THE MECHANISM OF EXCITATION OF GIANT RESONANCES IN NUCLEAR FISSION AND T-ODD CORRELATIONS FOR PRESCISSION GAMMA-QUANTA

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Abstract: In the framework of the quantum fission theory the conditions are investigated for the appearance and the observation of the pre-scission gamma-quanta which are emitted by the fissioning nucleus before its scission. It is shown that these conditions are fulfilled for the gamma-decay of the giant electric isovector dipole resonances whose excitation is caused by the non-adiabatic character of the nuclear collective motion at the final stages of its pre-scission evolution. The analysis is carried of the energy and angular distributions for these quanta emitted by the unpolarized nuclei. T-odd correlations are also studied in the angular distributions of these quanta emitted in the fission reactions induced by the polarized cold neutrons. The similarity of these correlations are shown to the T-odd ROT-correlations which were discovered earlier for the ternary fission alpha-particles.

1. Introduction

T-odd TRI correlations were discovered [1] in the angular distribution of the products of ^{233}U ternary fission induced by the cold polarized neutrons. They could be described by the expression:

$$\frac{d^2\sigma^{(TRI)}}{d\Omega_{LF}d\Omega_3} = A\vec{\sigma}_n\left[\vec{k}_{LF},\vec{k}_3\right], \tag{1}$$

where $\vec{\sigma}_n$, $\vec{k}_{LF}$, $\vec{k}_3$ are the unit vectors directed along the neutron polarization vector and the wave vectors of the light fragment and the ternary particle (predominantly alpha), respectively. A few years later another T-odd correlation was discovered [2,3] in ternary fission of ^{235}U

$$\frac{d^2\sigma^{(ROT)}}{d\Omega_{LF}d\Omega_3} = A'\vec{\sigma}_n\left[\vec{k}_{LF},\vec{k}_3\right]\left(\vec{k}_{LF},\vec{k}_3\right), \tag{2}$$

which was named ROT and interpreted [4] in terms of classical mechanics as the result of the fission fragments' emission by the rotating fissioning system.

The description of these effects in the framework of quantum theory was given in [5-7] which considered the influence of the fissioning system rotation on the angular distribution of the ternary fission products. This rotation causes the appearance of Coriolis interaction in the internal coordinate system between the orbital momentum $\vec{l}_3$ of the ternary particle and the nuclear total spin $\vec{J}$. An important role was demonstrated of the neutron resonances' interference which causes the damping of either even or odd orbital moments $\vec{l}_3$ thus strengthening either TRI- or ROT-correlation, respectively.

In ref [8] the analogous ROT-effect was found for gamma quanta emitted in binary fission of ^{235}U induced by the polarized neutrons. The angular dependence of the effect was similar to the ROT effect for alpha particles while its magnitude was about 10^{-4}.

In the present paper we shall use the approach of [5-7] to show that this latter effect could be explained by the T-odd asymmetry in the angular distribution of the pre-scission gammas emitted in binary fission induced by the polarized neutrons.

2. Giant resonances in the fissioning nuclei and the pre-scission quanta

It was shown in ref [5-7] that the polarized neutron capture by the target nucleus leads to the excitation of neutron resonances in the first potential well of the compound nucleus. The nuclear fission is caused by the evolution of the resonance wave functions during the system's motion along the axially symmetric deformation mode. This evolution ends at the scission point by the transition of these wave functions into those of the fission modes Ψ_K^{JM}. The non-adiabatic character of this motion might lead to the excitation of the system's states which emit the pre-scission gammas. The typical time for the system's transition from the exterior saddle-point to the scission point is $\tau_0 \approx 10^{-21}$ s. Therefore, in order to make these gammas observable it is necessary that the life-times τ_γ of those excited states should be of the same order as τ_0. This means that their gamma widths $\Gamma_\gamma = \hbar / \tau_\gamma$ should be of the order of 1 MeV. So large widths are characteristic only for the collective vibrations of the giant electric isovector dipole resonance (GDR) type. The typical energy of these resonances is $E_0 = 80 A^{-1/3}$ MeV. However, in the axially-symmetric deformed nuclei these resonances split into two components corresponding to the vibrations along the long and the short axes of the system. The magnitude of this splitting is defined [9] by the expression:

$$\Delta E \approx E_0 \beta_2 , \qquad (3)$$

where $E_0 \approx 12$ MeV for U isotopes and β_2 is the quadrupole deformation parameter.

