T-INVARIANCE AND NUCLEAR FISSION

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Abstract
It has been demonstrated that the using of the T-invariance condition for manyparticles multistep nuclear reaction $a \to b$, in which among $n_a (n_a \geq 2)$ and $n_b (n_b \geq 2)$ particles of initial a and final b channels there are the different elementary particles and atomic nuclei, allows to distinguish the possible mechanisms of the investigated reaction and to throw the mechanisms violating the T-invariance of the analyzed quantum system. The mechanisms of the appearance of anisotropies with different P- and T-parities in differential cross sections of nuclear reactions of the binary and ternary fission of oriented nuclei-targets by the cold polarized neutrons have been analyzed.

Key words: T-invariance, mechanisms of binary and ternary fission.

T-invariance in the quantum system

The T-invariance of the quantum system with the time independent Hamiltonian $\mathbf{H}(\xi)$, where ξ is the total set of spatial, spin and other coordinates of this system, consists [1-3] in that for any possible state of the investigated system with the wave function $\Psi(\xi,t)$ being the solution of Schrödinger equation:

$$ih\frac{\partial}{\partial t}\Psi(\xi,t) = \mathbf{H}\Psi(\xi,t), \tag{1}$$

there are time-reversed state with the wave function $\bar{\Psi}(\xi,t)$ being the solution of the same Schrödinger equation (1). The wave function $\bar{\Psi}(\xi,t)$ is connected [1-3] with the original wave function $\Psi(\xi,t)$ as

$$\bar{\Psi}(\xi,t) = \boldsymbol{\tau}\Psi(\xi,-t), \tag{2}$$

where $\boldsymbol{\tau}$ is the time reversion operator:

$$\boldsymbol{\tau} = \mathbf{OK}, \tag{3}$$

with the operator of the complex conjugation **K** and the unitary operator **O** which satisfies the condition:

$$\mathbf{OH}^*\mathbf{O}^+ = \mathbf{H}. \tag{4}$$

For the wave function $\Psi(\xi)$ of the stationary state satisfactory the stationary Schrödinger equation:

$$\mathbf{H}\Psi(\xi) = E\Psi(\xi), \tag{5}$$

it can be constructed the time-reversed wave function $\bar{\Psi}(\xi)$ being solution of the same Schrödinger equation (5) and connected with $\Psi(\xi)$ by condition:

$$\bar{\Psi}(\xi) = \boldsymbol{\tau}\Psi(\xi). \qquad (6)$$

Using the formulae (6,3) the matrix element $\langle \Psi_2(\xi) | \mathbf{Q} | \Psi_1(\xi) \rangle$ of the arbitrary operator **Q** can be represented as

$$\langle \Psi_2(\xi) | \mathbf{Q} | \Psi_1(\xi) \rangle = \langle \bar{\Psi}_1(\xi) | \bar{\mathbf{Q}} | \bar{\Psi}_2(\xi) \rangle, \qquad (7)$$

where operator $\bar{\mathbf{Q}}$ is the time-reversed operator $\mathbf{Q}$:

$$\bar{\mathbf{Q}} = \boldsymbol{\tau}\mathbf{Q}^{+}\boldsymbol{\tau}^{-1}. \qquad (8)$$

In this case the time-reversed Hermitian operators of coordinate $\mathbf{r}$, moment $\mathbf{p}$, orbital moment $\mathbf{L}$ and spin $\mathbf{s}$ of the particle are expressed as

$$\bar{\mathbf{r}} = \mathbf{r}\,;\ \bar{\mathbf{p}} = -\,\mathbf{p}\,;\ \bar{\mathbf{L}} = -\,\mathbf{L}\,;\ \bar{\mathbf{s}} = -\,\mathbf{s}\,. \qquad (9)$$

The conditions of the T-invariance for amplitudes of manyparticle multistep nuclear reactions

Let us present the Hamiltonian **H** of the quantum system participating in the manyparticle multistep nuclear reaction $a \to b$ as

$$\mathbf{H} = \mathbf{H}_a + \mathbf{V}_a = \mathbf{H}_b + \mathbf{V}_b, \qquad (10)$$

where $\mathbf{H}_a$, $\mathbf{H}_b$ and $\mathbf{V}_a$, $\mathbf{V}_b$ are nonperturbated parts of $\mathbf{H}$ and interaction potentials of particles in initial *a* and final *b* channels of the investigated reaction. Then the nonperturbated wave functions of initial *a* and final *b* channels are the solutions of Schrödinger equations:

$$(\mathbf{H}_a - E_a)\Phi_a = 0; \quad (\mathbf{H}_b - E_b)\Phi_b = 0, \qquad (11)$$

where energies E_a and E_b lie on the mass surface of investigated reaction: $E_a = E_b = E$, at that E is the reaction total energy incoming in equation (5).

