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C, P, T ARE BROKEN: WHY NOT CPT?

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Abstract

Two pillars of discrete asymmetry are discussed: 1. the breaking of the corresponding symmetry at the basic level (that of the (effective) lagrangian), 2. the manifestation of an asymmetry at the level of the square of the modulus of the amplitude. The classification of possible types of symmetry breaking interactions leads us to the Procrustian CPT-cube. The subtleties of asymmetry manifestations are illustrated by simple examples.

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1 Introduction

C, P, and T symmetries are known to hold with very high accuracy for electromagnetic and strong interactions [1]. For weak interactions the 100% breaking of P and C was discovered in 1957 [1] - [6] and served as a cornerstone of electroweak theory [7].

The CP violation was discovered as a tiny (milliweak) effect in the decays of neutral kaons in 1964 [8] and recently in the decays of B mesons [9]. But we still do not know the mechanism of this violation.

T violation was explicitly proved for neutral kaons [10] in accord with CPT invariance [11] which remains unshaken in spite of improved precision of experimental tests and increased number of theoretical speculations.

As for gravity, it is difficult to suggest an experimental test of C, P, or T in a classical weak gravitational field [12] - [14], while effects of quantum gravity belong to the big bang which sets the arrow of time in the universe [15], or to the black holes.

In this talk I will not speak about gravity and will try to classify effects of violation of seven symmetries – C, P, T, CP, PT, TC, and CPT – in laboratory experiments.

The subject has a vast literature. I apologize for making no attempt to cover it. My aim is to suggest a simple mnemonic approach.

2 CPT-cube

Let us start by considering three orthogonal axes representing violation of C, P and T (Fig. 1).

Point 0 at the origin of coordinates corresponds to the interactions (terms of the effective lagrangian), which are C even, P even, T even, and hence CP even, PT even, TC even, and CPT even.

Point 1 corresponds to the interactions which are C odd, P even, T even, and hence CP odd, PT even, TC odd, and CPT odd.

Point 2: C even, P odd, T even, CP odd, PT odd, TC even, and CPT odd.

Point 3: C even, P even, T odd, CP even, PT odd, TC odd, and CPT odd.

As a result we have the first four vertices of the CPT-cube. Let us now consider the other four vertices (Fig. 2): three in the planes CP (point 4), PT (point 5), TC (point 6), and the last – outside these planes (point 7).

Point 4: C odd, P odd, T even, CP even, PT odd, TC odd, and CPT even.

Point 5: C even, P odd, T odd, CP odd, PT even, TC odd, and CPT even.

Point 6: C odd, P even, T odd, CP odd, PT odd, TC even, and CPT even.

Point 7: C odd, P odd, T odd, CP even, PT even, TC even, and CPT odd.

Thus for each of the seven transformations there are four even vertices and four odd.

For C: 0, 2, 5, 3 are even; 1, 4, 7, 6 are odd (the rear and front sides of the cube, correspondingly).

For P: 0, 3, 6, 1 are even; 2, 5, 7, 4 are odd (the left and the right sides, correspondingly).

For T: 0, 1, 4, 2 are even; 3, 6, 7, 5 are odd (the lower and upper sides¡ correspondingly).

For CP: 0, 4, 7, 3 are even; 1, 2, 5, 6 are odd (two vertical diagonal planes).

For PT: 0, 5, 7, 1 are even; 2, 3, 6, 4 are odd (two diagonal planes orthogonal to the page).

For TC: 0, 2, 7, 6 are even; 1, 3, 5, 4 are odd (two diagonal planes whose intersection is parallel to the page).

For CPT: 0, 4, 5, 6 are even; 1, 2, 3, 7 are odd (four diagonals of lower and upper planes).

