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T-ODD, P-EVEN PHOTON-FERMION INTERACTIONS

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ABSTRACT

General structure of T-odd, P-even photon-fermion scattering amplitude is discussed. The corresponding operators are of high dimension. Therefore the experimental data on the high-energy cross-sections bound the effective constants so strictly that the possible manifestations of these interactions in the low-energy region are extremely small.

1. New upper limits on the T-odd, P-even (TOPE) electron-electron, electron-nucleon and nucleon-nucleon interactions, as well as on some β-decay parameters, were obtained recently in refs. [1–3] by transforming these interactions via P-odd part of the electroweak radiative corrections into T-odd and P-odd ones. The experimental information about T-odd, P-odd effects is so rich that the obtained limits are much better than those known previously.

Here we will obtain upper limits on possible TOPE photon interactions. As to TOPE one-photon vertex, simple analysis (see, e.g., ref. [4]) demonstrates that in the case of spin 1/2 there is no such vertex at all. And for an arbitrary spin any C-odd one-photon vertex, both P-odd and P-even, is necessarily of a contact nature.

Let us go over therefore to TOPE electromagnetic amplitudes of photon-fermion scattering, to two-photon interaction, or Compton one. A standard analysis (see, e.g., ref. [5]) demonstrates that there are two such amplitudes, nonvanishing for real photons. Below we will present a derivation which not only allows one to find the number of those amplitudes, but to derive them in an explicitly gauge-invariant form. This form seems to be more convenient, at least, for our purposes, than the standard one presented in ref. [5].

It is convenient to start from the annihilation channel $f\bar{f} \to 2\gamma$. The C-parity of the 2γ state is certainly positive. And since the interaction we are interested in violates the invariance under charge conjugation, the C-parity of the fermion-antifermion state should be negative.

At the vanishing total spin of the fermionic pair, $S = 0$, this means that its orbital angular momentum l should be odd and the parity positive, $P = +$. But at $l = 1$ the total angular momentum of a singlet state is $J = 1$ which is impossible for two photons (see, e.g., ref. [5]). Thus, one possibility corresponds to the annihilation in the positive-parity singlet states with odd total angular momenta starting from $J = 3$.

At $S = 1$ the negative C-parity of the fermion-antifermion pair implies even l and, correspondingly, $P = -$. And again $l = 0$ leads at $S = 1$ to $J = 1$ which is forbidden. Since the two-photon states with odd J have necessarily positive parity, $P = +$ [5], the second possibility corresponds to the annihilation from the negative-parity triplet state with even total angular momenta starting from $J = 2$.

In the last case the amplitude is more simple and looks as follows:

$$\gamma_5[\gamma_\mu(p'-p)_\nu + \gamma_\nu(p'-p)_\mu](k'-k)_\mu(k'-k)_\nu F_{\alpha\beta}\tilde{F}_{\alpha\beta}. \qquad (1)$$

Here p and p' are the momenta of the annihilating electron and positron respectively, k and k' are those of the photons, $\tilde{F}_{\alpha\beta} = \frac{1}{2}\epsilon_{\alpha\beta\gamma\delta}F_{\gamma\delta}$. To go over to the scattering channel we have to change p' to $-p'$, and k' to $-k$. The interaction discussed is of a high dimension, ten, not only due to two photons participating, but first of all due to a large number of momenta, or derivatives, in it. The reason is that the angular momenta in the annihilation channel are high, starting from $J = 2$. Finally, the interaction discussed can be presented as

$$\frac{A}{8m_p^6}(\bar{\psi}\gamma_\mu\gamma_5 i\overleftrightarrow{\partial}_\nu\psi)(F_{\alpha\beta}\, i\overleftrightarrow{\partial}_\mu\, i\overleftrightarrow{\partial}_\nu \tilde{F}_{\alpha\beta}). \qquad (2)$$

We single out here a dimensionless constant A, taking as the necessary dimensional parameter the proton mass m_p. The symbol $\overleftrightarrow{\partial}$ is $\overleftrightarrow{\partial} = \overrightarrow{\partial} - \overleftarrow{\partial}$ where the derivatives $\overrightarrow{\partial}$ and $\overleftarrow{\partial}$ are acting to the right and to the left, respectively. The annihilation from higher even angular momenta can be described by making A momentum-transfer dependent.

