RESONANCE INTERFERENCE AS A COMMON ORIGIN OF PSEUDO-T-NONINVARIANT ROT-EFFECT IN FISSION AND OTHER NEUTRON-INDUCED REACTIONS

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TRI- AND ROT-EFFECTS. FIRST OBSERVATION

Two types of T-odd correlations were observed in the ternary fission. The first one is TRI-$(\vec{k}_{ff} \cdot [\vec{\sigma} \times \vec{k}_\alpha])$

and the second one is ROT-effect $(\vec{k}_{ff} \cdot [\vec{\sigma} \times \vec{k}_\alpha])(\vec{k}_{ff} \cdot \vec{k}_\alpha)$

$\vec{k}_{ff}, \vec{k}_\alpha$ - linear momenta of fission fragment and α,

$\vec{\sigma}$ - the vector of neutron polarization.

These results attract a considerable interest of experimentalists and theoreticians. Both correlations are, in fact, pseudo-T-noninvariant. There is no connection of the correlations with actual time-reversal symmetry violation, the origin of them is the interaction of particles in final and/or initial state.

THE FORM OF T-ODD ANGULAR CORRELATIONS. HOW COULD ONE OBSERVE THEM?

For the ternary fission example the measure of the correlations has the form

$$W(\theta_{ff},\theta_{\alpha},\phi_{ff},\phi_{\alpha})=\frac{\sigma(\theta_{1\,ff},\phi_{1\,ff},\theta_{1\alpha},\phi_{1\alpha})-\sigma(\theta_{2\,ff},\phi_{2\,ff},\theta_{2\alpha},\phi_{2\alpha})}{\sigma(\theta_{1\,ff},\phi_{1\,ff},\theta_{1\alpha},\phi_{1\alpha})+\sigma(\theta_{2\,ff},\phi_{2\,ff},\theta_{2\alpha},\phi_{2\alpha})}$$

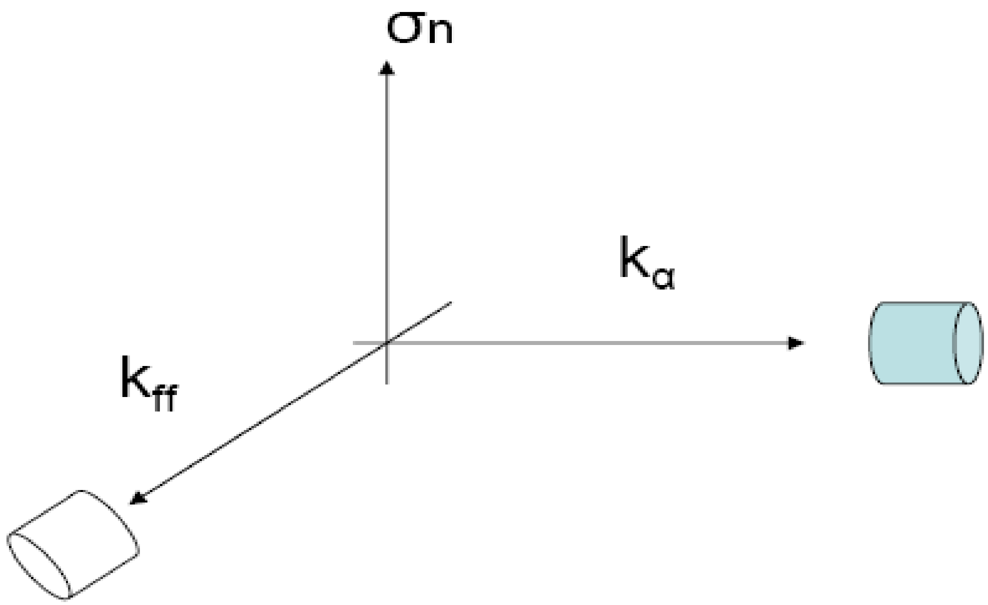
Where index 1 denotes the values obtained for a certain direction on neutron polarization, and index 2 – obtained for the opposite direction. The kinematic (normalized) TRI-correlation takes the form:

$$A=\sum_{m=-1,1}(1m1-m|10)(4\pi/3)\,\mathrm{Re}[Y_1^m(\vec{k}_{ff})Y_1^{-m}(\vec{k}_{\alpha})]=(1/\sqrt{2})\sin(\theta_{ff})\sin(\theta_{\alpha})\sin(\phi_{ff}-\phi_{\alpha}).$$