3 C and P violation with CP conservation

Let us start with the interaction of V-A weak charged currents discovered in 1957.The products VV and AA belong to point 0, while the product VA – to point 4. The experimental manifestation of the latter is seen directly in the decay $K_1 \to 2\pi$, while of the former in the decay $K_2 \to 3\pi$, where K_1 and K_2 are C odd and C even superpositions of K^0 and $\bar{K}^0$:

$$K_1 = \frac{1}{\sqrt{2}}(K - \bar{K}) \ , \ \ K_2 = \frac{1}{\sqrt{2}}(K + \bar{K}) \ . \ (1)$$

As both are P odd (pseudoscalar), K_1 is CP even, while K_2 is CP odd.

The 2π in $J = 0$ state is C even, P even, and CP even. Hence the decay $K_1^0 \to 2\pi$ is C odd, P odd, but CP even. As for the state of 3π with $J = 0$, it is P odd independent of values of relative angular momenta l and L. The dominant state with $L = l = 0$ is C even. Therefore the corresponding decay $K_2^0 \to 3\pi$ is C even, P even and CP even.

The manifestation of VA (point 4) in the spin-momentum angular correlations in β-decay, decays of μ and τ leptons, semileptonic decays of mesons and nonleptonic decays of hyperons is impossible without interference with terms VV and AA (point 0) in the square of modulus of amplitude.

The same refers to the P violating and C violating correlations induced by neutral currents which were discovered in the 1970's.

All the above processes are mediated by virtual W and Z bosons. After the discovery of these bosons in the early 1980's a lot of experimental data has been collected on C and P violating asymmetries in their production and decay processes caused by interference of points 4 and 0.

4 CP and T violation

The discovery in 1964 of the 2π decays of the long-lived neutral kaons revealed that CP is violated. For almost three decades the effective interaction responsible for these decays was consistent with point 6: C – odd, P even, T odd transition in vacuum of K_2 into K_1, described by parameter ε:

$$K_S = K_1 + \varepsilon K_2 \, , \quad K_L = K_2 + \varepsilon K_1 \ . \quad (2)$$

The presence of ε in eqs.(2) leads to the conclusion that the probability of transformation of K into $\bar{K}$ during a time interval t is not equal to the probability of transformation of $\bar{K}$ into K

during the same time interval. This prediction of violation of time reversal was experimentally confirmed [10] only a few years ago.

Only recently a consensus has been reached on the value of another parameter, ε', describing the direct decay of K_2 into 2π (point 5, which is C even, P odd and T odd).

Point 5 is [illegible] also responsible for the dipole electric moments of such particles as neutron and electron the search for which up to now brought no positive evidence. (The term $\boldsymbol{\sigma}\mathbf{E}$, where $\boldsymbol{\sigma}$ represents the spin of the particle, while $\mathbf{E}$ electric field, is C even, P odd, T odd.)

Of special interest in connection with point 5 is the vanishingly small upper limit on the so-called θ term in QCD:

$$\mathcal{L}_\theta = \theta G_{\mu\nu} G_{\rho\sigma} \varepsilon^{\mu\nu\rho\sigma} \quad , \tag{3}$$

where $G_{\mu\nu}$ is the gluonic field tensor.

5 CP violating charge asymmetries

Both points 5 and 6 must manifest in charge asymmetries. Thus from eq. (2) it follows immediately that the widths of the semileptonic decays $K_L \to e^+\nu_e\pi^-$ and $K_L \to e^-\bar{\nu}_e\pi^+$ must be different, the effect being proportional to $2Re\varepsilon$ (point 6). Such charge asymmetry was measured for both electronic and muonic channels.

Another effect, caused by point 6, had been predicted by Okubo [16] before CP-violation was discovered, but is still beyond the reach of experiments. According to Okubo,

$$\frac{\Gamma(\Sigma^+ \to p\pi^0)}{\Gamma(\Sigma^+ \to n\pi^+)} \neq \frac{\Gamma(\bar{\Sigma}^- \to \bar{p}\pi^0)}{\Gamma(\bar{\Sigma}^- \to \bar{n}\pi^-)} \quad . \qquad (4)$$