As to the amplitude corresponding to the annihilation from the singlet state and starting from $J = 3$, its fermionic part should be evidently

$$i\gamma_5 P_\kappa P_\lambda P_\mu;\ P_\kappa = (p'-p)_\kappa.$$

Then one should guarantee the Bose-statistics, the symmetry of the interaction under the permutation of the photons in the annihilation channel. In this way we come to the following form of the operator discussed:

$$\frac{B}{16m_p^9}(\bar{\psi}i\gamma_5 i\overleftrightarrow{\partial}_\kappa\, i\overleftrightarrow{\partial}_\lambda\, i\overleftrightarrow{\partial}_\mu\psi)(i\partial_\rho F_{\kappa\sigma}\, i\overleftrightarrow{\partial}_\mu\, i\partial_\sigma\tilde{F}_{\lambda\rho}). \qquad (3)$$

The dimension of this operator, thirteen, is even higher than that of the previous one. That is why we have to introduce the factor m_p^{-9} at the dimensionless constant B.

Now one can easily obtain possible three-photon TOPE fermion amplitudes. It is achieved by introducing into (2), (3) the extra "factor" $\sigma_{\gamma\delta}F_{\gamma\delta}$. Then one has to single out independent spinorial structures and to introduce, if necessary, the factor i to make the operator hermitian. In this way we get

$$[\bar{\psi}\gamma_5(\gamma_\mu i\overleftrightarrow{\partial}_\nu + \gamma_\nu i\overleftrightarrow{\partial}_\mu)\psi]F_{\mu\lambda}(F_{\rho\sigma} i\overleftrightarrow{\partial}_\lambda\, i\overleftrightarrow{\partial}_\nu\tilde{F}_{\rho\sigma}), \qquad (4)$$

$$[\bar{\psi}(\gamma_\mu i\overleftrightarrow{\partial}_\nu + \gamma_\nu i\overleftrightarrow{\partial}_\mu)\psi]\tilde{F}_{\mu\lambda}(F_{\rho\sigma} i\overleftrightarrow{\partial}_\lambda\, i\overleftrightarrow{\partial}_\nu\tilde{F}_{\rho\sigma}), \qquad (5)$$

$$(\bar{\psi}i\sigma_{\alpha\beta} i\overleftrightarrow{\partial}_\kappa\, i\overleftrightarrow{\partial}_\lambda\, i\overleftrightarrow{\partial}_\mu\psi)\tilde{F}_{\alpha\beta}[(i\partial_\rho F_{\kappa\sigma})\, i\overleftrightarrow{\partial}_\mu(i\partial_\sigma\tilde{F}_{\lambda\rho})]. \qquad (6)$$

A technical remark: one can get rid of tildes in (5), (6), but then the expressions become less compact.

Interactions (4) and (5) describe TOPE amplitudes of the three-photon annihilation of a fermion-antifermion pair with even total angular momenta starting from $J = 2$ and of negative and positive parity, respectively. Expression (6) should be expanded into irreducible structures. It corresponds to the annihilation from the positive-parity states of any J starting from 2^+.

But what about the three-photon annihilation from the fermion-antifermion ground states $^1S_0$ and $^3S_1$? The triplet state is of the same negative C-parity, as the three-photon one, so for it there is no TOPE amplitude at all. The P-even interaction which could be responsible for the three-photon decay of parapositronium or π^0-meson, was pointed out long ago in ref. [6]. In our notations it is

$$(\bar{\psi}i\gamma_5\psi)\partial_\alpha\tilde{F}_{\rho\sigma}\partial_\beta\partial_\gamma F_{\rho\sigma}\partial_\gamma F_{\alpha\beta}. \qquad (7)$$

One more operator of the type discussed can be obtained from the anapole interaction by multiplying it by $F\tilde{F}$. But in this case one of the three photons cannot be real, and we will not consider here the interactions of this kind.