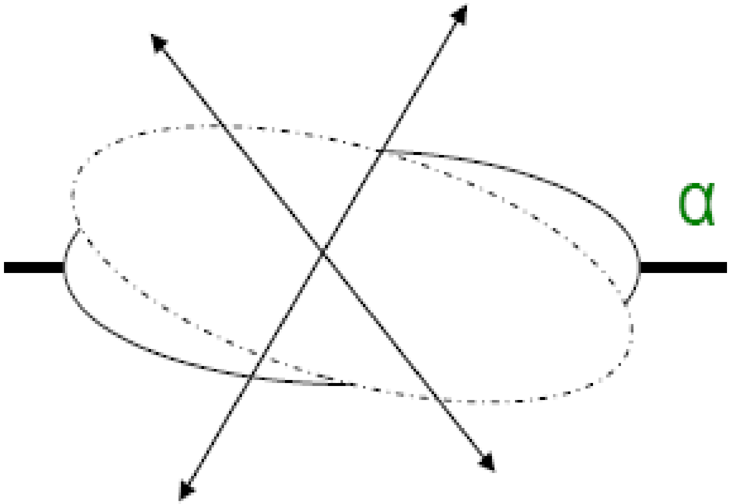
For the ROT-effect in **(n,αγ)**-process:

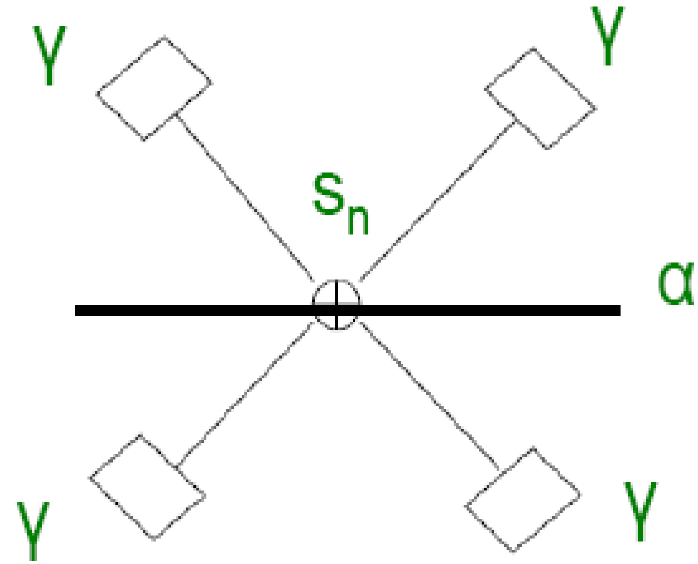
$$A=\sum_{m=-2}^{2}(2m2-m|10)(4\pi/5)\,\mathrm{Re}[Y_2^m(\vartheta_{\gamma},\phi_{\gamma})Y_2^{-m}(\theta_{\alpha},\phi_{\alpha})].$$

TRI-effect means that for the left-hand triple of vectors (see figure) the counting rate of coincidents of signals in the fission-fragment and the alpha detectors is not equal to the counting rate   in the right-hand triple.



The geometry of the ROT-correlation looks as follows:





So the optimal angles are the following: $\Delta\varphi=\pm\pi/2$, $\theta_\gamma=3\pi/4$ (or $\pi/4$), $\theta_\alpha= \pi/2$.

Correlations of this type in **(n,αγ)**-, **(n,γγ)**- and **(n,fγ)**-reactions is the subject of the current work.

Obviously due to the smallness of electromagnetic interaction constant these processes fall into sequential type. TRI-effect is not a feature of such processes. The actual time-reversal non-conservation or the parity violation in both vertexes is required for a sequential process to display the TRI-effect. The same is true for **(n,fγ)**-process.

At the same time the ROT-effect exists.

ROT-EFFECT IN THE FRAMEWORK OF THE ANGULAR CORRELATION THEORY

The "dynamic" form of correlation differs from the kinetic form in that it contains an expression of the correlation coefficient. Any two-particle cascade correlation for two overlapping resonances looks as follows:

$$W_{II'JF}(\theta_\alpha,\theta_\gamma,\phi_\alpha,\phi_\gamma)=\mathrm{Re}(\sum\rho_j^0(I,I')\varepsilon_{j_\alpha}^{m_\alpha *}(L_\alpha,L'_\alpha)$$

$$\varepsilon_{j_\gamma}^{m_\gamma *}(L_\gamma p_\gamma,L'_\gamma\, p'_\gamma)\varepsilon_{j'}^{m'*}(F)(j_\alpha m_\alpha j_\gamma m_\gamma|j0) \qquad (1)$$

