STUDY OF P-EVEN TIME REVERSAL NONINVARIANT AMPLITUDE IN (n, $\gamma\alpha$)-REACTIONS

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Abstract. The experimental study of the five-vector correlation $(\boldsymbol{k}_\alpha\cdot[\boldsymbol{k}_\gamma\times\sigma_n])(\boldsymbol{k}_\alpha\cdot\boldsymbol{k}_\gamma)$ of the products of (**n**,$\gamma\alpha$)–reaction on a light nucleus is proposed as a tool of search for P–even T–noninvariant effect.

Introduction

Previous measurements of parity conserving (P–even) time reversal (T–noninvariant) violation effect in nuclear processes both direct [1] and using correlation methods [2] result in rather high upper limits of the ratio of such effect to symmetry conserving one. First mentioned type of the experiments provide the value of this ratio about 10^{-2} and the other one – of about 10^{-3}. Reinterpretation [3] of the results of the measurement [1] on the basis of Bayesian statistical approach brings the lower value of the upper limit $\sim10^{-3}$. Recent-day study of the effect based on Moessbauer approach [4] decreased this limit up to the 10^{-4} level. Even this result does not approach the estimates of the effect provided by all reasonable theoretical predictions in the framework of the standard model. At the same time some of approaches which are irrelevant to the standard model predict T–noninvariant effects close to these values. Therefore search for another experimental methods aimed at setting of the discussed limit, using neutron beam in particular, remains a vital issue.

In the present talk we propose the experimental study of five-vector correlation $(\boldsymbol{k}_\gamma\cdot[\boldsymbol{k}_\alpha\times\sigma_n])(\boldsymbol{k}_\gamma\cdot\boldsymbol{k}_\alpha)$ of the spin of the polarized projectile σ_n and the linear momenta of the products of (**n**,$\gamma\alpha$)–reaction on a light nucleus $\boldsymbol{k}_\gamma$ and $\boldsymbol{k}_\alpha$ as a method of search for P–even T–noninvariant effect. This approach is a simple modification of the scheme presented in [5] for measurement of P–odd T–noninvariant effect using the same beam. In that talk the ($\alpha\gamma$)–correlation of the products of the reaction $^{10}B(n,\alpha_1\gamma)^7Li$ namely $(\sigma_n[k_\alpha \times c_\gamma])$, where c_γ – the circular polarization of the γ-quantum, was proposed as a tool of study PT–noninvariance.

Formalism

In the discussed case T–noninvariant effect in a γ-transition is investigated and a subsequent α-transfer is used as an analyzer. The opposite case in which T–noninvariant α-transfer amplitude is considered seems to be much more complicated in comparison with the proposed one because phases of T–invariant α-amplitudes are different from Nπ/2 (see a more sophisticated discussion bellow). So let us consider angular correlations in γα-cascade I→γ→J→α→F. The distribution of the products takes the form [6]:

$$W_{IJF}(\theta_\gamma,\theta_\alpha,\phi_\gamma,\phi_\alpha)=\sum \rho_j^m(I)\,\hat{F}\,\varepsilon_{j_\gamma}^{m_\gamma}*(L_\gamma p_\gamma,L'_\gamma p'_\gamma)\,\varepsilon_{j_\alpha}^{m_\alpha}*(L_\alpha L'_\alpha)\,\hat{I}^2\hat{J}^2$$

$$(j_\gamma m_\gamma j_\alpha m_\alpha|jm)\begin{Bmatrix} J & L_\gamma & I \\ J & L'_\gamma & I \\ j_\alpha & j_\gamma & j \end{Bmatrix}\begin{Bmatrix} F & L_\alpha & J \\ F & L'_\alpha & J \\ 0 & j_\alpha & j_\alpha \end{Bmatrix}\hat{j}_\gamma\hat{j}_\alpha^2\langle J|L'_\gamma p'_\gamma|I\rangle*\langle J|L_\gamma p_\gamma|I\rangle$$

$$\langle J|L'_\alpha|F\rangle*\langle J|L_\alpha|F\rangle. \qquad (1)$$

Here $\rho_j^m(I)$ – the component of the orientation tensor of the initial state, $\langle J|L_\gamma p_\gamma|F\rangle$ and $\langle J|L'_\gamma p'_\gamma|F\rangle$ -- amplitudes of electromagnetic transitions of $L_\gamma p_\gamma$ and $L'_\gamma p'_\gamma$ multipolarities, $\langle J|L_\alpha|I\rangle$ and $\langle J|L'_\alpha|I\rangle$ -- respective α-decay amplitudes. The notation $\hat{b}=\sqrt{2b+1}$ is used, other notations of the elements of Wigner-Racah algebra are conventional. The summation should be extended over all indexes contained in the expression (1) besides I, J, F.

