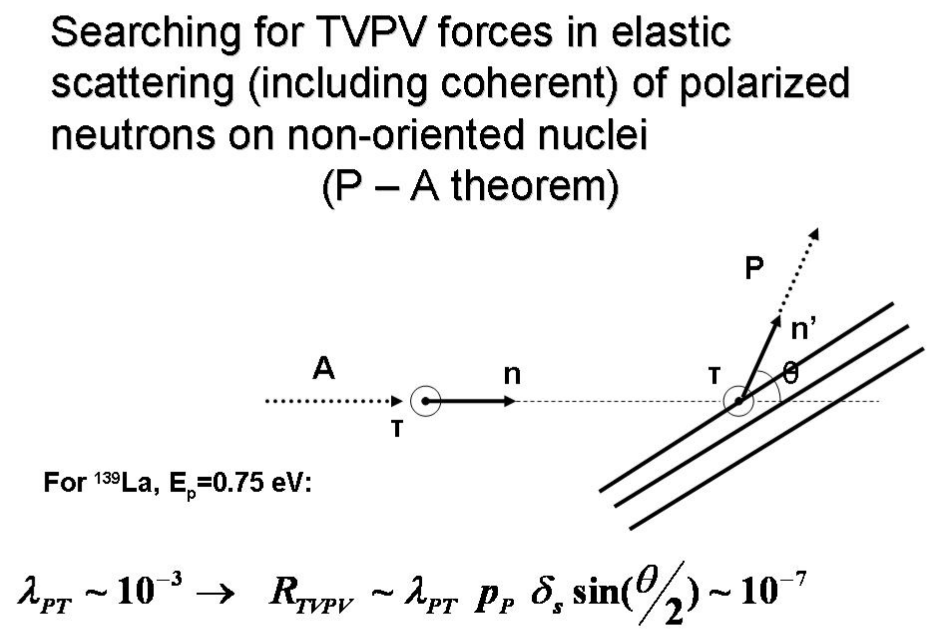


Figure 9

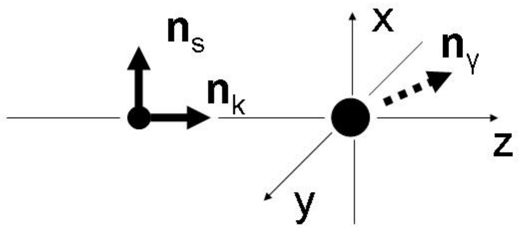
The principal disadvantage of the check of the P-A theorem is low intensity of elastic scattered neutrons. The situation may be improved by the use of coherent Bragg scattering. This variant of experiment was first proposed in [20] and is shown in Figure 9. The estimates have been obtained in [19] for relative violation R_{TVPV} of equalities (imposed by the P-A theorem) for given scale of TVPV forces.

6. Spin-angular correlations in radiative capture

Let us pass to radiative capture of slow neutrons. If we take into account only three vectors, $\mathbf{n}_s$, $\mathbf{n}_k$ and $\mathbf{n}_\gamma$ - along the neutron spin **s,** the neutron momentum **k** and the γ quantum momentum $\mathbf{p}_\gamma$, as well as only P even correlations, we obtain "fore-aft" (FA) and "left-right" (LR) asymmetries of emission of γ quantum (see, e.g., [21, 22] and references therein). They are caused by interference of two channels of the reaction, one of which is induced by neutron s-wave, while another - by neutron p-wave. The situation is presented in Figure 10. Curiously, however, there is a sensitivity to the forces breaking T invariance, more accurately, to TVPC forces.

Really, let us pass to Figure 11. For the sake of simplicity we consider the case when the reaction amplitudes in both channels can be presented in the Breit-Wigner form. Then, for example, "fore-aft" asymmetry, $A_1(E)$, goes to zero in the same point E_p where the p-wave cross section reaches the maximum. Herewith the reality of the amplitudes is assumed owing to the presence of T invariance.