There are two possibilities to excite GDR in the fissioning nucleus. If its neck has not completely developed and the nucleus still conserves its ellipsoidal shape the GDR involves all the nucleons (in order to conserve total parity and the projection K of the total spin on the symmetry axis this resonance should be built on the excited state with negative parity and K'=K quantum number). Since the typical deformation of the heavy fissioning nuclei at the last stages before scission $\beta_2 \approx 1$, the energy of the lowest GDR component with spin`s projection $\nu = 0$ onto fissile nucleus symmetry axis might be quite low ($E_{\nu=0} \approx (4-5)$ MeV). If the system's neck is already well developed and the pre-fragments appear the simultaneous excitation of two GDR's of the pre-fragments is possible caused by their mutual Coulomb interaction. However, the maximal deformation values β_2 of the fragments with $A_1 \approx A_2 \approx A/2$ do not exceed 0.3. Therefore the characteristic GDR energies of the fragments are rather large ($E_{\nu=0} \approx 14$ MeV). The spectral analysis [10] of the gammas which follow the fission of ^{235}U shows the almost exponential decrease by 4 orders of magnitude in the energy range between $E_\gamma \approx 0.5$ MeV and $E_\gamma \approx 8$ MeV. One should expect that this decrease would continue at higher energies. This seems to cancel the case of the two GDR excitations of the pre-fragments and leaves us only with the first possibility – GDR excitation of the whole fissioning nucleus.

3. **The wave functions of the fissioning system which emit the pre-scission gamma-quanta**

The wave function of the fission mode Ψ_K^{JM} for the deformed axially symmetric fissioning nucleus can be written [9] as:

$$\Psi_K^{JM} = \sqrt{\frac{2J+1}{16\pi^2}}\left\{\left[D_{MK}^J(\omega)\chi_K(\xi)+(-1)^{J+K}D_{M-K}^J(\omega)\chi_{\bar{K}}(\xi)\right](1-\delta_{K,0})+ \right. \\ \left. +\sqrt{2}D_{M0}^J(\omega)\chi_0(\xi)\delta_{K,0}\right\}. \tag{4}$$

In order to describe the pre-scission gamma emission we shall introduce the vector spherical function [11]:

$$\vec{Y}_{jl\mu}(\Omega_{\vec{r}},\vec{s}) = \left\{Y_{lm}(\Omega_{\vec{r}})\vec{e}_{1t}(\vec{s})\right\}_{j\mu} \ , \tag{5}$$

where $\vec{e}_{1t}(\vec{s})$ is the spin function which depends on the spin variables $\vec{s}$ of the γ-quantum and its projection t ($t=0,\pm 1$) on the Z- axis of the laboratory system; $Y_{lm}(\Omega_{\vec{r}})$ is the spherical function which depends on the solid angle $\Omega_{\vec{r}}$ of the quantum radius-vector $\vec{r}$ and corresponds to the orbital momentum l and its projection m on Z-axis.. The curly brackets in (5) means the vector addition of the spin and the angular momentum of the quantum forming its total momentum $\vec{j}$.

One can use Wigner's transformation relating $\vec{Y}_{jl\mu}(\Omega_{\vec{r}},\vec{s})$ of (5) to the vector spherical function $\vec{Y}_{jl\eta}(\vec{s}\,')$ in the co-ordinate system K' where the vector $\vec{r}$ defines the Z' axis direction and which realizes the helicity representation [9]:

$$\vec{Y}_{jl\mu}(\Omega_{\vec{r}},\vec{s}) = \sum_{\eta=\pm 1} D_{\mu\eta}^j(\Omega_{\vec{r}})\vec{Y}_{jl\eta}(\vec{s}\,'). \tag{6}$$

Here $D_{\mu\eta}^j(\Omega_{\vec{r}})$ is the generalized spherical function which depends on the Euler's angles connected with the radius-vector $\vec{r}$; $\vec{Y}_{jl\eta}(\vec{s}\,')$ is the vector spherical function in the K'co-ordinate system:

$$\vec{Y}_{jl\eta}(\vec{s}\,') = \left(\frac{2j+1}{4\pi}\right)^{1/2} C_{j1-\eta\eta}^{l0}\vec{e}_{1\eta}(\vec{s}\,'). \tag{7}$$