$$\begin{pmatrix}\mathbf{J} & \mathbf{L}_{\boldsymbol{\alpha}} & \mathbf{I}\\ \mathbf{J} & \mathbf{L'}_{\boldsymbol{\alpha}} & \mathbf{I'}\\ \mathbf{j}_{\boldsymbol{\gamma}} & \mathbf{j}_{\boldsymbol{\alpha}} & \mathbf{j}\end{pmatrix}\begin{pmatrix}F & L_\gamma & J\\ F & L'_\gamma & J\\ 0 & j_\gamma & j_\gamma\end{pmatrix}\langle J|L'_\alpha|I'\rangle^*\langle J|L_\alpha|I\rangle$$

$$\langle F|L'_\gamma\, p'_\gamma|J\rangle^*\langle F|L_\gamma p_\gamma|J\rangle); \text{for ROT}\, j_\alpha=2;\, j_\gamma=2;\, j=1,$$

The sum is over all contained indexes besides *I, I', J, F* and the ones characterizing a chosen correlation.

The expression of the statistical tensor produced by the *s*-neutron capture has the form:

$$\rho_k^0(I,I')=\frac{1}{\sqrt{2}}P_z(-1)^{I_0-I'-1/2}\hat{I}_0^{-1}\begin{pmatrix} I_0 & 1/2 & I \\ I_0 & 1/2 & I' \\ 0 & 1 & 1 \end{pmatrix}\langle I'|\hat{T}|I_0\rangle^*\langle I|\hat{T}|I_0\rangle$$

P_z - the degree of the neutron polarization, $\hat{j}=\sqrt{2j+1}$.

The efficiency tensors of the gamma- and alpha-detectors take the forms:

$$\varepsilon_{j_\alpha}^{m_\alpha}(l,l')=(1/\sqrt{4\pi})(\hat{l}\hat{l}'/\hat{j}_\alpha)(-1)^{l'}(l0l'0|j_\alpha 0)Y_{j_\alpha}^{m_\alpha}(\theta_\alpha,\phi_\alpha); \quad j_\alpha=j_\gamma=2$$

and

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

respectively. *S(r)* is a Stokes parameter. Efficiency tensor of unobserved residual must also be written:

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

RESONANCE INTERFERENCE AS AN ORIGIN OF ROT-EFFECT

The object which determines specificity of odd correlations is the first 9j-symbol in (1). The sum of the correlation indexes j in the last line of it is odd. In the case that the spatial parity is conserved (for the α-transitions that means that L_α and L'_α are both odd or both even) and l=l' the 9j-symbol changes sign and therefore the correlation coefficient turns out to be equal to zero. In the case that l≠l' (resonance interference) the odd correlations exist.

Let us consider two-resonance pattern. The resonances with different spin are necessary to obtain nonzero effect. The amplitude has the form:

$$\langle I|\hat{T}|I_0\rangle = \frac{\sqrt{\Gamma^n}}{E - E_r + i\Gamma_{tot(r)}/2}$$

Thus alpha-emission amplitudes with one and the same angular momentum may contribute in this instance. So the energy dependence of the correlation takes the form:

$$A \sim \frac{2[(E-E_1)(E-E_2)+\Gamma_{tot(1)}\Gamma_{tot(2)}/4]\sqrt{\Gamma_1^n\Gamma_2^n\Gamma_1^\alpha(L_\alpha)\Gamma_2^\alpha(L_\alpha)}}{[(E-E_1)^2+\Gamma_{tot(1)}^2/4][(E-E_2)^2+\Gamma_{tot(2)}^2/4]},$$

Here E_i is the resonance energy and $\Gamma_i^n, \Gamma_i^\alpha(L_\alpha), \Gamma_{tot\{i)}$ are the respective widths of the resonance.

The relative (normalized by the cross section) value of the correlation is proportional to:

$$W \sim \frac{2[(E-E_1)(E-E_2)+\Gamma_{tot(1)}\Gamma_{tot(2)}/4]\sqrt{\Gamma_1^n\Gamma_2^n\Gamma_1^\alpha(L_\alpha)\Gamma_2^\alpha(L_\alpha)}}{[(E-E_2)^2+\Gamma_{tot(2)}^2/4]\Gamma_1^n\Gamma_1^\alpha(L_\alpha)+[(E-E_1)^2+\Gamma_{tot(1)}^2/4]\Gamma_2^n\Gamma_2^\alpha(L_\alpha)}$$

$$\cong \frac{2(E-E_1)(E-E_2)\sqrt{\Gamma_1^n\Gamma_2^n\Gamma_1^\alpha(L_\alpha)\Gamma_2^\alpha(L_\alpha)}}{(E-E_2)^2\Gamma_1^n\Gamma_1^\alpha(L_\alpha)+(E-E_1)^2\Gamma_2^n\Gamma_2^\alpha(L_\alpha)},$$

i. e. it is the ratio of the geometric mean to the arithmetic mean. This value is not small and can be maximized by use of a neutron source with variable energy.

