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НЕЙТРОННАЯ ФИЗИКА

T-ODD CORRELATIONS IN $(n, \alpha\,\gamma)$ REACTIONS

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The T-odd correlation $(\mathbf{k}_\alpha \cdot [\boldsymbol{\sigma} \times \mathbf{k}_\gamma])(\mathbf{k}_\alpha \cdot \mathbf{k}_\gamma)$, where $\boldsymbol{\sigma}$ is the vector of the neutron polarization and the symbols $\mathbf{k}$ denote the respective linear momenta (all vectors are unit ones), in the sequential alpha-gamma cascade induced by a thermal-neutron capture is studied. The study is performed in the one-resonance approximation. Both the final-state interaction of the alpha particle with the residual nucleus and the actual T-noninvariant phase shift are considered as possible origins of the correlation. The problem of suitable target isotopes is analyzed. Related correlations in other neutron- and proton-induced reactions are discussed.

Исследована T-нечетная корреляция $(\mathbf{k}_\alpha \cdot [\boldsymbol{\sigma} \times [\mathbf{k}_\gamma])(\mathbf{k}_\alpha \cdot \mathbf{k}_\gamma)$, где $\boldsymbol{\sigma}$ — вектор поляризации нейтрона, а символами $\mathbf{k}$ обозначаются соответствующие импульсы (все эти векторы подразумеваются единичными), в последовательном альфа-гамма-каскаде, возникающем в результате захвата теплового нейтрона. Используется приближение одного резонанса. В качестве механизмов, за счет которых может возникнуть эта корреляция, рассматриваются как взаимодействие альфа-частицы и ядра-остатка в конечном состоянии, так и реальное нарушение инвариантности относительно обращения времени. Анализируется проблема мишени, удобной для наблюдения корреляции. Обсуждаются соответствующие корреляции в других реакциях, вызванных нейтронами или протонами.

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INTRODUCTION

The three- and the five-vector P-even T-odd (pseudo-T-noninvariant) correlations of fission products — the so-called TRI- [1, 2] and ROT-effect [3] — are now the subject of active investigations and discussions [4, 5]. In the fission process, however, these effects manifest themselves in extremely complicated events. A huge number of possible exit microchannels which differ by the masses of fragments, their spins, relative angular momentum, etc. contribute. Furthermore, the emission of some number of various unregistered light particles attends any fission event and introduces distortions. These and other properties make any correlation of fission fragments with other emitted particles very hard for interpretation. The $(n, \alpha\gamma)$ process looks essentially simpler and nevertheless offers some analogous properties. In particular, one would expect the same P-even T-odd correlations. The idea to consider such a reaction as a process which is reference one for the study of the TRI-effect in fission is realized in the experiment [6]. The ^{10}B target is used. In the paper [7] a theoretical interpretation of the experimental result obtained in [6] — zero TRI-effect — is presented. The fact that a T-odd effect is not necessarily an actual T-violating one is declared in [7]. It is also declared (before the observation of the ROT-effect) that five-vector and higher-rank T-odd correlations may manifest themselves in this reaction in the case that other targets are used.

In the current paper, these properties of the $(n, \alpha\gamma)$ process are considered in detail. The formalism of the angular correlations in two-step reactions suitable for description of an arbitrary correlation is presented. The selection rules classifying T-odd effects into zero and nonzero ones are discussed. A scheme which may be used to search for actual T-violating effect is demonstrated. Suitable target isotopes are proposed. The reactions $(n, p\gamma)$, $(n, \gamma\alpha)$, and $(p, \alpha\gamma)$ are also considered.