Introduce now the vector potential $\vec{A}_{jl\mu}(x)$ (where $x \equiv \vec{r},\vec{s}$ are the photon co-ordinates), which is normalized by the unit photon flux in the $\vec{r}$ direction [11]:

$$\vec{A}_{jl\mu}(x) = \left(\frac{kc}{2\pi\hbar}\right)^{-1/2} k\left(n_l(kr)+ij_l(kr)\right)\vec{Y}_{jl\mu}(\Omega_{\vec{r}},\vec{s})i^l . \tag{8}$$

Here $j_l(kr)$ and $n_l(kr)$ are the Bessel and Neuman spherical functions while k is the modulus of the photon wave vector. Then the vector potentials $\vec{A}_{\lambda l\mu}(x)$ corresponding to electric $(\lambda = E)$ and magnetic $(\lambda = M)$ γ- quanta have the form:

$$\vec{A}_{\lambda j\mu}(x)=\begin{cases}-\sqrt{2}\sum_{l}C_{j1-11}^{l0}\vec{A}_{jl\mu}(x)\delta_{j,l} & ,\ \lambda=M,\\ -\sqrt{2}\sum_{l\neq j}C_{j1-11}^{l0}\vec{A}_{jl\mu}(x) & ,\ \lambda=E.\end{cases}$$

(9)

In general the Hamiltonian H' for the interaction of the electro-magnetic radiation with the atomic nucleus can be represented as [11]:

$$H'=-\frac{1}{c}\int\vec{A}\vec{j}d\tau\ . \qquad (10)$$

Here $\vec{j}$ is the density operator of the convectional and spin currents in the nucleus; $\vec{A}$ is the vector potential of the electro-magnetic field. The integration is carried over all the nuclear coordinates τ.

The fission mode wave function (4) after the emission of the γ-quantum transforms into the wave function $\tilde{\Psi}_K^{JM}$ of the system which consists of the daughter nucleus plus the photon. Its asymptotic form for large r ($r > R_A$, where R_A is the nuclear radius) is:

$$\tilde{\Psi}_K^{JM}=\sum_{\alpha}\left\{\Psi_{K'}^{J'M'}\vec{A}_{\lambda j\mu}\right\}_{JM}\sqrt{\frac{\Gamma_{\gamma\alpha}^{JK}}{\hbar}}, \qquad (11)$$

where $\sqrt{\Gamma_{\gamma\alpha}^{JK}}$ is the partial width amplitude for the gamma decay of the fissioning nucleus into the channel α:

$$\sqrt{\Gamma_{\gamma\alpha}^{JK}}=-\sqrt{\frac{\pi}{2\hbar}\left(\frac{1}{2\pi ck}\right)}\left\langle\left\{\Psi_{K'}^{J'M'}\tilde{\tilde{A}}_{\lambda j\mu}\right\}_{JM}\left|\vec{j}\right|\Psi_K^{JM}\right\rangle,$$

(12)

where potential $\tilde{\tilde{A}}_{\lambda j\mu}$ differs from $\vec{A}_{\lambda j\mu}$ (8) by substitution of the function $\left(n_l(kr)+ij_l(kr)\right)$ to the function $j_l(kr)$. Now one can show that in the long-wave approximation ($kR_A<<1$) the total width $\Gamma_{\gamma E1}^{JK}$ of the electric dipole gamma decay is:

$$\Gamma_{\gamma E1}^{JK}=\sum_{J'K'}\Gamma_{\gamma E1J'K'}^{JK}=\Gamma_{\gamma K}^{0}.$$

(13)

Here the summation goes over the quantum numbers of the final states, while $\Gamma_{\gamma K}^{0}$ is defined by the equation:

$$\sqrt{\Gamma_{\gamma K}^{0}}=-\sqrt{16\pi k}\left(\frac{k}{3!!}\right)\left\langle\chi_K^{'}\left|Q_{10}^{0}\right|\chi_K\right\rangle. \qquad (14)$$

Here $Q_{1K_1}^{0}$ is the electric dipole moment operator of the nucleus in the intrinsic coordinate system.