The origin of polarization (the orientation characterized by the tensor of the rank j = 1) in the proposed scheme is a polarized neutron beam. Let us choose z-axes to be parallel to the direction of neutron polarization. In this condition if S-resonance polarized neutron absorption is dominating the components of the polarization tensor have the form:

$$\rho_{j=0}^0(I)=(-1)^{A-I-1/2}\,\hat{I}^2/(\sqrt{2}\hat{A}^2)W(\tfrac{1}{2}I\tfrac{1}{2}I;A0)\,\langle I|n|A\rangle\langle I|n|A\rangle*=$$

$$\hat{I}/(2\hat{A}^2)\,\langle I|n|A\rangle\langle I|n|A\rangle^*;$$

$$\rho_{j=1}^0(I)=(-1)^{A-I+1-1/2}\,\hat{I}^2/(\sqrt{2}\hat{A}^2)p_nW(\tfrac{1}{2}I\tfrac{1}{2}I;A1)\,\langle I|n|A\rangle\langle I|n|A\rangle*, \qquad (2)$$

where $\langle I|n|A\rangle$ – the amplitude of the resonance neutron absorption, $W(\frac{1}{2}I\frac{1}{2}I;A1)$ – Racah symbol, A – target spin, p_n – the degree of neutron polarization.

For simplicity let us consider the magnitudes characterizing the geometry of the detectors to be equal to unity in the following expressions: $Q_\gamma(1)$, $Q_\alpha(1)$ =1.

The efficiency tensor of γ-transition in this condition has the form:

$$\varepsilon_{j_\gamma}^{m_\gamma}(lp,l'p')=(1/16\pi)(-1)^{l'-1}\hat{l}\hat{l}'(l1l'-1|j_\gamma 0)[S(0)+S(3))+(-1)^f(S(0)-S(3))] \\ (\sqrt{4\pi}/\hat{j}_\gamma)Y_{j_\gamma}^{m_\gamma}(\vec{k}_\gamma), \tag{3}$$

where $S(k)$ is a Stokes parameter and $f=(p-p')/2-j_\gamma$. According to the formula (3) for γ-transition taking place under the condition of parity conservation a study of the efficiency tensor of the first rank (j_γ=1) requires the measurement of the circular polarization. To circumvent this difficulty it is preferable to study second-rank (j_γ=2) tensor.

Analogous efficiency tensor for α-transfer can be expressed as:

$$\varepsilon_{j_\alpha}^{m_\alpha}(ll')=(1/4\pi)\hat{l}\hat{l}'(l0l'0|j_\alpha 0)(-1)^{l'}(\sqrt{4\pi}/\hat{j}_\alpha)Y_{j_\alpha}^{m_\alpha}(\vec{k}_\alpha). \tag{4}$$

For P–conserving level-to-level α-transfer the parity of the values l and l' is one and the same. Therefore due to the properties of the Clebsh-Gordan coefficient in (4) j_α – even, so minimal value $j_\alpha = 2$ is required for the discussed purposes.

For the chosen number of tensors the symmetry properties of the first 9j-symbol of the expression (1) and phase $(-1)^{L'_\gamma}$ contained in the expression (3) result in annihilation of the correlation if the product $\langle J|L'_\gamma p'_\gamma|I\rangle * \langle J|L_\gamma p_\gamma|I\rangle$ does not change sign under the permutation $L'_\gamma p'_\gamma \leftrightarrow L_\gamma p_\gamma$. In other words this product must contain a nonzero imaginary part for the correlation to be surviving. If the effect of T–invariance violation takes place, the respective electromagnetic amplitude can be parametrized in the form:

$$\langle J|L'_\gamma(t)|I\rangle = \langle J|L'_\gamma|I\rangle\ e^{i\nu}, \tag{5}$$

where $\langle J|L'_\gamma|I\rangle$ is ordinary electromagnetic amplitude possessing the phase 0, π or π/2 and ν – T–noninvariant phase shift. Due to this shift the correlation under discussion turns out to be nonzero. There exists, however, another origin of the correlation namely finite state interaction (T–invariant) of γ-quanta with the electrons of atomic shells resulting in absorption and so giving rise to certain phase shift. This effect is measurable in independent experiments with rather high precision and the limit on the measurability of the T–noninvariant effect set by this interaction is approximately equal to this precision.

It should be noted here that if T–violating effect in α-transfer but not in γ-transition is investigated the final state interaction of the α-particle with the core play the same role as the mentioned absorption. The respective phase shift β depends on both nuclear and Coulomb interaction. If the process is deeply subbarrier the Coulomb phase shift the value of which is known is dominating. Total (Coulomb + nuclear) phase shift is measurable in independent experiments. Nevertheless the effect appearing due to this phase shift is rather large and give rise to the detectable background.