1. FORMALISM OF THE ANGULAR CORRELATIONS

The definitions of angular correlations are formulated in a variety of ways. The vector form serves usually for their notation. As an example, the correlation related to the TRI-effect in the ternary fission is defined by the three-vector form $(\mathbf{k}_{ff} \cdot [\boldsymbol{\sigma} \times \mathbf{k}_\alpha])$, where the subscripts ff and α denote the type of emitted particles: the fission fragment and the alpha particle. If the axis of quantization is chosen to be parallel to the vector of polarization $\boldsymbol{\sigma}$, the explicit kinematic form of this correlation is the following:

$$\sum_{m=-1,1} (1m1-m|10)\frac{4\pi}{3}\,\mathrm{Re}\,[Y_1^m(\vartheta_{ff}, \phi_{ff})Y_1^{-m}(\theta_\alpha, \phi_\alpha)]. \tag{1}$$

The correlation associated with the ROT-effect is defined by the five-vector form $(\mathbf{k}_{ff} \cdot [\boldsymbol{\sigma} \times \mathbf{k}_\alpha])(\mathbf{k}_{ff} \cdot \mathbf{k}_\alpha)$. Evidently, it may be written explicitly in the form of the product of five Y functions of the rank 1 with the proper vector coupling. However, a much more convenient expression appears after the convolutions of the Y functions depending on one and the same arguments:

$$\sum_{m=-2}^{2} (2m2-m|10)\frac{4\pi}{5}\,\mathrm{Re}\,[Y_2^m(\vartheta_{ff}, \phi_{ff})Y_2^{-m}(\theta_\alpha, \phi_\alpha)]. \tag{2}$$

Naturally, the presented formulas do not depend on types of emitted particles and the dynamics of the process. In particular, the kinematics of the correlation $(\mathbf{k}_\alpha \cdot [\boldsymbol{\sigma} \times \mathbf{k}_\gamma])(\mathbf{k}_\alpha \cdot \mathbf{k}_\gamma)$ denoting the ROT-effect in the neutron-induced alpha-gamma cascade is expressed by formula (2) with the replacements of the subscripts: $ff \to \alpha$ and $\alpha \to \gamma$. The current paper is focused on this example of the five-vector correlation; therefore, sizable expressions of the general formalism are presented below, being indexed by these subscripts.

The dynamic form of any correlation must evidently be constituted as a bilinear form of the amplitudes of an investigated process. The overall (i.e., including all possible correlations) and general (i.e., valid for any sequential two-step cascade of an oriented or nonoriented sample) expression can be presented as

$$\begin{aligned} W_{IJF}(\theta_\alpha, \theta_\gamma, \phi_\alpha, \phi_\gamma) = \sum \rho_j^0(I, I')\varepsilon_{j_\alpha}^{m_\alpha^*}(L_\alpha, L'_\alpha)\varepsilon_{j_\gamma}^{m_\gamma^*} \times \\ \times (L_\gamma p_\gamma, L'_\gamma p'_\gamma)\varepsilon_{j'}^{m'*}(F)\widehat{I}^{\,2}\widehat{J}^{\,2}(j_\alpha m_\alpha j_\gamma m_\gamma|j0) \begin{Bmatrix} J & L_\alpha & I \\ J & L'_\alpha & I' \\ j_\gamma & j_\alpha & j \end{Bmatrix} \begin{Bmatrix} F & L_\gamma & J \\ F & L'_\gamma & J \\ 0 & j_\gamma & j_\gamma \end{Bmatrix} \times \\ \times \widehat{j}_\alpha \widehat{j}_\gamma^{\,2} \langle J|\, L'_\alpha \,|I'\rangle^* \langle J|\, L_\alpha \,|I\rangle \, \langle F|\, L'_\gamma p'_\gamma \,|J\rangle^* \langle F|\, L_\gamma p_\gamma \,|J\rangle \,. \end{aligned} \tag{3}$$

Here the notation $\widehat{b} = \sqrt{2b+1}$ is used; $(j_\alpha m_\alpha j_\gamma m_\gamma|j0)$ is the Clebsh–Gordan coefficient, 3×3 tables are $9j$-symbols; $\rho_j^m(I, I')$ is the statistical tensor of a state in which spins I and I' are mixed; I and I' denote the spins of initial compound nucleus state, J is an intermediate one, and F is a final state; $\langle J|\, L\, p\, |I\rangle$ is the amplitude of a transition; $L_{\gamma_i} p_{\gamma_i}$, $L'_{\gamma_i} p'_{\gamma_i}$ are the angular momenta and parities of the amplitudes determining the multipolarities of the transitions; $\varepsilon_j^m(lp, l'p')$ is the m component of the efficiency tensor of the rank j which characterizes the capability of a detector to register a product which appears in the transition described by the respective pair of the amplitudes. The sum is over all indices contained in (3) besides I, J, F. A particular correlation is defined by the ranks of the statistical tensor j and the efficiency tensors of the detector system j_α, j_γ. For more details concerning the expression (3) and the formulas below, see the monograph [8].