4. **The angular distribution of the pre-scission gamma-quanta emitted by the unpolarized fissioning nucleus**

In order to describe the angular distribution of the pre-scission electric dipole quanta one can use Eq. (11), which can be written as:

$$\tilde{\Psi}_K^{JM} = \sum_{J'K'} \left\{ \Psi_{K'}^{J'M'} \vec{A}_{E1\mu} \right\}_{JM} \sqrt{\Gamma_{\gamma E1J'K'}^{JK}} \ . \tag{15}$$

With the use of Eqs. (8), (6) one can obtain the following expression for the vector potential $\vec{A}_{E1\mu}(x)$:

$$\vec{A}_{E1\mu}(x) = \sqrt{\frac{3}{4\pi}} \sum_{\eta=\pm1} D_{\mu\eta}^{1}(\Omega_{\vec{r}}) \vec{e}_{1\eta}(\vec{s}\,') B(r), \tag{16}$$

where function $B(r)$ is defined as:

$$B(r) = -\left(\frac{kc}{2\pi\hbar}\right)^{-1/2} 2\sum_{l\neq1} \left(C_{1-1-11}^{l0}\right)^2 k\left(n_l(kr) + ij_l(kr)\right) i^l . \tag{17}$$

Now the wave function $\tilde{\Psi}_K^{JM}$ of Eq. (15) can be written in the form:

$$\begin{aligned} \tilde{\Psi}_K^{JM} &= \sum_{\eta=\pm1} \sqrt{\frac{3}{4\pi}} D_{0\eta}^{1}(\Omega'_{\vec{r}}) \vec{e}_{1\eta}(\vec{s}\,') \left(\frac{2J+1}{16\pi^2}\right)^{1/2} B(r) \times \\ &\times \left\{ D_{MK}^{J}(\omega) \chi'_K(\xi) + (-1)^{J+K} D_{M-K}^{J}(\omega) \chi'_{\bar{K}}(\xi) \right\} \sqrt{\Gamma_{\gamma K}^{0}} . \end{aligned} \tag{18}$$

The fission fragments are emitted along the nuclear symmetry axis. Therefore if one chooses the Z-axis of the laboratory system to be directed along the light fragment momentum then the solid angle $\Omega'_{\vec{r}}$ in (19) will coincide with the solid angle $\Omega_{\vec{r}}$ which defines the direction of gamma emission with respect to the direction of the light fragment momentum.

With the help of Eq. (18) one can find the current density of the pre-scission gammas for $r \to \infty$ and obtain the following expression for their angular distribution normalized by the total width $\Gamma_{\gamma K}^{0}$:

$$\frac{d\Gamma_{\gamma K}(\Omega_{\vec{r}})}{d\Omega_{\vec{r}}} = \sum_{\eta=\pm1} \frac{3}{4\pi} \left| D_{0\eta}^{1}(\Omega_{\vec{r}}) \right|^2 \Gamma_{\gamma K}^{0} = \frac{3}{4\pi} \Gamma_{\gamma K}^{0} \sin^2\theta_{\vec{r}} . \tag{19}$$

We see that this angular distribution has a well - defined maximum in the direction perpendicular to the light fragment momentum when $\theta_{\vec{r}} = \pi/2$.

This expression holds irrespective of whether the emitting compound nucleus is polarized or not.

Now one can apply the technique of refs. [5-7] to obtain the differential cross section for the (n,γ) fission reaction with the emission of the pre-scission gamma :

$$\frac{d\sigma_{n\gamma}}{d\Omega_{\vec{r}}} = \frac{4\pi}{k_n^2} F^0(\Omega_{\vec{r}}), \tag{20}$$

where

$$F^0\left(\Omega_{\vec{r}}\right)=\sum_{sJ_s s'J_{s'}K_s} D_{K_s}^{sJ_s s'J_{s'}}\Gamma_{\gamma K_s}^0 B_{K_s}^{sJ_s s'J_{s'}}, \tag{21}$$

$$D_{K_s}^{sJ_s s'J_{s'}}=b_{sK_s}^{J_s} b_{s'K_s}^{J_{s'}}\left|h_s^{J_s}\right|\left|h_{s'}^{J_{s'}}\right|, \tag{22}$$

$$h_s^{J_s}=\frac{\sqrt{\Gamma_s^{J_s}}}{E-E_s^{J_s}+\dfrac{i\Gamma_s^{J_s}}{2}}=\left|h_s^{J_s}\right|e^{i\delta_{sJ_s}}, \tag{23}$$

$$B_{K_s}^{sJ_s s'J_{s'}}=\delta_{J_s,J_{s'}}\frac{1}{16\pi^2}\frac{3}{4\pi}\sin^2\theta_{\vec{r}}\frac{\left(2J_s+1\right)}{2\left(2I+1\right)}\cos\delta_{sJ_s s'J_{s'}}, \tag{24}$$

and $\delta_{sJ_s s'J_{s'}}=\delta_{sJ_s}-\delta_{s'J_{s'}}$, I is the target spin.

