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Search for P-odd time reversal noninvariance in nuclear processes

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Abstract. The scheme of search for time reversal noninvariance in nuclear processes based on the measurement of linear polarization of gamma radiation of a sample aligned by a preceding nuclear decay or by cryogenic means is presented.

PACS. 11.30.Er Charge conjugation, parity, time reversal, and other discrete symmetries

Time reversal noninvariant (T-violating) terms are contained in the standard model. However, twofold suppression of the simultaneous parity and time reversal (PT-) violation effect in all processes besides purely weak ones makes the effect extremely small. Therefore even the detection of a very small PT-violating correlation produced by NN-interaction is a sign of the effect falls beyond the standard model.

If one assumes that PT-violation effect reveals itself mainly in nucleon-meson $N \to N + \pi$ vertex than it is possible to estimate upper limits to PT-violating π-meson constants $g_{pt}^{\Delta T}(\pi)$ determined by the electric dipole moment (EDM) of neutron measurements [1,2,3]:

$$g_{pt}^{\Delta T}(\pi) \leq \left\{ \begin{array}{cc} 1.4 \cdot 10^{-11}, & \Delta T = 0 \\ 1 \cdot 10^{-10}, & \Delta T = 1 \\ 1.4 \cdot 10^{-11}, & \Delta T = 2 \end{array} \right\}, \qquad (1)$$

where the value ΔT denotes the isospin change.

Thus to set an upper limit on isovector PT-violating amplitude W_{pt} being of order 10^{-3} of a measured P-odd one would be a vital issue. The PT-violation effect manifesting in nuclear processes possess the isospin structure other than that producing the EDM of neutron. Therefore even a larger value of this limit ($10^{-1.5}$–10^{-2}) could provide an important information. Moreover the nuclear processes are promising tools for the investigation of PT-violation because the isovector constant $g_{pt}^{1}(\pi)$ is anticipated to be dominating in this case. In addition there are the mechanisms of enhancement of PT-violation effect in such processes analogous to those of P-violation one.

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Performed experiments devoted to attacking the discussed problem are few in number. Up to now the most reliable is the measurement of PT-noninvariant $(\boldsymbol{k}_{\gamma_2}\boldsymbol{J})(\boldsymbol{k}_{\gamma_1}[\boldsymbol{k}_{\gamma_2} \times \boldsymbol{J}])$ correlation in the γ-cascade of the oriented ^{180m}Hf 1142 keV state (here $\boldsymbol{k}$ is the vector of the direction of the respective linear momentum, $\boldsymbol{J}$ is the vector of the alignment) [4]. The upper limit of the ratio of the discussed amplitude to the value of P-odd one measured before in this transition $W_{pt}/W_p \leq 1$ was obtained.

Unfortunately, the most popular subject of discussions namely the $\boldsymbol{\sigma}[\boldsymbol{k} \times \boldsymbol{J}]$ correlation in $\boldsymbol{n} + {}^{139}$La collision which could result in the upper limit of the ratio $W_{pt}/W_p \leq 10^{-4}$ [5] remains planned experiment only.

Thus, new approaches seem to be desirable.

In the present work a widespread analysis of approaches of this type is performed. There are many methods of attack. According to our estimates the scheme based on the measurement of the linear polarization of gamma radiation $\boldsymbol{\epsilon}$ of a sample aligned by cryogenic means or by a preceding decay seems to be optimal. It should be noted that the linear polarization measurements of the PT-violation effect were already performed in [6] but in the combination with the Mössbauer method of orientation.

Let us consider a single γ-transfer in an aligned sample $I \to J$ or an $\alpha\gamma$-cascade $I_0 \to I \to J$ and characterize the relative directions of the three vectors by the Euler angles θ, ϕ, and ψ determining the coordinate system x', y', z' (z'-axis is the direction of the photon emission $\boldsymbol{k}_\gamma$, x' the direction of the vector $\boldsymbol{\epsilon}$, and the condition ($\boldsymbol{k}_\gamma \perp \boldsymbol{\epsilon}$) takes place) measured from the laboratory one where z-axis is the direction of the alignment (coinciding with the direction of α-emission $\boldsymbol{k}_\alpha$ in the second case) $\boldsymbol{J}$.