The efficiency tensor of an alpha detector j_α can be expressed as

$$\varepsilon_{j_\alpha}^{m_\alpha}(l, l') = \frac{1}{\sqrt{4\pi}} \frac{\hat{l}\hat{l}'}{\hat{j}_\alpha} (-1)^{l'} (l0l'0|j_\alpha 0) Y_{j_\alpha}^{m_\alpha}(\theta_\alpha, \phi_\alpha). \tag{4}$$

The efficiency tensor of the gamma detector insensitive to the polarization takes the form

$$\varepsilon_{j_\gamma}^{m_\gamma}(lp, l'p') = \frac{1}{16\pi} \hat{l}\hat{l}'(-1)^{l'-1}(l1l'-1|j0)[1 + pp'(-1)^{j_\gamma}]\, S(0) Y_{j_\gamma}^{m_\gamma}(\theta_\gamma, \phi_\gamma), \tag{5}$$

where $S(r)$ is the Stokes parameter. The parameter $S(0)$ signifies the polarization insensitivity. The residual nucleus is not registered; therefore, the tensor of the efficiency of such a «registering» $\varepsilon_{j'}^{m'}(F)$ should be written as

$$\varepsilon_{j'}^{m'}(F) = \hat{F} \delta_{j'0} \delta_{m'0}. \tag{6}$$

Analysis of the multiresonance problem is a subject of special interest because, as pointed out in [9], overlapping of resonances of different spin may be the origin of T-odd correlation. If several resonances contribute significantly to the correlation, then all quantum numbers characterizing the amplitudes should be indexed by the resonances numbers; the sum over these indices appears. The respective resonance amplitudes should be involved in the formalism. Such a cumbersome formalism requires a presentation in a full-size paper. One-resonance case, being a particular one, is adequate to explain selection rules and other qualitative properties of the problem, and to demonstrate the formal scheme. Because of that, we limit ourselves by it in the current paper. In this case, the expression of the statistical tensor produced by the polarized s-neutron capture has the form

$$\rho_k^0(I, I') \equiv \rho_k^0(I) = \frac{1}{4\pi} Q \hat{I}_0^{-3} \hat{k} \hat{I}^2 \hat{j}^{-1} \begin{Bmatrix} I & j & I_0 \\ I & j & I_0 \\ k & k & 0 \end{Bmatrix} \langle I_0|\, j\, |I\rangle^* \langle I_0|\, j\, |I\rangle\,, \tag{7}$$

where Q is the degree of the neutron polarization, $s = 1/2$ denotes neutron spin, $j = 1/2$ is the total contributed angular momentum, and $k = 1$. The quantum number I_0 is the spin of the initial nucleus state, I is the final one.

The discussed correlations are characterized by the tensor ranks: $j_\alpha = 1; j_\gamma = 1; j = 1$ for the TRI-effect and $j_\alpha = 2; j_\gamma = 2; j = 1$ for the ROT-effect, respectively. The Y functions, presented in formulas (1) and (2), are involved in expression (3) through expressions of the efficiency tensors.

The existenceof the Clebsh–Gordan coefficients and the $9j$-symbols in formulas (3)–(7) determines the selection rules for the amplitudes of a certain correlation. Analyzing the TRI-effect, one can find a very expressive example of application of the presented formulas to visualize these rules. Indeed, in the absence of the (parity-conserving or parity-violating) mixing of even and odd amplitudes, the value of efficiency tensor of an alpha detector (4) turns out to be zero because of zero value of the coefficient $(l0l'0|j_\alpha 0)$. The same is true for a detector of arbitrary heavy particle independently of its spin. The efficiency tensor of gamma detector (5) also takes zero value due to the parity-dependent factor contained in the expression. Thus, in the absence of the mixing of even and odd amplitudes, the TRI-effect never appears in any sequential cascade. Therefore, the observed TRI-effect in the ternary fission arises in a simultaneous tripartition in which parity-conserving mixing takes place (see [7]). The case in which parity violation is taken into account is also considered in [7]. The effect is extremely small because the sole nonzero term must contain the product of two parity-violating amplitudes.