The direct measurement of the pre-scission gammas' angular distribution is complicated by the background of the much more intensive "statistical" gammas emitted by the thermalised fission fragments. Therefore in order to prove the existence of the pre-scission gammas one should investigate also the correlation effects which might be either larger or of the same scale as the analogous correlations for the statistical gammas. A good example of such effects is the T-odd correlation in the angular distributions of the pre-scission quanta emitted in fission reaction induced by the cold polarized neutrons which is caused by the influence of the polarized compound nucleus rotation on the angular distribution of the emitted quanta.

5. T-odd asymmetry in the angular distribution of pre-scission quanta

We shall study the influence of the polarized compound nucleus rotation on the angular distribution of the pre-scission quanta by introducing into the Hamiltonian the term H_{Cor} [9] coming from the Coriolis interaction of the total nuclear spin $\vec{J}$ with the total momentum $\vec{j}$ of the pre-scission quantum:

$$H_{\text{Cor}}=-\frac{\hbar^2}{2\mathcal{J}_0}\left(J_+j_-+J_-j_+\right), \tag{25}$$

where

$$J_\pm=\left(J_{x'}\pm iJ_{y'}\right),\ j_\pm=\left(j_{x'}\pm ij_{y'}\right), \tag{26}$$

and x', y' indicate the axes in the intrinsic coordinate system. The symbol $\mathcal{J}_0$ means the moment of inertia of the fissioning system which evolves from the compound nucleus moment of inertia at the scission point up to the value M_cR^2 for $R\to\infty$ (M_c is the reduced mass for the fission channel c. The action of the operators $J_\pm$ on the function $D_{MK}^J\left(\omega\right)$ which describes the collective rotation of the whole system and of the operators $j_\pm$ on the function $D_{0\eta}^1\left(\Omega'_{\vec{r}}\right)$ describing the angular distribution of the pre-scission quanta is defined as:

$$J_\pm D_{MK}^J\left(\omega\right)=\left[\left(J\pm K\right)\left(J\mp K+1\right)\right]^{1/2}D_{M\left(K\mp1\right)}^J\left(\omega\right), \tag{27}$$

$$j_{\pm} D^1_{0\eta}\left(\Omega'_{\vec{r}}\right) = \sqrt{2} D^1_{(\pm 1)\eta}\left(\Omega'_{\vec{r}}\right). \tag{28}$$

By using the technique of ref. [5] one can take into account the influence of the Coriolis interaction on the fission mode wave function Ψ^{JM}_K by adding to it (in the region where the pre-scission quanta and the daughter nucleus are already formed) the wave function $\Delta\tilde{\Psi}^{JM}_K$:

$$\Delta\tilde{\Psi}^{JM}_K(x) = \sum_{m=\pm1,\eta=\pm1} \left\{ D^J_{MK+m}(\omega')\chi'_K b^m_{KJ} + (-1)^{J+K} D^J_{M(-K+m)}(\omega')\chi'_{\bar{K}} b^m_{-KJ} \right\} \times \\ \times \sqrt{\frac{2J+1}{16\pi^2}} D^1_{m\eta}\left(\Omega'_{\vec{r}}\right) \vec{e}_{1\eta} \sqrt{\Gamma^0_{\gamma K}} \alpha^{\mathrm{Cor}} B(r) \sqrt{2} \sqrt{\frac{3}{4\pi}}, \tag{29}$$

where

$$b^{+1}_{KJ} = b^{-1}_{-KJ} = \sqrt{(J-K)(J+K+1)}; \; b^{-1}_{KJ} = b^{+1}_{-KJ} = \sqrt{(J+K)(J-K+1)} \tag{30}$$

and

$$\alpha^{\mathrm{Cor}} = \frac{k^2}{\hbar^2 c} \int_{R_A}^{\infty} \tilde{B}(r) \left(-\frac{\hbar^2}{2\mathcal{J}_0} \right) B(r) r^2 dr . \tag{31}$$