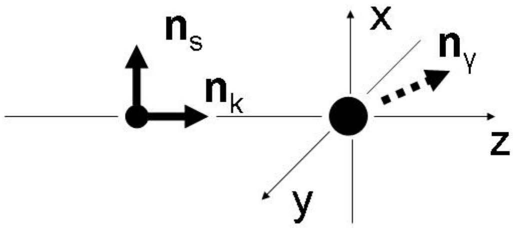
«Ordinary» (P and T invariant) spin-angular correlations in (n,γ) reaction in a p-wave resonance are sensitive to p1/2- and p3/2-contributions, negative s-wave resonances and TVPC forces



$$\frac{d\sigma_{n\gamma}(\vec{n}_\gamma, E)}{d\Omega} = A_0(E) + A_1(E)(\vec{n}_\gamma \vec{n}_k) + B_1(E)(\vec{n}_\gamma[\vec{n}_s, \vec{n}_k]) + \dots$$

Figure 10

If, however, T invariance is violated, the neutron and radiative amplitudes have phases. As a result the zero-point of the "fore-aft" asymmetry shifts a little from the position E_p of the p-wave resonance as it is presented in Figure 12.



$$f_s(E) = \frac{g_s^n(0\,\tfrac{1}{2})g_s^\gamma}{E - E_s + i\Gamma_s/2}$$

$$f_{pj}(E) = \frac{g_{pj}^n(1j)g_p^\gamma}{E - E_p + i\Gamma_p/2}$$

$$\frac{d\sigma_{n\gamma}(\vec{n}_\gamma, E)}{d\Omega} = A_0(E) + A_1(E)(\vec{n}_\gamma\vec{n}_k) + B_1(E)(\vec{n}_\gamma[\vec{n}_s,\vec{n}_k]) + \ldots$$

Near p-wave resonance:

$$A_1(E) \sim \mathrm{Re}\left(f_s^*(E)\left(f_{p\frac{1}{2}}(E) - \frac{1}{\sqrt{2}}f_{p\frac{3}{2}}(E)\right)\right) \sim \frac{E - E_p}{(E - E_p)^2 + \Gamma_p^2/4}$$

Figure 11

In Figure 13 the formula for the energy shift ΔE_p is presented together with the Dubna data [23, 24] on "fore-aft" and "left-right" asymmetries for the reaction n + ^{117}Sn near the p-wave resonance with the energy E_p=1.33 eV. It has been shown [25] that the similar data [26] for the reaction n + ^{113}Cd near the p-wave resonance with the energy E_p=7 eV lead to the same scale of limitation on TVPC forces as the other experiments performed in this time. Notice that no more strong restrictions have appeared until now.

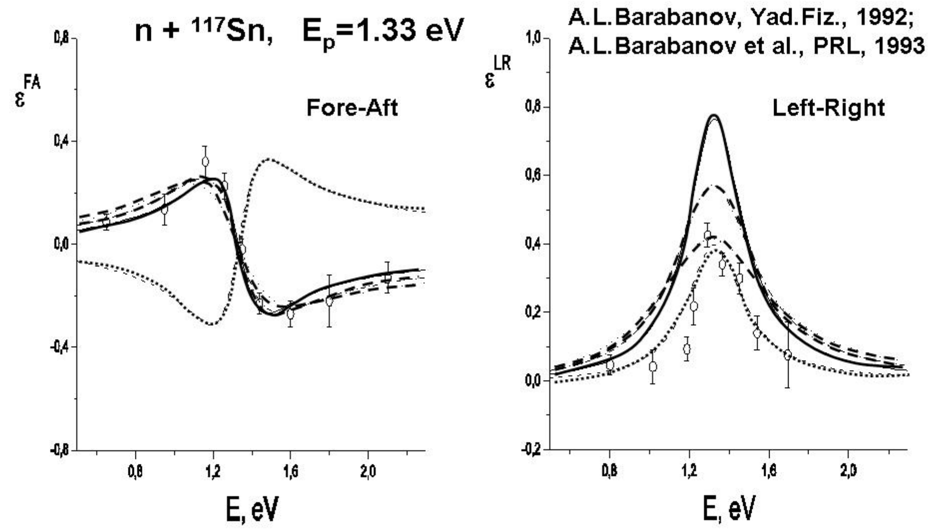
Near p-wave resonance:

$$A_1(E) \sim \mathrm{Re}\left(f_s^*(E)\left(f_{p\frac{1}{2}}(E) - \frac{1}{\sqrt{2}}f_{p\frac{3}{2}}(E)\right)\right) \sim \frac{E - E_p - \Delta E_p}{(E - E_p)^2 + \Gamma_p^2/4}$$