ROT-EFFECT IN (n,γγ) REACTIONS

For the (**n,γγ)-**correlations the resonance interference is the sole origin of the ROT-effect.

For this mechanism the formalism of the (**n,γγ)-** and **(n,αγ)-**correlations is one and the same. However for typical (**n,γγ**)-process, in contrast to **(n,αγ)**-process, a multitude of γγ-cascades appear. That is why an inclusive or semi-inclusive approach to the measurements – search for **(n,γγ)-**correlations in the integral spectrum or in the chosen part of it – looks promising. The correlation coefficient takes the following form:

$$W_{IJF}(\theta_{\gamma 1},\theta_{\gamma 2},\phi_{\gamma 1},\phi_{\gamma 2}) = \mathrm{Re}(\sum \rho_j^0(I,I')\varepsilon_{j_{\gamma 1}}^{m_{\gamma 1}*}(L_{\gamma 1}p_{\gamma 1},L_{\gamma 1}p_{\lambda 1})$$

$$\varepsilon_{j_{\gamma 2}}^{m_{\gamma}*}(L_{\gamma 2}p_{\gamma 2},L_{\gamma 2}p_{\gamma 2})\varepsilon_{j'}^{m'*}(F)(j_{\gamma 1}m_{\gamma 1}j_{\gamma 2}m_{\gamma 2}|j0)$$

$$\sum_{J,F}\begin{pmatrix} J & L_{\gamma 1} & I \\ J & L_{\gamma 1} & I' \\ j_{\gamma} & j_{\alpha} & j \end{pmatrix}\begin{pmatrix} F & L_{\gamma 2} & J \\ F & L_{\gamma 2} & J \\ 0 & j_{\gamma} & j_{\gamma} \end{pmatrix}\sum_i \langle I|L_{\gamma 1}p_{\gamma 1}|J\rangle_i * \langle J|_i L_{\gamma 1}p_{\gamma 1}|I'\rangle \qquad (2)$$

$$\sum_k |\langle F|_k L_{\gamma 2}p_{\gamma 2}|J\rangle_i|^2); \qquad j_{\gamma 1} = j_{\gamma 2} = 2;\ j = 1.$$

The interference of the γ-transitions of different multipolarity is negligible due to stochastic distribution of the amplitude signs. In fact the sum of squared amplitudes all final states of the γγ- cascade contributes. As usual a dominating amplitude is E1 or M1. The second 9jcoefficient is one and the same. So one can perform a semi-inclusive experiment without measuring of the energy of the second γ-quantum.

PROMISSING EXAMPLES

In the light nuclei area 55Mn example merits attention. For thermal neutron capture the resonance pair –50 eV and +337 eV results in the effect A~1 (σ=13.1 b). In the heavy nuclei area 149Sm example looks promising.

$^{149}_{62}\mathrm{Sm}$ $I^{\pi}_{\circ} = 7/2^{-}$ *Abundance:* 13.8(1) % $T_{1/2} > 2 \cdot 10^{15}$ yr $S_{\mathrm{n}} = 7985.7(7)$ keV

$E_{\circ}$ [eV]	J	ℓ	$2g\Gamma_{\mathrm{n}}$ [meV]	$2g\Gamma^{0}_{\mathrm{n}}$ [meV]	Γ_{γ} [meV]	Γ_{α} [μeV]	Ref.		
–0.285	3	0		0.277	⟨62⟩	0.28(13)	74W	84M5	
0.0973(2)	4	0	0.600(9)	1.924(29)	60.5(6)	0.037(10)	74W	84M5	
0.872(3)	4	0	0.835(45)	0.894(48)	59.8(10)	0.023(6)	75B6	84M5	
4.940(30)	4	0	2.41(3)	1.084(13)	59(2)	0.025(7)	81M4	84M5	
6.428(30)	3	0	1.05(2)	0.414(8)	68(5)	0.059(15)	81M4	75B6	72K

In the case that two-resonance approximation is used the effect is A~0.28 (σ=41 kb).

For the **(n,αγ)**-reaction the effect is A~0.6. Unfortunately the cross section is small.