The amplitude of reaction $a \to b$ can be expressed [2-3] by the matrix element $\mathcal{T}_{b,a}$:

$$\mathcal{T}_{b,a} = \langle \Phi_b | \mathcal{T} | \Phi_a \rangle, \qquad (12)$$

where the reaction operator T has the form:

$$\mathcal{T} = \mathbf{V}_a + \mathbf{V}_b \left(E - \mathbf{H} + i\eta\right)^{-1} \mathbf{V}_a, \qquad (13)$$

which demonstrates the visible dependence of this operator in matrix element (12) from the structures of the interactions in initial *a* and final *b* channels.

Analogously the amplitudes of the reverse reaction $b \to a$ can be expressed [4, 5] by the matrix element $\tilde{\mathrm{T}}_{a,b}$ of the reverse reaction operator $\tilde{\mathcal{T}}$ by the formula:

$$\tilde{\mathcal{T}}_{a,b} = \langle \Phi_a | \tilde{\mathcal{T}} | \Phi_b \rangle, \qquad (14)$$

where the operator $\tilde{\mathcal{T}}$ is determinated as

$$\tilde{\mathcal{T}} = \mathbf{V}_b + \mathbf{V}_a \left(E - \mathbf{H} + i\eta\right)^{-1} \mathbf{V}_b \qquad (15)$$

and is different from the operator T (12) by not only the transposition of potentials $\mathbf{V}_a$ and $\mathbf{V}_b$ of initial and final channels but and the transposition of potentials of intermediate stages of the reverse reaction in the comparison with analogical stages of the original reaction.

Using the formulae (6, 2-4) it can be got the T-invariance condition of the matrix element $\mathrm{T}_{b,a}$ (12) for the manyparticle multistep nuclear reaction $a \to b$, connected with the coincidence of the matrix element $\mathcal{T}_{b,a}$ of original reaction with the matrix element $\tilde{\mathcal{T}}_{\bar{a},\bar{b}}$ of time-reversed reaction $\bar{b} \to \bar{a}$, in the form:

$$\tilde{\mathcal{T}}_{b,a} = \langle \Phi_b | \mathcal{T} | \Phi_a \rangle = \langle \Phi_{\bar{a}} | \tilde{\mathcal{T}} | \Phi_{\bar{b}} \rangle = \tilde{\mathcal{T}}_{\bar{a},\bar{b}}, \qquad (16)$$

where $\Phi_{\bar{a}}$, $\Phi_{\bar{b}}$ are time-reversed wave functions Φ_a, Φ_b and reaction operators $\mathcal{T}$ (13) и $\tilde{\mathcal{T}}$ (15) correspond to the original and the reverse reactions.

Therefore the energies E_a and E_b of initial and finale channels of the original reaction lie on the mass surface of this reaction in the formula (16) the reverse reaction operator $\tilde{\mathcal{T}}$ (15) can be changed [2] by the original reaction operator $\mathcal{T}$ (13) and the T-invariance condition can be represented to the formula:

$$\mathcal{T}_{b,a} = \mathcal{T}_{\bar{a},\bar{b}}, \qquad (17)$$

which demands the coincidence of the amplitude of original reaction $\mathcal{T}_{b,a}$ (12) with the amplitude of time-reversed reaction $\mathcal{T}_{\bar{a},\bar{b}}$ and is connected with the realization of two procedures: firstly, the exchange of the initial and final channels of the original reaction and, secondly, change of wave functions of the initial Φ_a and final Φ_b channels to time-reversed wave functions $\Phi_{\bar{a}}$ and $\Phi_{\bar{b}}$. In the first procedure in the matrix element $\mathcal{T}_{\bar{a},\bar{b}}$ the reaction operator T (13) must be changed to the operator $\tilde{\mathcal{T}}$ (15), which is significantly different from original reaction operator T and the properties of which discussed above for the reverse reaction.