In the presence of TVPC forces: $\Delta E_p \neq 0$

Figure 12

In fact, the study of the "fore-aft" and "left-right" asymmetries in the radiative capture [23, 24, 26] had been made not for investigation of T invariance (limitation on TVPC forces was a by-product). The main purpose was measurement of $p_{1/2}$ and $p_{3/2}$ contributions into the p-wave resonances. The formula for the "fore-aft" asymmetry $A_1(E)$ presented in Figures 11 and 12 clearly shows that this asymmetry should be sensitive to the ratio between the specified contributions.



$$\Delta E_p = \frac{\Gamma_p}{2}\left(-\frac{\Gamma_s/2}{E_p - E_s} - \frac{v_p^T}{D_p}\left(\frac{g_p^{\gamma(2)}}{g_p^{\gamma(1)}} + \dots\right)\right) \qquad \frac{v_p^T}{D_p} < 10^{-1} \rightarrow \; v_p^T < 1 \;\; eV$$

Figure 13

The results, however, were strange for both nuclei: ^{117}Sn and ^{113}Cd. Let us take for definiteness the data for ^{117}Sn. If we choose parameters of the p-wave resonance from the fitting of the "fore-aft" asymmetry, then the description of the "left-right" asymmetry is unsatisfactory (solid curves in Figures 13 and 14). But, on the contrary, the parameters that are found from the fitting of the "left-right" asymmetry give very bad description of the "fore-aft" asymmetry (dotted curves in Figures 13 and 14). All these calculations were performed for the "standard" parameters of the s-wave resonances among which the negative resonance is dominating.

I have assumed [22], that the source of the problem is not the p-wave but the negative s-wave resonance. Its "standard" parameters, probably, are not true. I have shown that more accurate description of both measured asymmetries may be achieved by means of shifting the s-wave resonance with respective change of its neutron width (dashed curves in Figures 13 and 14). The experiments were proposed to check this hypothesis (they are not performed so far).

Thus, spin-angular correlations in the reaction (n,γ) may be used not only for checking fundamental symmetries but also for studying positions and other parameters of neutron resonances (including negative).