ROT-EFFECT IN (n,fγ)-REACTIONS

The interference may be an origin of the ROT-effect in fission too. Let us consider **(n,fγ)**-process. In this case the interference under discussion manifests itself in the most uncombined “pure” form compared to the **(n,fα)**- and **(n,fn)**-reactions because: a) the process is simultaneous due to the smallness of the electromagnetic interaction constant, b) the angular distribution of gamma-quanta is not affected by fission fragment motion. The basic obstacle for a detail analysis of the effect is the broad variety of the fragments by masses, internal states and relative motion quantum numbers. So there is no way to study the ROT-effect except inclusive measurements.

The corresponding correlation is written in the form similar to (2), but the γ-transition in both fragments should be taken into account.

$$W_{JF}(\theta_f,\theta_\gamma,\phi_f,\phi_\gamma)=\mathrm{Re}(\sum\rho_j^0(I,I')\varepsilon_f^{m_f *}(L_f p_f,L_f p_f)$$

$$\varepsilon_{j_\gamma}^{m_\gamma *}(L_\gamma p_\gamma,L_\gamma p_\gamma)\varepsilon_{j'}^{m'*}(F)(j_f m_f j_\gamma m_\gamma|j0)$$

$$\sum_{J_1,J_2,F_1,F_2}\begin{pmatrix} J_1 & L_f & I \\ J_2 & L_f & I' \\ j_\gamma & j_f & j \end{pmatrix}\begin{pmatrix} F_1 & L_{\gamma 1} & J_1 \\ F_1 & L_{\gamma 1} & J_1 \\ 0 & j_\gamma & j_\gamma \end{pmatrix}\sum_{i_1,i_2}\langle I|L_f p_f|J_1,J_2\rangle_{i_1,i_2} * \langle J_1,J_2|_{i_1,i_2} L_f p_f|I'\rangle$$

$$[\sum_{k_1}|\langle F_1|_{k_1} L_{\gamma 1}p_{\gamma 1}|J_1\rangle_{i1}|^2+\sum_{k_2}|\langle F_2|_{k_2} L_{\gamma 2}p_{\gamma 2}|J_2\rangle_{i_2}|^2]); \qquad j_f=j_\gamma=2;\ j=1;$$

235U AS A PROMISSING EXAMPLE

A fragment of the resonance spectrum of 235U.

$^{235}_{92}\mathrm{U}$ $I_\circ^\pi = 7/2^-$ *Abundance:* 0.720(1) % $T_{1/2} = 703.8(5) \cdot 10^6$ yr $S_\mathrm{n} = 6544.8(6)$ keV

$E_\circ$ [eV]	J	ℓ	Γ_n [meV]	Γ_n^0 [meV]	Γ_γ [meV]	Γ_{f1} [meV]	Γ_{f2} [meV]	Ref.
–100	3	0	11.458		⟨38.9⟩	0.123	72.26	91L1
–90	4	0	0.002422		⟨37.0⟩	56.11	–216.7	91L1
–4.298	4	0	7.1641		⟨35.0⟩	319.0	–115.2	91L1
–3.493	3	0	0.0000847		⟨38.0⟩	–6.753	12.97	91L1
–1.504	3	0	0.0000852		⟨37.8⟩	–7.004	12.31	91L1
–0.412	3	0	0.14875		⟨30.0⟩	–1.026	–155.3	91L1
–0.194	4	0	0.0005045		⟨35.2⟩	198.76	–1.692	91L1
0.000037	4	0	0.000000065	0.0000107	⟨30.0⟩	–0.526	0.964	91L1
0.2819	3	0	0.00444	0.00836	38.6	106.4	–4.845	91L1

Although a quantitative prediction of the ROT-effect magnitude in fission presents difficulties, overlapping of 3- and 4- resonances looks attractive. Another point is that ROT-effect both in the (**n,fγ)**-process and in the **(n,γγ)-**process can be measured simultaneously.

CONCLUSIONS

ROT-effect is a natural property of cascade processes.

The interference of resonances with different spin may be and probably is the basic origin of ROT-effect in all reaction besides the ternary fission.

The observation of the effect is realistic both in exclusive and inclusive schemes.

To study the effect in (**n,αγ)**- and **(n,γγ)**-reactions a powerful neutron source and high-rate detector system are required.

Studying of the ROT-effect by use of a variable neutron energy source is of special interest because a chance to make unambiguous conclusion concerning actual origins of it appears. Besides that this approach provides a possibility to perform measurement in areas corresponding to the t maximum of the effect.

Measurements of the effect may produce an independent information about resonance spectra.

In the case that the basic effect is accurately taken into account one may, in principle, search for the the contribution of the actual time-reversal noninvariant amplitudes.

THANK YOU FOR ATTENTION!