The PT-violating term of interest takes the form [7]

$$W_{pt}(\theta\psi) = 6^{-1/2} B_2(I) A_{22}(pt) \sin\psi P_2^{(2)}(\cos\theta), \qquad (2)$$

where $B_2(I)$ is the alignment *i.e.* the component of the orientation tensor of the rank 2 characterizing the level I, $P_2^{(2)}(\cos\theta)$ is the generalized Legendre polynomial. Naturally the term is independent of ϕ because this angle determines the rotation of the system as a whole. The spin-angular distribution coefficient has the form [7]

$$A_{22}(pt) = \sum_{ll'} (-1)^l \hat{l}\hat{l}' \hat{I}\hat{J}(l1l'1|22) \begin{Bmatrix} J & l & I \\ J & l' & I \\ 2 & 2 & 0 \end{Bmatrix} \sqrt{\Gamma_\gamma(pt)/\Gamma_\gamma}. \qquad (3)$$

Here Γ_γ is the amplitude of the respective γ-transition, l, l' are the multipole characteristics of γ-quanta, the three-line table is $9j$-symbol, and the notation $\hat{a} \equiv \sqrt{2a+1}$ is used. Expressions of the value $B_2(I)$ for both "cryogenic" and "decay" orientation method can be found in [7].

The choice of optimal angles to observe the correlation is evident from expression (2): $\theta = \pi/2$, $\psi = 3\pi/4$ and $\pi/4$.

Let us discuss the advantages of the schemes:

1. No beam machine is required.
2. A broad assortment of promising subjects —radionuclides which are rather easily obtainable and contain parity mixing doublets so that the strong "dynamic" enhancement of both P- and PT-violation effects is typical for them. The "structural" enhancement is not a rare case for the discussed nuclides.
3. The linear polarization measurement instead of the γ-γ detection makes the total efficiency of the experiment considerably larger.
4. Values of the spin factor appearing in the expression of PT-violating observable through the amplitude (the $W_{pt}(\theta\psi)$ through the $\sqrt{\Gamma_\gamma(pt)}$ in the discussed case) turns out to be essentially greater than those in just mentioned coincidence scheme.
5. The cross-shaped four-γ-detector setup enables one to get read of the most part of systematic errors.
6. Both schemes are inexpensive and labor-saving.

Comparing two possibilities one can conclude:

1. A polarization of a sample is not wanted in the "decay" version of the scheme unlike in the "cryogenic" one. No refrigerator is required.
2. The "decay" version is the simplest and the cheapest.
3. The cryogenic method of polarization results in higher counting rate because the coincidence scheme is necessary in the opposite case.

Evident way of search for PT-violation effect is to investigate an example used before to study P-odd one.

The parity violation effect is known for the following example of the $\alpha\gamma$-cascade:

$$^{241}\text{Am} \to {}^{237}\text{Np}\,(5/2^-, 59.5\ \text{keV}) \to {}^{237}\text{Np (g.s.)}.$$