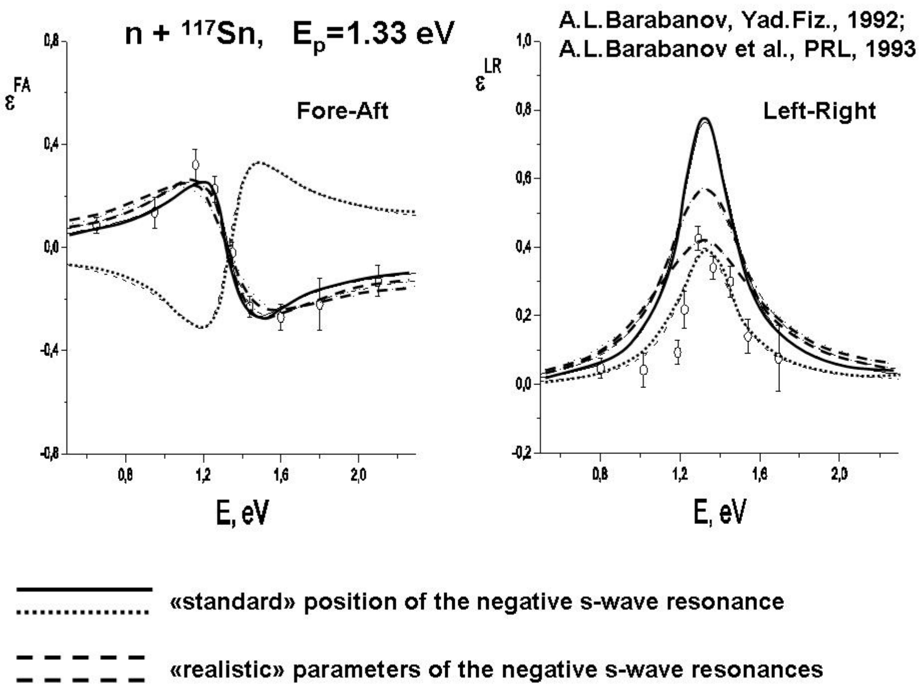


Figure 14

7. Spin-angular correlations in nuclear fission

Similar situation takes place for correlations in the reaction (n,f). There is, however, a serious difference between fission and radiative capture. As a rule, a certain exit channel is separated in the reaction (n,γ) - a quantum state of the nucleus that emits the γ quantum. At the same time summation over a huge number of exit channels is performed in fission - over differing quantum states of fragments (formed in highly excited states). Thus, there is a question: why spin-angular correlations that are, generally speaking, very sensitive to quantum numbers of final states, do not vanish in summation over the huge number of fission final states?

O. Bohr [27] has answered this question in 1950th years. He related the angular distribution of fragments (the simplest spin-angular correlation) with distribution of fission probability over the states with certain projection K of the nucleus spin J on the deformation axis at the barrier. This result is illustrated in Figure 15. Slightly later V.M. Strutinsky has shown [28], that after scission the number K transfers into the total helicity (the projection of the total spin F of both fragments on the fission axis). The identity of this quantum number for all fission final state provides the "survival" of spin-angular correlations in summation over the huge number of final states.

Consistent description of P even and P odd spin-angular correlations in (n, f) reaction with the use of the (|K|,Π) representation (K – helicity, Π – parity)

A.L.Barabanov and W.I.Furman, Z.Phys.A, 1997; Czech.J.Phys., 2003

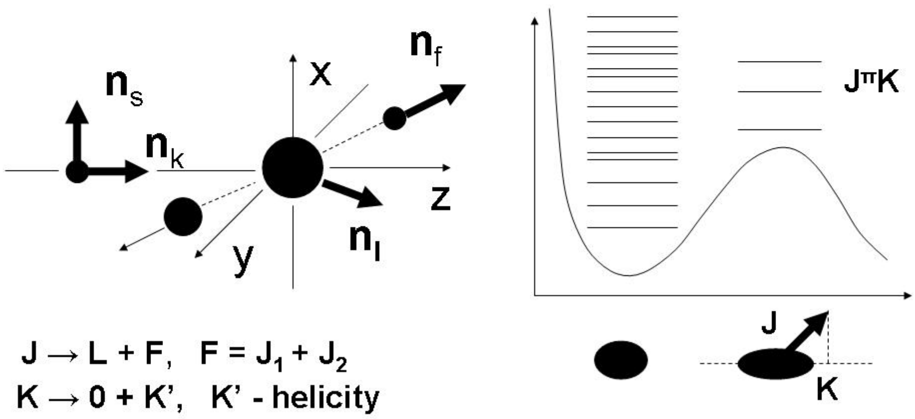


Figure 15

Differential cross section of nuclear fission induced by slow polarized neutrons

$$\frac{d\sigma_f}{d\Omega} = \frac{1}{4\pi}\Big(\sigma_f^0 + p\sigma_f^{(0)PV}(\vec{\mathbf{n}}_s\vec{\mathbf{n}}_k) + p\sigma_f^{(1)PV}(\vec{\mathbf{n}}_f\vec{\mathbf{n}}_s) + $$
$$+ p\sigma_f^{(2)PV}\Big((\vec{\mathbf{n}}_s\vec{\mathbf{n}}_k) - 3(\vec{\mathbf{n}}_f\vec{\mathbf{n}}_s)(\vec{\mathbf{n}}_f\vec{\mathbf{n}}_k)\Big) + \sigma_f^{FA}(\vec{\mathbf{n}}_f\vec{\mathbf{n}}_k) +$$
$$+ p\sigma_f^{LR}(\vec{\mathbf{n}}_f[\vec{\mathbf{n}}_k\vec{\mathbf{n}}_s])\Big)$$