2. Let us go over now to the TOPE photon-fermion interaction in an atom, confining ourselves to amplitude (2) which is of the lowest possible dimension. We will consider the case when one of the field strengths refers

to the interatomic Coulomb field and so we are dealing with a TOPE one-photon emission or absorption amplitude. If the interaction discussed refers to electron, the amplitude is reduced to

$$-4A_e\frac{m_e^2}{m_p^6}i\omega Z\mu\sigma_m[\delta_{mn}\frac{4\pi}{3}\delta(\mathbf{r})-\frac{3r_mr_n-\delta_{mn}r^2}{r^5}]B_n. \quad (8)$$

Here $\mu=|e|/2m_e$ is the Bohr magneton, Z is the nuclear charge, ω and $\mathbf{B}$ are the frequency and magnetic field of the emitted photon. We have taken into account here that the interaction is concentrated at short distances, so the Coulomb field is essentially that of an unscreened nucleus.

When dealing with the photon-nucleon interaction, the analogous emission amplitude is

$$2A_p\frac{1}{m_p^4}i\omega\mu^N\sigma_m^N[\delta_{mn}\frac{4\pi}{3}\delta(\mathbf{r})-\frac{3r_mr_n-\delta_{mn}r^2}{r^5}]B_n. \quad (9)$$

where $\mu^N=|e|/2m_p$ is the nuclear magneton. The explanation of the extra factor $-1/Z$ as compared to the previous formula, is that here the electric field is created by one valence electron, but not by Z protons. An overall factor 2, instead of 4, can be traced back to a somewhat different nonrelativistic reduction.

3. It is only natural to assume that the deviations of the interactions discussed from the contact type start at least as high as a hundred GeV. Then even the consideration of their possible contributions to the high-energy total cross-sections allows one to get very strict upper limits on the TOPE constants. To demonstrate it let us consider the contribution σ_A of interaction (2) to the total cross-section of the two-photon annihilation of an electron-positron pair. Simple calculations give

$$\sigma_A=\frac{A^2}{3840\pi}\frac{s^5}{m_p^{12}} \quad (10)$$

where $s=4E^2$ is the total cms energy squared. Since the standard two-photon annihilation cross-section

$$\sigma_{2\gamma}=\frac{4\pi\alpha^2}{s}\log\frac{E}{m_e} \quad (11)$$

has been measured at $\sqrt{s}=91$GeV with the accuracy about 10% [7,8], we get

$$A<10^{-11}. \quad (12)$$

The total cross-section generated by interaction (3) is

$$\sigma_B=\frac{B^2}{1720320\pi}\frac{s^8}{m_p^{18}}. \quad (13)$$

In the same way we get the upper limit for the constant B:

$$B<10^{-16}. \quad (14)$$

At last, upper limits for the TOPE photon-quark interactions can be extracted from the experimental data on the $p\bar{p}$ scattering at $2E$ about 1 TeV. To this end we assume that the typical quark (antiquark) energy constitutes roughly 1/3 of the proton (antiproton) energy, so that total $q\bar{q}$ energy $2E_q$ is about 300 GeV. As an upper limit for the total cross-section induced by the TOPE interactions we will take 100 mb. It is close to the typical high-energy $p\bar{p}$ cross-section which varies slowly with energy, as distinct from the TOPE cross-sections. In such a way we get for the TOPE photon-quark constants the following limits:

$$A_q<10^{-9},\ B_q<10^{-15}. \quad (15)$$

The upper limits obtained do not leave much hope for the observation of the TOPE photon-fermion interactions in low-energy experiments. In particular, their manifestations are extremely small in atomic and nuclear transitions. For instance, the effective transitional magnetic moment induced by interaction (8) in atoms does not exceed $10^{-35}\mu$. A rough estimate for the TOPE nuclear M1 amplitude induced by the photon-nucleon interaction with the constant A_p is $A_pZ(m_\pi/m_p)^5$ in the units of the nuclear magneton $\mu_N=|e|/2m_p$. It does not exceed $10^{-16}\mu_N$ at $A_p\sim A_q$.

The evident weak point in the arguments of this section is the assumption of the contact behaviour of the TOPE amplitudes up to the energies about 100 GeV. Of course, the existence of a TOPE interaction which is cut off at much lower energies, does not look attractive from the theoretical point of view. However, such questions can be solved finally only by experiment.

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Т-четные, Р-нечетные взаимодействия фотонов с фермионами

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