Here the quantity $\tilde{B}(r)$ is defined by Eq. (17) with the substitution of the function $j_l(kr)$ instead of the quantity $\left(n_l(kr) + i j_l(kr)\right)$. After adding the function $\Delta\tilde{\Psi}^{JM}_K(x)$ to the unperturbed function $\tilde{\Psi}^{JM}_K(x)$ of Eq. (18) one can find the current density of the pre-scission quanta $\vec{j} = \vec{j}^{\,0} + \Delta\vec{j}$. Performing the integration over the internal co-ordinates ξ of the daughter nucleus one obtains the first-order correction $F^{(1)}\left(\Omega_{\vec{r}}\right)$ to the quantity $F^0\left(\Omega_{\vec{r}}\right)$ of (21) which defines the cross-section $\frac{d\sigma_{n\gamma}}{d\Omega_{\vec{r}}}$ of Eq. (20). Thus we obtain the additional term $\frac{d\sigma^{Cor}_{n\gamma}}{d\Omega_{\vec{r}}}$ to the cross-section coming from the Coriolis interaction. This term is defined by the non-diagonal part of the spin density matrix $\rho^{J_s J_{s'}}_{MM'}$ which is proportional to the neutron polarization p_n. Therefore $\frac{d\sigma^{Cor}_{n\gamma}}{d\Omega_{\vec{r}}}$ is defined by the Eqs. (20-23) with the quantity $B^{sJ_s s' J_{s'}}_{K_s}$ of Eq. (24) substituted by:

$$\left(B^{sJ_s s' J_{s'}}_{K_s}\right)^{\mathrm{Cor}} = \left(\frac{1}{8\pi^2}\right) \alpha^{\mathrm{Cor}} \frac{3}{4\pi} \frac{\sqrt{(2J_s+1)(2J_{s'}+1)}}{2(2I+1)} g_{K_s J_s J_{s'}} p_n \sqrt{2} \times \\ \times \sum_{\eta=\pm1} \left[D^1_{-1\eta}\left(\Omega_{\vec{r}}\right) - D^1_{1\eta}\left(\Omega_{\vec{r}}\right) \right] D^{1*}_{0\eta}\left(\Omega_{\vec{r}}\right) \sin\delta_{sJ_s s' J_{s'}}, \tag{32}$$

where

$$g_{K_s J_s J_{s'}} = A(J_s, J_{s'}) \Big[\sqrt{(J_s + K_s)(J_s - K_s + 1)} C^{J_{s'} K_s}_{J_s 1 (K_s - 1) 1} - \\ - \sqrt{(J_s - K_s)(J_s + K_s + 1)} C^{J_{s'} K_s}_{J_s 1 (K_s + 1) - 1} \Big], \tag{33}$$

$$A(J_s, J_{s'}) = \delta_{J_s, J_{s'}} \left(\sqrt{\frac{J_s}{2(J_s+1)}} \delta_{J_s, J_<} - \sqrt{\frac{J_s+1}{2J_s}} \delta_{J_s, J_>} \right) - \\ - \sqrt{\frac{2J_s+1}{2J_s}} \delta_{J_s, J_{s'}+1} + \sqrt{\frac{2J_s+1}{2(J_s+1)}} \delta_{J_s, J_{s'}-1}, \tag{34}$$

$J_> = I + 1/2, \qquad J_< = I - 1/2.$

The component of the angular distribution of pre-scission quanta arising from the neutron polarization is:

$$J(\Omega_{\vec{r}}) = \sum_{\eta = \pm 1} \left[D^1_{-1\eta}(\Omega_{\vec{r}}) - D^1_{1\eta}(\Omega_{\vec{r}}) \right] D^{1*}_{0\eta}(\Omega_{\vec{r}}). \tag{35}$$

This expression can be reduced to the form:

$$J(\Omega'_{\vec{r}}) = -C^{20}_{11-10} \left[Y_{2(-1)}(\Omega'_{\vec{r}}) - Y_{21}(\Omega'_{\vec{r}}) \right] \sqrt{\frac{4\pi}{5}} (-1) C^{20}_{11-11} 2 = -\frac{1}{\sqrt{2}} \sin 2\theta_{\vec{r}} \cos\varphi_{\vec{r}}.$$

(36)