In the common case the matrix element $\mathrm{T}_{b,a}$ (12) can be represented [5] by the sum of matrix elements:

$$\mathcal{T}_{b,a} = \sum_e (\mathcal{T}_e)_{b,a} + \sum_o (\mathcal{T}_o)_{b,a}, \qquad (18)$$

which corresponds one of two groups of T-even $(\mathcal{T}_e)_{b,a}$ and T-odd $(\mathcal{T}_o)_{b,a}$ matrix elements defined as:

$$(\mathcal{T}_e)_{b,a} = (\mathcal{T}_e)_{\bar{b},\bar{a}} \;;\; (\mathcal{T}_o)_{b,a} = -(\mathcal{T}_o)_{\bar{b},\bar{a}}. \qquad (19)$$

Using the T-invariance conditions (16) the following relations can be obtained for matrix elements of the original $a \to b$ and reverse $b \to a$ reactions:

$$(\mathcal{T}_e)_{b,a} = (\tilde{\mathcal{T}}_e)_{a,b}, (\mathcal{T}_o)_{b,a} = -(\tilde{\mathcal{T}}_o)_{a,b}. \qquad (20)$$

The differential cross section of the original reaction $\frac{d\sigma_{b,a}}{d\Omega_b}$ has the form:

$$\frac{d\sigma_{b,a}}{d\Omega_b} \sim \mathcal{T}_{b,a}\mathcal{T}^*_{b,a}. \qquad (21)$$

Then the T-even $\frac{(d\sigma_e)_{b,a}}{d\Omega_b}$ and T-odd $\frac{(d\sigma_o)_{b,a}}{d\Omega_b}$ asymmetries in the differential cross section (19), defined as

$$\frac{(d\sigma_e)_{b,a}}{d\Omega_b} = \frac{(d\sigma_e)_{\bar{b},\bar{a}}}{d\Omega_b}, \quad \frac{(d\sigma_o)_{b,a}}{d\Omega_b} = -\frac{(d\sigma_o)_{\bar{b},\bar{a}}}{d\Omega_b} \qquad (22)$$

and with the usage of formula (21) can be brought to forms:

$$\frac{(d\sigma_e)_{b,a}}{d\Omega_b} \sim \left[\sum_{ee'} (\mathcal{T}_e)_{b,a} (\mathcal{T}_{e'})^*_{b,a} + \sum_{oo'} (\mathcal{T}_o)_{b,a} (\mathcal{T}_{o'})^*_{b,a} \right],$$
$$\frac{(d\sigma_o)_{b,a}}{d\Omega_b} \sim \sum_{eo} \left[(\mathcal{T}_e)_{b,a} (\mathcal{T}_o)^*_{b,a} + (\mathcal{T}_e)^*_{b,a} (\mathcal{T}_o)_{b,a} \right]. \quad (23)$$

The differential cross section $\frac{d\sigma_{b,a}}{d\Omega_b}$ of the investigated reaction $a \to b$ contains the different asymmetries $\frac{\left(d\sigma_{e(o)}\right)_{b,a}}{d\Omega_b}$ with coefficients $(D_e)_{b,a}$ and $(D_o)_{b,a}$ defined [6, 7] as

$$\left(D_{e(o)}\right)_{b,a} = \left[\left(\frac{(d\sigma_{e,o})_{b,a}}{d\Omega_b} \right)^+ - \left(\frac{(d\sigma_{e,o})_{b,a}}{d\Omega_b} \right)^- \right] \Big/ \left[\left(\frac{(d\sigma_{e,o})_{b,a}}{d\Omega_b} \right)^+ + \left(\frac{(d\sigma_{e,o})_{b,a}}{d\Omega_b} \right)^- \right], \quad (24)$$

where the signs +/− correspond signs of orientations of certain vector-spin parameters connected with investigated asymmetries.

Using of results of articles [2,5,8], in which the T-invariance conditions have been analyzed for manyparticle multistep nuclear reaction $a \to b$, it can been shown that the coefficients $D_{b,a}$ and $\tilde{D}_{\bar{a},\bar{b}}$ for similar asymmetries in differential cross sections of original $a \to b$ and time-reversed $\bar{b} \to \bar{a}$ nuclear reactions, the appearances of which are caused by the uniform mechanism, can be represented by the unified scalar (pseudo scalar) function D, depending from wave vectors and spins of particles of initial and final channels of investigated reactions, which changes it's sign correspondingly by the formula (9) for the transition from the original to the time-reversed nuclear reactions:

$$D_{b,a} = D(\mathbf{k}_b, \mathbf{s}_b; \mathbf{k}_a, \mathbf{s}_a); \; \tilde{D}_{\bar{a},\bar{b}} = D(-\mathbf{k}_a, -\mathbf{s}_a; -\mathbf{k}_b, -\mathbf{s}_b). \quad (25)$$

Then the T-invariance condition (25) brings to condition for the coefficient D:

$$D(\mathbf{k}_b, \mathbf{s}_b; \mathbf{k}_a, \mathbf{s}_a) = D(-\mathbf{k}_a, -\mathbf{s}_a; -\mathbf{k}_b, -\mathbf{s}_b). \quad (26)$$