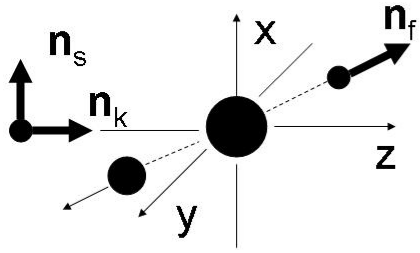


Figure 16

Explicit expression for the differential cross section of fission of non-oriented target nuclei by polarized neutrons is presented in Figure 16. It is obtained in the assumption that only neutron s-waves and interference of s- and p-waves are of importance. We see the terms related to P odd (PV) correlations as well the "fore-aft" (FA) and "left-right" (LR) correlations. Exactly as in the reaction (n,γ), these correlations are caused by the interference of amplitudes describing the states with opposite parities. But the operator of helicity does not commutate with the operator of spatial inversion. Thus, the usual representation of helicity does not allow to describe the fission final states with certain parity.

«Fore-Aft» and «Left-Right» correlations in nuclear fission at «one-level» approximation

$$\frac{d\sigma_f}{d\Omega} = \frac{1}{4\pi}\left(\sigma_f^0 + \frac{\pi}{k^2}\sum_{j,K\geq 0} q(jKJ_sJ_p)\,\mathrm{Im}\Big(S_{Js}(0\tfrac{1}{2}\to K\Pi_s)S^*_{Jp}(1j\to K\Pi_p)\times \times\big((\vec{\mathbf{n}}_f\vec{\mathbf{n}}_k) - i\beta_j p(\vec{\mathbf{n}}_f[\vec{\mathbf{n}}_k\vec{\mathbf{n}}_s])\big)\Big)\right)$$

$$\sigma_f^0 = \frac{\pi}{k^2} g_{Js}\frac{\Gamma_s^n\Gamma_s^f}{(E-E_s)^2+\Gamma_s^2/4}+\dots$$

$$S_{Js}(0\tfrac{1}{2}\to K\Pi_s) = -ie^{i\delta_s^C}\,\frac{g_s^n(0\frac{1}{2})g_s^f(K\Pi_s)}{E-E_s+i\Gamma_s/2}$$

$$S_{Jp}(1j\to K\Pi_p) = -ie^{i\delta_p^C}\,\frac{g_p^n(1j)g_p^f(K\Pi_p)}{E-E_p+i\Gamma_p/2}$$

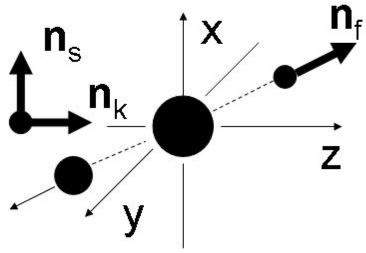


Figure 17

To solve this problem we have introduced [29, 30] a new representation in which final states of two fragments are determined by the modulus of helicity, |K|, and by the parity, Π. In the framework of this formalism we have obtained explicit expressions for all terms in the differential fission cross section. Resonance overlapping was accurately taken into account. It is of great importance for heavy nuclei, because distances between neutron resonances for such nuclei are rather small.

It is interesting to consider the simplified case when it is possible to use the one-resonance approach both in s- and p-wave neutron channels. Results for P even spin-angular correlations are presented in Figure 17. Earlier similar results in the specified assumption have been obtained by O.P. Sushkov and V.V. Flambaum [31] in the framework of O. Bohr's hypothesis (without helicity representation). Notice that in our formulas the fission amplitudes have no phases. Thus, our approach implies essentially smaller number of free parameters.