So, in fact, the TRI-effect is not a peculiarity of the considered process and we now turn to the discussion of the conditions in which ROT-effect may exist. Let us consider the first $9j$-symbol in expression (3). It is clear that the values of spins of the compound and the intermediate states must be not less than 1/2 and 1, respectively, for its existence. Further, if there is no parity mixing in the initial and final states of the alpha transition, then the sum of the indices of this coefficient is odd and, therefore, it changes the sign under the permutation of two its lines. This coefficient is zero if these two lines are equivalent. Thus, the interference of two amplitudes of the alpha transfers with different multipolarities is one of the necessary conditions of the effect. Bilinear combination of these amplitudes in the sum (3) contains the complex conjugated terms. Due to the change of sign of the $9j$-symbol under the transposition $L_\alpha \leftrightarrow L'_\alpha$, the imaginary part of this combination is survived only. As a result, the dependence of the correlation formula on the amplitudes of α transition takes the form

$$\begin{aligned}\mathrm{Im}\,\left(\langle J|\,L'_\alpha\,|I\rangle^*\langle J|\,L_\alpha\,|I\rangle - \langle J|\,L'_\alpha\,|I,p\rangle\,\langle J|\,L_\alpha\,|I\rangle^*\right) = \\ = 2[\Gamma(L'_\alpha)\Gamma(L_\alpha)]^{1/2}[\sin(\Delta\beta) - w_t\cos(\Delta\beta)], \quad (8)\end{aligned}$$

where w_t denotes the actual T-noninvariant alpha-transition amplitude which is involved in the formula for generality. The value $\Delta\beta = \beta_1 - \beta_2$ is the difference of phase shifts of two amplitudes. For one-resonance case, if the time-reversal invariance is assumed, it is this difference that simulates the pseudo-T-noninvariant effect. So, it is the second necessary condition of its existence.

Usually, correlations are considered in another form being normalized by the respective cross section. In that case, the additional dependence on the amplitudes turns out to be involved in the denominator:

$$\frac{2[\Gamma(L'_\alpha)\Gamma(L_\alpha)]^{1/2}}{\Gamma(L'_\alpha)+\Gamma(L_\alpha)}[\sin(\Delta\beta) - w_t\cos(\Delta\beta)]. \quad (9)$$

The asymptotics of the diverging wave of a charged particle is written as

$$G_l\,(\eta, kr) + iF_l\,(\eta, kr) \sim \exp\,(i[kr - \eta \ln 2kr - l\pi/2 + \beta_l]), \tag{10}$$

where $\eta = \alpha Z_1 Z_2 \sqrt{\mu c^2/(2E)}$ is the Coulomb parameter. As a result, the difference of phase shifts has the form

$$\Delta\beta = \sum_{\lambda=L_<}^{L_>} \arctan\frac{\eta}{\lambda+1}, \tag{11}$$

where $L_< = \min\{L_\alpha, L'_\alpha\}$; $L_> = \max\{L_\alpha, L'_\alpha\}$. In the typical case that $\Delta L = 2$, the formula looks very simple:

$$\Delta\beta = \arctan\frac{(2L_< + 3)\eta}{(L_< + 1)(L_< + 2) + \eta^2}. \tag{12}$$

The widths contained in the correlation formula can be expressed more or less accurately [11] as $\Gamma_\alpha = (\hbar\omega/\pi) S_\alpha P$.