With the usage of the definitions of T-even $(D_e)_{b,a}$ and T-odd $(D_o)_{b,a}$ coefficients:

$$(D_e)_{b,a} = (D_e)_{\bar{b},\bar{a}}; \;\; (D_o)_{b,a} = -(D_o)_{\bar{b},\bar{a}}, \quad (27)$$

the T-invariance conditions for these coefficients can be presented by the forms:

$$D_e(\mathbf{k}_b, \mathbf{s}_b; \mathbf{k}_a, \mathbf{s}_a) = D_e(\mathbf{k}_a, \mathbf{s}_a; \mathbf{k}_b, \mathbf{s}_b),$$
$$D_o(\mathbf{k}_b, \mathbf{s}_b; \mathbf{k}_a, \mathbf{s}_a) = -D_o(\mathbf{k}_a, \mathbf{s}_a; \mathbf{k}_b, \mathbf{s}_b) \quad (28)$$

The dependence of the functions D_e and D_o from wave vectors and spins of particles can be found (experimentally or theoretically) for the original reaction $a \to b$ and can be used on the basis of T-invariance conditions (28) for testing of mechanisms of the appearance of anisotropies with different P- and T-parities in differential cross sections of different nuclear reactions for the T-invariant nuclear systems.

The mechanisms of formation of different asymmetries in differential cross sections of binary and ternary fission of oriented target-nuclei by cold polarized neutrons

In the experimental differential cross sections of the reactions of the binary and ternary fission of non-oriented target-nuclei by cold polarized neutrons the asymmetries with the coefficients $D(\mathbf{k}_b,\mathbf{s}_b;\mathbf{k}_a,\mathbf{s}_a)$ (25) of types $(\mathbf{s}_n,\mathbf{k}_{LF})$ [9], $(\mathbf{s}_n,[\mathbf{k}_n,\mathbf{k}_{LF}])$ [10-12], $(\mathbf{s}_n,\mathbf{k}_3)$ [13], $(\mathbf{s}_n,[\mathbf{k}_3,\mathbf{k}_{LF}])$ [14-17], where $\mathbf{s}_n$ is the vector of the neutron spin, $\mathbf{k}_n$, $\mathbf{k}_{LF}$ $\mathbf{k}_3$ are wave vectors of going neutron, light fission fragments and third particles appear. For these asymmetries in papers [18-25] the different mechanisms of their appearances were proposed. P-even T-even asymmetry $(\mathbf{k}_3,\mathbf{k}_{LF})$ is connected with the mechanisms, based on the interference of fission amplitudes different s-neutron resonances with the same and different spins. P-odd T-even asymmetries $(\mathbf{s}_n,\mathbf{k}_{LF})$, $(\mathbf{s}_n,\mathbf{k}_3)$ and P-even T-odd asymmetry $(\mathbf{s}_n,[\mathbf{k}_n,\mathbf{k}_{LF}])$ appear by taking into account the mechanisms connected with the interference of fission amplitudes of s- and p-neutron resonances of fissile compound nuclei. Used mechanisms of the appearance of all named above experimental asymmetries and too analyzed theoretically asymmetries $(\mathbf{I},\mathbf{k}_{LF})$, $(\mathbf{I},[\mathbf{k}_n,\mathbf{k}_{LF}])$, $(\mathbf{I},\mathbf{k}_3)$, $(\mathbf{I},[\mathbf{k}_n,\mathbf{k}_3])$ in the differential cross sections of the binary and ternary fission of the oriented target-nucleus satisfy the T-invariance conditions (28).

In the same time the asymmetry $(\mathbf{s}_n,[\mathbf{k}_3,\mathbf{k}_{LF}])$ and the theoretically investigated asymmetry $(\mathbf{I},[\mathbf{k}_3,\mathbf{k}_{LF}])$ caused by the influence of the Coriolis interaction on the angular distributions of the third particle don't satisfy the T-invariance condition (28) for the mechanism of the ternary fission connected with simultaneous flights from the fissile compound nuclei of the third particle and fission fragments. Only for the ternary fission mechanism connected with the sequential flights from the fissile compound nucleus the third particle and fission fragments, which is connected with the non-evaporation mechanism [18, 26, 25] of the third particle flight caused by the non-adiabatical motion of the fissile compound nucleus near it's scission point, the named above asymmetries satisfy of the T-invariance condition (28).