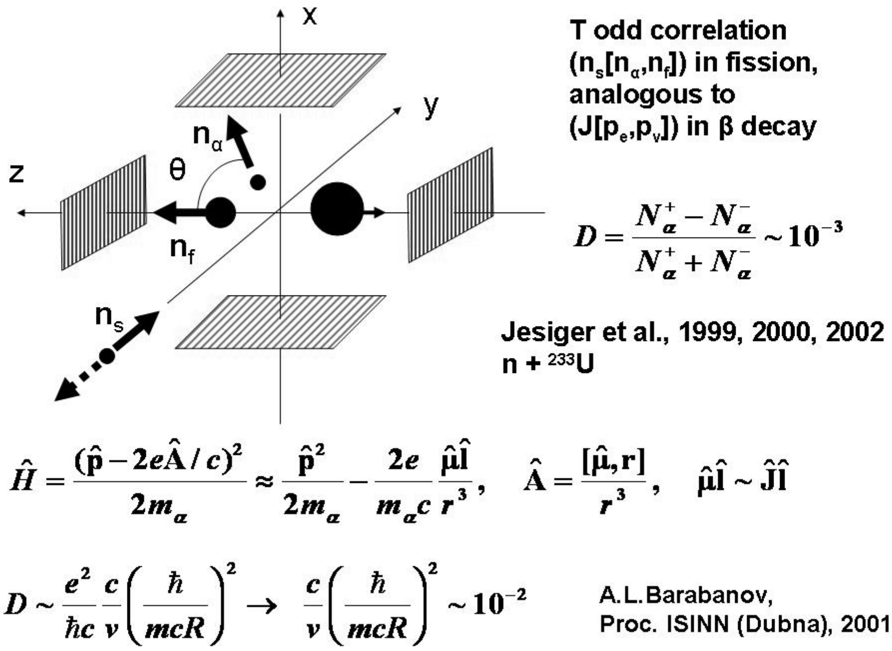


Figure 18

8. T odd correlation in ternary fission

At last, let us discuss the T odd correlation in ternary fission. Three unit vectors are of importance here, $\mathbf{n}_s$, $\mathbf{n}_f$ and $\mathbf{n}_\alpha$ - along spin of the incident neutron, momentum of the light fragment and momentum of the third particle (e.g., the α particle). The scheme of experiment is presented in Figure 18. The asymmetry of α particle emission upwards and downwards of the scale 10^{-3} has been found in fission of ^{233}U nuclei by thermal polarized neutrons [32,33].

Similar correlation, $(\mathbf{J}[\mathbf{p}_e,\mathbf{p}_\nu])$, is subject of searches in β decay of free neutrons and nuclei where its detection will give the evidence for T invariance violation. It is known, however, that electromagnetic interaction in the final state may induce a false effect, fortunately, very insignificant. Up to now searches of the specified 3-fold correlation in β decay gave neither true, nor false effect.

However, in the final state of the fission reaction besides the electromagnetic interaction, there is the strong interaction between particles. A model of the interaction that leads to the required asymmetry has been proposed [34]. The main point of this model is the interaction between the spin of fissioning nucleus and the orbital momentum of α particle, i.e. specific spin-orbital interaction. The corresponding nuclear forces surpass electromagnetic forces at least by two orders of magnitude. Thus, they are strong enough to provide the observable effect.

The formula describing the asymmetry of α particle emission upwards ($\varphi=0^0$) and downwards ($\varphi=180^0$) depending on the angle θ between the momenta $\mathbf{p}_\alpha$ and $\mathbf{p}_f$ has been derived [34]. Its general form is presented in Figure 19. Arguments in favor of smooth dependence of the factor B(θ) on the angle θ have been proposed.