Thus, all values involved into the formula of the correlation are known except the spectroscopic factors S_α. The idea to calculate the alpha-particle spectroscopic factor of a neutron resonance in a certain theoretical approach looks hopeless, because the components of the wave function of any resonance are legion. Nevertheless, there is another way. For the most part analyzing the penetrability P, one may believe that one of two amplitudes is dominating. In that case, only the ratio of these two amplitudes is the value of interest. This value may be in some cases a subject of an independent study. Using $(n, \alpha\gamma)$ reaction induced by the unpolarized neutron beam, one can measure the eight-vector correlation, which may be roughly denoted as $(\mathbf{k}_\alpha \cdot \mathbf{k}_\gamma)^4$. This notation is not adequate enough because, being written explicitly in the form of the product of eight Y functions of the rank 1, it includes the scalar products of the $\mathbf{k}_\alpha$- and $\mathbf{k}_\gamma$-dependent tensors of the ranks 0, 2, and 4, while only the last product is the proper correlation by definition. More precisely, this correlation can be expressed through the components of irreducible tensors $Y_4^m(\vartheta_\alpha, \phi_\alpha)$ and $Y_4^{-m}(\theta_\gamma, \phi_\gamma)$ in the kinematic form:

$$\sum_{m=-4}^{4} (4m4 - m|00)\frac{4\pi}{9}\mathrm{Re}\,[Y_4^m(\vartheta_\alpha, \phi_\alpha) Y_4^{-m}(\theta_\gamma, \phi_\gamma)]. \tag{13}$$

The dynamic form of this correlation is defined by formula (3). The special feature of it is the ranks of the measured tensors: $j_\alpha = j_\beta = 4$ and $j = 0$. If the dominating amplitude is related to the angular momentum $L < 2$, then the eight-vector correlation appears due to the minor amplitude only and the ratio $[\Gamma(L'_\alpha)\Gamma(L_\alpha)]^{1/2}$ determines the normalized $(\mathbf{k}_\alpha \cdot \mathbf{k}_\gamma)^4$ correlation. Thus, this ratio turns out to be measurable.

If the ratio of the amplitudes is known, it is possible to calculate the coefficient of the correlation $(\mathbf{k}_\alpha \cdot\ [\boldsymbol{\sigma} \times \mathbf{k}_\gamma])(\mathbf{k}_\alpha \cdot \mathbf{k}_\gamma)$ using the formalism presented above and after that to measure the ROT-effect. A discrepancy between the experimental and calculated results, if it took place, would be an evidence of the T-noninvariant effect. So, it is possible in principle to estimate an upper limit of the actual T-noninvariant phase shift after the discussed measurements and calculations.

2. PERFORMED EXPERIMENT AND PROMISING EXAMPLES

The capabilities of experimental tools in the studies under discussion may be estimated due to the experiment devoted to the measurement of TRI-correlation which has been carried out yet [6]. The following reaction was used:

$$^{10}\mathrm{B}(n,\alpha\gamma)^{6}\mathrm{Li} \quad (E_\gamma = 478\ \mathrm{keV}).$$

The upper limit of the effect $\sim 0.5 \cdot 10^{-4}$ was established. Unfortunately, it was testing experiment. The matter is that the spin of the intermediate state of ^{6}Li is 1/2; therefore, in consequence of the selection rules $j \leqslant 1$ and thus not only the TRI- but also the ROT-effect is precisely zero in this case. Experiments with other isotopes are significantly harder, because the heavier the target nucleus, the lower the contribution of the $(n, \alpha\gamma)$ channel. So, the problem of more or less suitable target isotope turns out to be a basic one. Continuous searching for an optimal reaction allowed us to extract two promising examples.