From the theoretical point of view there are P-odd T-odd $([\mathbf{I},\mathbf{s}_n],\mathbf{p}_{LF})$, $([\mathbf{I},\mathbf{s}_n],\mathbf{p}_3)$ and P-even T-even $([\mathbf{I},\mathbf{s}_n],[\mathbf{p}_n,\mathbf{p}_{LF}])$, $([\mathbf{I},\mathbf{s}_n],[\mathbf{p}_n,\mathbf{p}_3])$, $([\mathbf{I},\mathbf{s}_n],[\mathbf{p}_3,\mathbf{p}_{LF}])$ asymmetries in reactions of the binary and ternary fission of polarized target-nuclei by cold polarized neutrons, which become zero when the T-invariance condition (28) is realized even for taking into account the named above representation about the sequential multistep character of the binary and ternary fission of nuclei. It's connected with the absence of the change of the sign of the vector product $[\mathbf{I},\mathbf{s}_n]$ at the transition from the original reaction to the time-reversed reaction because of the simultaneity of the appearance of polarizations of the incident neutron and target-nuclei in the differential cross section of the investigated reactions.

The fact of the equality to zero (for the T-invariant quantum systems) coefficients of the P-odd T-odd $([\mathbf{I},\mathbf{s}_n],\mathbf{p}_n)$ and P-even T-odd $([\mathbf{I},\mathbf{s}_n],\mathbf{p}_n)(\mathbf{I},\mathbf{p}_n)$ asymmetries, appearing in the amplitude of the elastic scattering of polarized neutrons on the polarized target-nuclei at the angle 0, was proposed [28-31, 27] to use for the analysis of T-non-invariant interactions in nuclear systems.

The related with the P-odd T-odd asymmetry $([\mathbf{I},\mathbf{s}_n],\mathbf{p}_n)$ discussed in papers [28-31, 27] the P-odd T-odd asymmetry $([\mathbf{I},\mathbf{s}_n],\mathbf{p}_{LF})$ having the non-zero coefficient only for the violation of the T-invariance also can be used for researches of T-non-invariant interactions in nuclear systems. In the same time P-even, T-even asymmetries $([\mathbf{I},\mathbf{s}_n],[\mathbf{p}_n,\mathbf{p}_{LF}])$, $([\mathbf{I},\mathbf{s}_n],[\mathbf{p}_n,\mathbf{p}_3])$, $([\mathbf{I},\mathbf{s}_n],[\mathbf{p}_3,\mathbf{p}_{LF}])$ in the reactions of the binary and ternary fission of the polarized target-nuclei by cold polarized neutrons because of their P-parity are especially interesting for researches of the T-invariance violation in nuclear systems. Especially beneficial for such researches is the asymmetry $([\mathbf{I},\mathbf{s}_n],[\mathbf{p}_3,\mathbf{p}_{LF}])$, the appearance of which is connected with the interference of the s-neutron resonances of the fissile compound nucleus.

Conclusion

In the present paper it has been demonstrated that the condition of T-invariance for the manyparticle multistep nuclear reactions $a \to b$ requires the coincidence of the amplitude $\mathcal{T}_{b,a}$ of the original reaction with the amplitude $\tilde{\mathcal{T}}_{\bar{a},\bar{b}}$ of the time-reversed reaction $\bar{b} \to \bar{a}$, where $\tilde{\mathcal{T}}$ – the operator of the reverse reaction, which differs from the operator of the original reaction $\mathcal{T}$ by changing of the order of appearance of the particles and their interaction potentials for the initial, intermediate and final stages of the investigated reactions. It has been found that the coefficients *D* of the asymmetries with various P- and T-parities, appearing in the differential cross sections of the original and time-reversed nuclear reactions for general T-invariant mechanisms of their appearance can be represented through a unified scalar (pseudo-scalar) function, which depends on the wave vectors and the spins of the particles included in the initial and final reaction channels. It has been shown that the use of T-invariance condition (28) for the coefficients *D* of various asymmetries in the differential cross section of the investigated reactions allow to exclude from consideration of the mechanisms analyzed reactions, which don't satisfy to the condition (28). It has been leaded to the exception of the mechanism of the simultaneous flight of the third particle and two fission fragments from the fissile compound nucleus.

At the same time it has been found that in the reactions of the binary and ternary fission oriented target-nuclei by cold polarized neutrons the coefficient of all ternary and quaternary asymmetries, including vector product $[\mathbf{I},\mathbf{s}_n]$, are non-zero only for T-invariance violation and because the research of these asymmetries can be used for the analyze of the nature of the T-non-invariant interactions in nuclear systems.

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