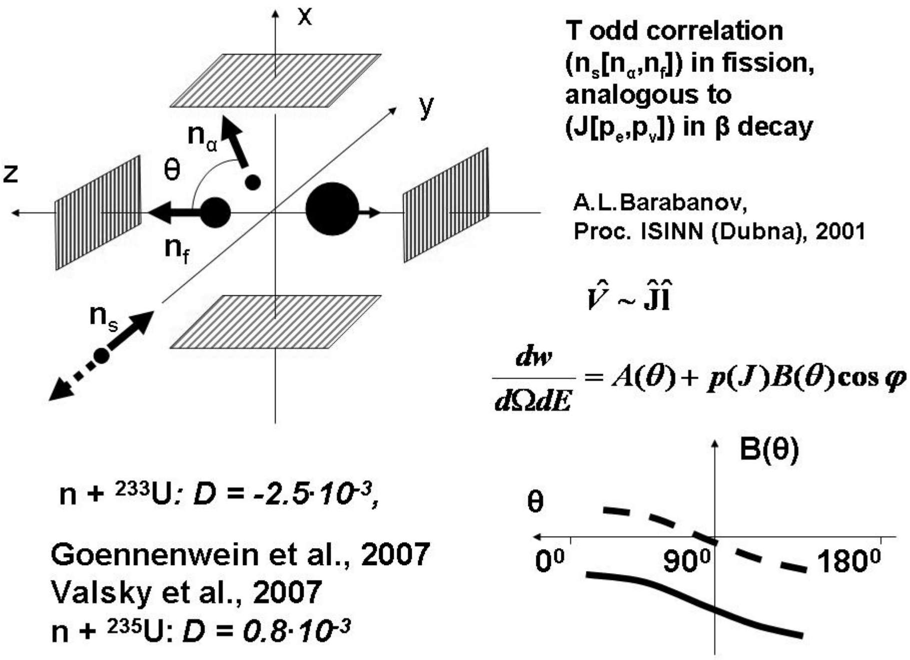


Figure 19

Notice that for ^{233}U target nuclei [32, 33] no significant dependence of the factor B(θ) (of "the correlation coefficient D" - in terms of the authors of [32, 33]) on the angle θ was found. Furthermore, this fact was interpreted as an argument against the spin-orbital interaction in the final state: "… in case of the spin-orbit interaction is at work, the correlation coefficient D should have opposite signs for the angles smaller or larger than the average angle 83^0… However,... experiment clearly tells that the correlation coefficient D is independent from the emission angle of the TP [third particle]. The spin-orbit interaction thus appears to be ruled out …" [33]. But in fact, the results of the measurements [32, 33] may correspond to the behavior B(θ) that is presented in Figure 19 by the solid curve.

However, in recent searches of the T odd correlation for ^{235}U target nuclei [35, 36], it was discovered that the correlation coefficient D really has opposite signs for the angles smaller or larger than the average angle 83^0! In the model of spin-orbital interaction it may be explained by the behavior B(θ) that is presented in Figure 19 by the dashed curve. Obviously, herewith the total asymmetry (the coefficient D) should be small, and it is really the case for ^{235}U target nuclei.

9. Conclusion

Possible subjects of future studies of spin-angular correlations in neutron-nucleus interaction are presented in Figure 20. Searching for 3-fold and 5-fold correlation in the total cross section would give new information about the magnitude of TVPV and TVPC forces breaking T invariance. Searches of P odd and P even correlation are also of great perspective because new data on neutron resonances, fission and radiative channels as well as on PV nuclear forces may be obtained.

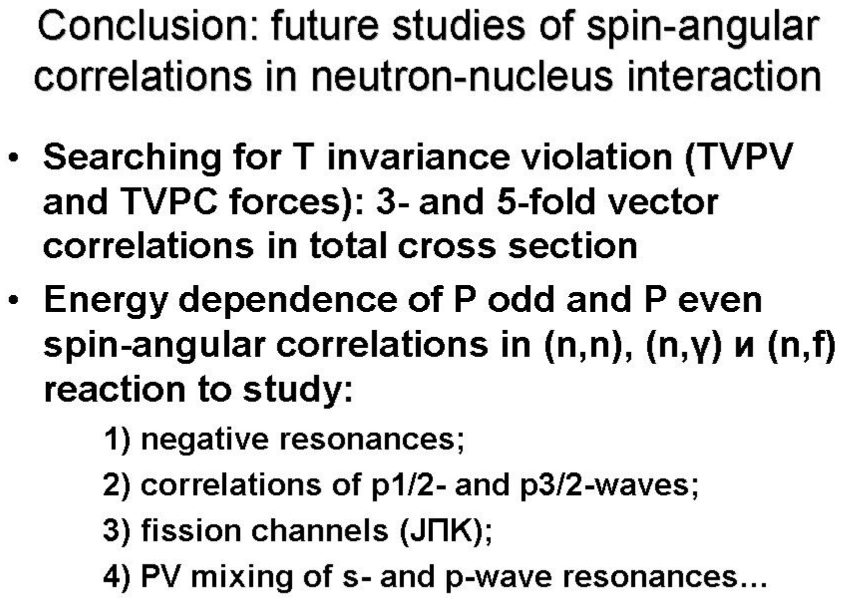


Figure 20

This work was supported in part by the grant NS-3004.2008.2.

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