Among the stable targets the reaction on Zn seems to be the best. The characteristics of the reaction under study are the following:

$$^{67}\mathrm{Zn}(n,\alpha\gamma)^{64}\mathrm{Ni}\ (E_\gamma = 1340\ \mathrm{keV}),\ I_0 = 5/2^-,\ I = 3^-,\ J = 2^+,\ F = 0^+,\ L_\alpha, L'_\alpha = 1, 3.$$

The compound state spin $I = 3^-$ is chosen because the alpha decay of $I = 2^-$ resonances is not observed in ^{68}Zn. The abundance of the ^{67}Zn isotope is 4.1%, the thermal neutron cross section is $\sigma_{\mathrm{therm}} = 6.9$ b. Unfortunately, even in this case, the flux of the gamma quanta produced by (n, γ) reaction on ^{67}Zn and the admixtures of all other Zn isotopes is about 10^5 times more intensive ($\sigma_\gamma = 1.1$ b for the natural Zn) than the gamma flux of the reaction under study ($\sigma_{\alpha\gamma} = 160\ \mu$b [10]). Thus, a very fast gamma detector, such as BaF_2, is required for such measurements. The enriched target makes the situation slightly better.

An interesting example is the reaction on the radioactive target ^{41}Ca ($t_{1/2} = 1.03 \cdot 10^5$ y, γ rays are not observed):

$$^{41}\mathrm{Ca}(n,\alpha\gamma)^{38}\mathrm{Ar}\ (E_\gamma = 2167\ \mathrm{keV}),\ I_0 = 7/2^-,\ I,\ J = 2^+,\ F = 0^+,\ L_\alpha, L'_\alpha = 3, 5.$$

A number of the resonances are known in the ^{42}Ca compound nucleus. Unfortunately, the values of spins I are not determined for them. At first glance, the example looks more promising because the ratio of the cross sections $\sigma_{\alpha\gamma} = 140$ mb ($\sigma_\gamma = 4$ b) is large enough; thus, the use of this target is free of the disadvantage mentioned above. However, such an experiment requires: extremely powerful reactor-producer to create a sample of satisfactory mass; isotope separation to obtain a significant resulting percentage of the isotope and to get rid of the radioactive ^{45}Ca admixture; a high-flux beam of polarized neutrons to achieve a satisfactory value of the counting rate on the small sample; and a well-developed technology of the experimental work with the targets which are soft radioactive sources of high intensity. At last, the value $L_\alpha(\mathrm{min}) = 3$ prevents the use of the above-presented method of measurement of the minor alpha-width.

An example of the reaction $(n, p\gamma)$ or $(n, \gamma\alpha)$ suitable for the investigation of the ROT-effect is not found. There is a broad spectrum of reactions $(p, \alpha\gamma)$ in the proton resonance area (targets with the masses $A \sim 30$) which can be analyzed in searching for examples promising for the study of the ROT-effect. This analysis is however beyond the scope of the present paper.

CONCLUSIONS

In the present paper, the properties of the five-vector correlation $(\mathbf{k}_\alpha \cdot [\boldsymbol{\sigma} \times \mathbf{k}_\gamma])(\mathbf{k}_\alpha \cdot \mathbf{k}_\gamma)$ in the reactions $(n, \alpha\gamma)$ $(n, p\gamma)$, $(n, \gamma\alpha)$, and $(p, \alpha\gamma)$ are analyzed in detail. The emphasis is on the selection rules which must be fulfilled to obtain the nonzero effect. Two examples of reactions more or less promising for the observation of the correlation are proposed. The method suitable to evaluate the value of the ROT-effect by the use of other experimental data is proposed. The scheme that allows one, in principle, to search for the contribution of the actual time-reversal noninvariant amplitude is proposed.

Summing up the discussions presented in the current and preceding papers, it is important to stress the following essential points:

1. The ROT-effect is a natural property of $(n, \alpha\gamma)$, $(n, p\gamma)$, $(n, \gamma\alpha)$, and $(p, \alpha\gamma)$ reactions.
2. The ROT-effect may be manifested in both sequential and simultaneous processes.
3. In a sequential cascade, the interference of two amplitudes of the alpha or proton transfer with different multipolarities is necessary for the existence of the ROT-effect.
4. The interference may appear due to the difference of phase shifts, which in turn is originated by the Coulomb interaction. The interference of the amplitudes of different resonances may also be the origin of the effect.
5. The effect seems to be accessible to observation in the $(n, \alpha\gamma)$ reaction.
6. If the basic effect is accurately taken into account, one may, in principle, search for the contribution of the actual time-reversal noninvariant amplitude.

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