The isotope ^{241}Am is reactor produced; the half-life time is $T_{1/2} = 232$ y; the contribution of the necessary α-transition to the total α-width $B = 84.5\%$ is large; the doublet splitting $\Delta E = 59.5$ keV is not small but there is a great structural enhancement $\sqrt{\Gamma_{\text{irreg}}/\Gamma_{\text{reg}}} \sim 10^3$. Resulting value of the circular polarization is $P_\gamma = (-1.23 \pm 0.25)10^{-3}$ [8], *i.e.* one can expect a strong enhancement of PT-violation effect in the process. The disadvantage of the discussed process is a large contribution of S-wave in the α-decay channel, in other words the angular momentum $L_\alpha = 0$ which is not capable to produce the alignment is allowed. Because of this the degree of the alignment of ^{237}Np sample decreases. Another obstacle to high-precision measurement of the discussed effect in this case is the use of low-energy γ-transition resulting in the false effect of γ-e_{atomic} final-state interaction. However, this effect is measurable in independent experiments with a rather high precision. Moreover it is a pure P-even one. Therefore a PT-simulating correlation is generated in the discussed scheme by P-odd amplitudes only. In many cases these two properties make it possible to subtract the false effect from the measured value with an accuracy which is superior to the potentiality of the "decay" scheme.

Promising variants of the $\alpha\gamma$-cascade are legion. In addition the $\beta\gamma$-cascade can be used for the same purposes. However, first-order forbidden β-transition with $\Delta J = 2$ is necessary in this case.

The "cryogenic" variant of the scheme can be used for the study of the above-mentioned example of the isomeric transition of $^{180\text{m}}$Hf [4]. Two lines:

$$^{180}\text{Hf}\,(8^-, 1141.5\ \text{keV}) \to {}^{180}\text{Hf}\,(8^+, 1083.9\ \text{keV}) \quad \text{and}$$
$$^{180}\text{Hf}\,(8^-, 1141.5\ \text{keV}) \to {}^{180}\text{Hf}\,(6^+, 840.9\ \text{keV})$$

are the subjects of interest. The isomer is reactor produced; the half-life time is $T_{1/2} = 5.5$ h; the branching ratios are $B1 = 51.0\%$ and $B2 = 15.2\%$, respectively; the doublet splitting and the structural enhancement are $\Delta E = 57.5$ keV and $\sqrt{\Gamma_{\text{irreg}}/\Gamma_{\text{reg}}} \sim 10^7$, respectively. The P-odd effect is measured and turns out to be extremely large: $P_\gamma = (-2.3 \pm 0.6)10^{-3}$ for 57 keV γ-line [9] and $A_\gamma = (-1.66 \pm 0.18)10^{-2}$ for 501 keV γ-line [10], respectively. Estimates demonstrate that there is a possibility to create a setup which offers a way to achieve the upper limit of the ratio $W_{pt}/W_p \le 10^{-3}$. The problem of the false effect is in this case a subject of special investigations.

There are many isomers and β-sources of delayed γ-transitions promising for using in the "cryogenic" scheme.

We consider presented examples as good ones but in our opinion search for processes which are superior to just-mentioned should be continued.

So presented approach to PT-violation problem looks viable.

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References

1. P. Herczeg, Hyperfine Interact. **75**, 127 (1992).
2. P. Herczeg, *Tests of Time Reversal Ivariance*, edited by N.R. Robertson, C.R. Gould, J.D. Bowman (World Scientific, Singapore, 1987) p. 24.

3. I.S. Towner, A.C. Hayes, Phys. Rev. C **49**, 2391 (1994).
4. B.T. Murdoch *et al.*, Phys. Lett. B **52**, 325 (1974).
5. Y. Masuda, *Time Reversal Ivariance and Paruty Violation in Neutron Reactions*, edited by C.R. Gould, J.D. Bowman, Yu.P. Popov (World Scientific, Singapore, 1993) p. 126.
6. V.G. Tsinoev *et al.*, Phys. At. Nucl. **61**, 1357 (1998).
7. R.M. Steffen, K. Adler, *The Electromagnetic Interaction in Nuclear Spectroscopy*, edited by W.D. Hamilton (North-Holland, Amsterdam, 1975) p. 505.
8. L.V. Inzhenchik *et al.*, Phys. At. Nucl. **51**, No. 2, 391 (1990).
9. E.D. Lipson *et al.*, Phys. Lett. B **35**, 307 (1971).
10. K.S. Krane *et al.*, Phys. Rev. C **4**, 1906 (1971).