The form of angular correlation is determined by Y–functions contained in the formulas (3) and (4). The angular-dependent part of the discussed expression can be rewritten as:

$$\sum_{m=-2,-1,1,2} (2m2-m|10)(\sqrt{4\pi}/\hat{2})Y_2^m(\vec{p}_\gamma)(\sqrt{4\pi}/\hat{2})Y_2^{-m}(\vec{k}_\alpha)=$$

$$\sum_{m=1,2} (2m2-m|10)2\mathrm{Im}\{(\sqrt{4\pi}/\hat{2})Y_2^m(\vec{p}_\gamma)(\sqrt{4\pi}/\hat{2})Y_2^{-m}(\vec{k}_\alpha)\}=$$

$$(3/2\sqrt{10})\{(1/2)\sin(2\theta_\gamma)\sin(2\theta_\alpha)\sin(\phi)+\sin^2(\theta_\gamma)\sin^2(\theta_\alpha)\sin(2\phi)\}, \qquad (6)$$

where ϕ is the azimuth between $\hat{k}_\gamma$ and $\hat{k}_\alpha$. Thus two correlations contribute the angular distribution. Second of them possesses the larger norm and, in addition, looks more illustrative. It is this correlation is formally denoted as $(k_\gamma[k_\alpha \times \sigma_n])(k_\gamma k_\alpha)$. What about the first one it is possible that in certain cases the measurement of it would be preferable for some reasons. Besides, in case if not only two lowest multipolarities (M1 and E2 or E1 and M2) play a significant role in the γ-transition, the tensors of higher rank ($j_\gamma = j_\alpha = 4, 6, \ldots$) contribute to the angular distribution. Nevertheless in the present work we restrict our consideration to the second correlation presented in (6) only. The form of the correlation unambigously determines the optimal arrangement of the axises of detectors. The axises must be perpendicular to the direction of the neutron spin and the angle between them must be π/4. So there are only two distinctions between this experimental scheme and the scheme of the paper [5]: in the latter case the azimuth is π/2 and the detector sensitive to the circular polarization is required. The reactions which are optimal for producing γα- and αγ-cascades are however different, therefore the experimental conditions are also different for these two cases. We discuss the peculiarities of the proposed scheme in the next chapter.

Experimental conditions

It is important to note that γα-cascades are exotic processes for neutron induced reactions. Their cross sections are not large. Furthermore high precision geometry which is required for angular correlation measurements and the necessity of using a think target to detect emitted α-particles do not allow the operations with a large sample. Realistic limitation of its parameter are: the area $S \le 1cm^2$, the thickness 2 – 4 μm, and thus the number of atoms of about 10^{19}. This circumstances determine the requirements to an experimental setup in the most part. It is obvious that the efforts should be mounted to make the statistics as much as possible. For these purposes it is necessary to use the powerful source of thermal polarized neutrons. The maximal existing beam flux is about $\sim 10^9$ neutrons/cm^2·sec. The solid angle of a single γ- or α-detector is $\Omega_{\gamma(\alpha)} \sim 10^{-1.0(1.5)}$, therefore taking into account the nonunit efficiency of γ-detector ξ the registration capability of two-γ two-α-detector scheme could not be higher than $\xi\Omega_1,\Omega_2 \sim 10^{-3}$.

Assuming that the cross section of (n,γα)–reaction is 1b one can conclude that the number of cascades producing by a powerful beam in the sample would be 10^4 and the counting rate of the discussed above scheme would be 10^1.

This value demonstrates that the requirements to the time resolution of the detectors and the coincidence system are not rigid if the sample is not extraordinary source of γ- or α-radiation unrelated to the discussed cascade.

Let the beam time be very long $T \sim 10^7$. In this case the upper limit of the effect could be set at the level 10^{-4}. An array containing some tens of the presented schemes may be created to use larger part of the beam intensity. It does not seem to be too expensive. Such a setup could decrease the upper limit almost by one order of magnitude.

Problem of optimal target

As it is pointed out above γα-cascades are poorly known and their cross sections are rather small in neutron induced reactions. Therefore the basic problem of the discussed approach to the study of P–even T–noninvariant amplitudes is to find a convenient target. The cross sections are known for very few cases [7]. Among them the example of ^{33}S seems to be reasonable for our purposes. Here the cross section of the cascade of interest is $\sigma(n,\gamma\alpha) =$ 1.7 mb, spin of the initial state is $I^\pi = 2^+$, spin of the intermediate state takes the value $J^\pi = 2^+$ compatible with the required tensor ranks $j_\gamma = j_\alpha = 2$, optimal multipolarities M1 and E2 are dominating in the γ-transition, the energy yield $Q_{n\alpha} = 3.5$ MeV does not present obstacles for the experiment.