Thus the expression for the polarization-dependent addition to the differential cross-section is:

$$\frac{d\sigma^{Cor}_{n\gamma f}}{d\Omega_{\vec{r}}} = \frac{p_n}{2(2I+1)k_n^2} \sum_{ss' J_s J_{s'} K_s} |h^{J_s}_s| |h^{J_{s'}}_{s'}| b^{J_s}_{sK_s} b^{J_{s'}}_{s'K_{s'}} \Gamma^0_{\gamma K_s} \sqrt{(2J_s+1)(2J_{s'}+1)} \times \\ \times g_{K_s J_s J_{s'}} \left(-\frac{3\alpha^{Cor}}{8\pi^2} \right) \sin 2\theta_{\vec{r}} \cdot \cos\varphi_{\vec{r}} \cdot \sin\delta_{sJ_s s' J_{s'}}. \tag{37}$$

One can see from Eq. (36) that the part of the angular distribution connected with the collective rotation of the polarized nucleus is defined by the spherical functions $Y_{2,\pm 1}$ coming from the even value $l = 2$ of the angular momentum. As shown in [7] for the case of T-odd correlation of alpha particles, this means that the T-odd correlation for the pre-scission gammas are only of the type of the ROT-effect.

Eq. (37) shows that this correlation appears only in the case of the neutron resonances interference when the value $\delta_{sJ_s s' J_{s'}} \neq 0$. Since the pre-scission gammas are observed on the strong background of statistical quanta with rather small anisotropy, the angular dependence of the asymmetry coefficient $D_\gamma(\Omega_{\mathbf{r}})$ is of the form:

$$D_\gamma(\theta_{\vec{r}}) = A \sin 2\theta_{\vec{r}}, \tag{38}$$

which is close to that observed in ref. [8].

In order to estimate the coefficient D_γ for the pre-scission quanta one can use the qualitative classical picture which was applied in ref. [4] to the case of the alpha particles' ROT asymmetry. Consider the rotating nucleus emitting electric dipole quanta. Their angular distribution without rotation should be (19):

$$P(\theta) = B \sin^2\theta, \tag{39}$$

where θ is the angle between the nuclear symmetry axis and the direction of the gamma emission. However the nucleus rotates with the angular velocity $\omega \approx 2 \cdot 10^{19}$ 1/s while emitting the pre-scission quanta and manages to turn since the initial moment of this emission through the angle:

$$\theta_0 = \omega\tau + \alpha \quad , \tag{40}$$

where τ is the pre-scission gamma emission time and α is the rotation angle of the system after scission, which was estimated in [4] as $\alpha \approx 3 \cdot 10^{-3}$. Therefore the angular distribution for the rotating nucleus in the laboratory system is:

$$P_{\pm}(\theta) \approx B \sin^2[\theta \pm (\omega\tau + \alpha)] \approx B\{\sin^2\theta \pm (\omega\tau + \alpha)\sin 2\theta\} \ . \tag{41}$$

Here the subscript $\pm$ defines the polarized neutron helicity (i.e. the direction of nuclear rotation). Therefore the numerator of the asymmetry coefficient D_γ is:

$$P_+(\theta) - P_-(\theta) = B(2\omega\tau + 2\alpha)\sin 2\theta \ . \tag{42}$$

Taking the emission time of the GDR gammas to be $\tau \approx \hbar/\Gamma \approx 10^{-21}$ s, we obtain

$$(2\omega\tau + 2\alpha) \approx 4 \cdot 10^{-2} \ . \tag{43}$$

Dividing this quantity by twice the number of statistical gammas one obtains for the magnitude of the ROT asymmetry effect the value $B \cdot 2.5 \cdot 10^{-3}$.

The analysis [10] of gamma spectrum following the ^{235}U fission by thermal neutrons shows that the number *B* of quanta per fission in the range of E_γ=4-6 MeV is about 0.1. This seems to be in agreement with the experimental value 10^{-4} obtained in ref. [8].

6. Summary

Our studies of the possible T-odd asymmetry for the pre-scission gammas carried in the framework of the quantum theory of fission allow to obtain the angular dependence and the magnitude of the asymmetry coefficient D_γ in agreement with experiment [8]. In order to make the final conclusions about the existence of the pre-scission quanta one should investigate the possibility to obtain the T-odd correlation with the statistical quanta, its magnitude and angular dependence.

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Ректорат Воронежского государственного университета разрешает публикацию в материалах семинара следующего доклада:

THE MECHANISM OF EXCITATION OF GIANT RESONANCES IN NUCLEAR FISSION AND T-ODD CORRELATIONS FOR PRESCISSION GAMMA-QUANTA

V.E. Bunakov, S.G.Kadmensky, S.S.Kadmensky (8 c.)

Ректор ВГУ, профессор В.Т. Титов