Evidently the cross section of this process by three orders of magnitude lower than ideal one discussed in the previous chapter. So one can expect that the upper limit of about 10^{-3} is attainable for the discussed example. Thus the proposed cascade in ^{34}S compound nuclei turned out to be incompatible with γγ-cascade in ^{36}Cl compound nucleus investigated in the work [2]. The equivalent result was achieved there in the conditions being far short of listed above ideal ones. Remeasuring of this γγ-cascade by use of modern equipment would be essentially more promising than the reaction with ^{33}S nucleus.

Consequently the prospects of the proposed correlation depend on a result of search for a promising target. It may be a subject of special-purpose investigation. Lightest nuclei seem to be more interesting from this viewpoint because, first, the probabilities of α-particle emission are larger in such cases. Second, it is relatively simple systems with the spectra of low density, therefore it is more easy to isolate a certain cascade experimentally and to consider the effect theoretically.

First feasible example is ^{6}Li target. The spin of the initial state is $I^{\pi} = 1/2^{+}$ here. The sole possible variant of the intermediate level J of γα-cascade in ^{7}Li compound nucleus is $5/2^{-}$ $E^* = 6680$ keV one, the energy yield $Q_{n\alpha} = 4.8$ MeV so, on one hand, one deals with a near barrier α-emission and, on the other hand, mixing multipolarities are M2 and E3 here. The first circumstance makes the cross section larger, the second one suppresses it. The experimental value of the cross section of the (**n**,γα)–reaction here is not known probably due to the very large cross section of photonless α-emission producing a strong background.

Another example is the ^{7}Be target. The spin of the initial state is $I^{\pi} = 2^{-}$. Photonless α-emission is strongly forbidden by parity conservation law therefore all α-particles appear in the γα-cascades. There are two levels 2^{+} possess a large α-decay width in compound nucleus ^{8}Be: $E^* = 16626$ keV and 16992 keV. The γ-transitions between initial state and these levels are observed. This circumstances make the example very interesting. In addition the energy yield of the reaction takes unique value $Q_{n\alpha} = 18.9$ MeV. High energy of the γ-transitions allows one to get rid of final state interaction in fact entirely. High energy of α-particles makes natural α-background insignificant. Recently the $10^{16.5}$-atom ^{7}Be samples are produced and 10^{18}-atom ones are expected (U.Koester, CERN) thus it is possible to make the ^{7}Be target large enough. The sole disadvantage of the example is that E1 + M2 but not M1 + E2 mixture contributes here to the T–noninvariant γ-amplitude. Obviously this property makes T–noninvariant effect essentially smaller at one and the same given value of the phase ν.

In these examples preliminary measurement of α-spectra is necessary. These measurements may reveal continuous (non-resonance, direct) component of the spectra. Although internal bremsstrahlung in α-decay of lightest nuclei is extremely weak, another, so-called disentangle radiation appearing, as it is proved in [8], due to the amplitude M of direct γ-transition from discrete energy level (it may be a resonance state of a nucleus or even a ground state of a heavy nucleus if energy conservation law fulfilled) characterized by a wave function $|\Psi^{J^\pi}{}_{discrete}\rangle$ to the continuum state of the relative motion of α-particle and a daughter nucleus characterized by a wave function $|\Psi^{E,J^\pi}_{continuum}(\rho)\rangle$:

$$M = \left\langle \Psi^{E,J^\pi}_{continuum}(\rho) \,|\, \hat{H}_\gamma \,|\, \Psi^{J^\pi}{}_{discrete} \right\rangle. \tag{7}$$

This mechanism of γ-emission is much different from the mechanism of ordinary bremsstrahlung because it is independent on photonless α-decay process and may occur when this process is forbidden as it is in ^{8}Be 2^- level. In addition the form of the spectra of these two types of radiation bear no resemblance to each other. Evidently multipolarities of all kinds are presented in the direct mechanism therefore it is easy to find the most convenient mixture M1 + E2. For the first presented example of ^{6}Li target one needs $J^\pi = 3/2^+$ continuum, for the second example of ^{7}Be target – $J^\pi = 1^-$ one. To use such cascades perhaps even preferable than resonance ones, for ^{7}Be in particular, because the ratio of the direct and the resonance amplitudes here is relatively large due to the possibility to work with γ-radiation of extremely high energy produced by direct mechanism.

Evidently the study of disentangle radiation is of its own significance.

Conclusion

All discussed above allows us to conclude the following.

1.Measurement of γα-correlations in neutron induced reactions are interesting tool for investigation of P–even time reversal noninvariance.

2.The lightest nuclei are preferable for the proposed investigations.

3.It is convenient to study both PT–, and T–nonivariant effects contemporaneously in one and the same research program.

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