In order to show how this effect appears let me remind that for amplitudes of both S and P waves the following equalities hold

$$A(\Sigma^+ \to p\pi^0) = \sqrt{\frac{2}{3}}A_3 - \sqrt{\frac{1}{3}}A_1 \ ,$$
$$A(\Sigma^+ \to n\pi^+) = \sqrt{\frac{1}{3}}A_3 + \sqrt{\frac{2}{3}}A_1 \ , \qquad (5)$$

where A_3 and A_1 are amplitudes for final states with isospin $T = 3/2$ and $T = 1/2$ correspondingly. Similar relations hold for antiparticles:

$$\bar{A}(\bar{\Sigma}^- \to \bar{p}\pi^0) = \sqrt{\frac{2}{3}}\bar{A}_3 - \sqrt{\frac{1}{3}}\bar{A}_1 \ ,$$
$$\bar{A}(\bar{\Sigma}^- \to \bar{n}\pi^-) = \sqrt{\frac{1}{3}}\bar{A}_3 + \sqrt{\frac{2}{3}}\bar{A}_1 \ , \quad (6)$$

For simplicity let us consider only S wave amplitudes. In doing so we do not lose generality because S and P waves do not interfere in the expressions for partial widths.

The moduli of isotopic amplitudes $|A|$, as well as the final state interaction phase shifts δ, are the same for particle and antiparticle, while the CP violating phases Δ have opposite signs. As a result we get inequality (4) if $\delta_3 \neq \delta_1$ and $\Delta_3 \neq \Delta_1$.

A similar reasoning was applied by Sakharov when in 1967 he addressed the problem of baryonic asymmetry of the universe. He assumed CP violation for baryon number violating processes in order to get different cross-sections for specific processes with nucleons and antinucleons [17]. The difficulties in working out a consistent theory of baryogenesis have directed theoretical thinking towards leptogenesis caused by CP-violation in leptonic sector, including neutrino oscillations.

6 Testing CPT

The faith in CPT invariance is based on quantum field theory, in particular on locality and hermiticity of lagrangian and its Poincaré invariance. QFT might be an effective approximate manifestation of a more fundamental superstring theory. But I am unaware of any proof that superstrings violate CPT.

Most of the phenomena suggested for testing CPT belong to the point 1: they are C-odd, but PT-even. Examples are:

1. the search for mass differences of particles and corresponding antiparticles: $m_{K^0} - m_{\bar{K}^0}$, $m_{K^+} - m_{K^-}$, $m_{e^-} - m_{e^+}$, $m_{\mu^-} - m_{\mu^+}$, $m_n - m_{\bar{n}}$, $m_{\nu_e} - m_{\bar{\nu}_e}$, etc. Especially popular nowadays are speculations on non-vanishing mass differences between neutrinos

and antineutrinos [18] - [24].

2. the search for nonvanishing sum of magnetic moments of a particle and its antiparticle: $\mu_{\mu^+} \neq -\mu_{\mu^-}$, $\mu_{e^+} \neq -\mu_{e^-}$, $\mu_p \neq -\mu_{\bar{p}}$, etc.

A manifestation of point 2 would be the discovery of longitudinal polarization of a photon from the decay $\pi^0 \to \gamma\gamma$. C is conserved in this decay. The product **sk** is P odd, but T even. The correlation **sk** could appear due to interference of points 2 (CPT odd amplitude $\phi F_{\mu\nu}F^{\mu\nu}$) and 0 (amplitude $\phi F_{\mu\nu}F_{\rho\sigma}\varepsilon^{\mu\nu\rho\sigma}$); note that ϕ is a pseudoscalar. However it would prove CPT violation, only if the magnitude of polarization is large enough. That is conected with phase δ caused by the final state interaction of photons (Fig. 3) whose contribution is of the order α^2. By accounting for this phase in point 0 (amplitude $e^{i\delta}\phi F_{\mu\nu}F^{\mu\nu}$) one would get longitudinal polarization in the case of interference with point 5 (CPT even and hermitian amplitude $i\phi F_{\mu\nu}F_{\rho\sigma}\varepsilon^{\mu\nu\rho\sigma}$). To my knowledge, nobody has tried to search for the helicity of photons from $\pi^0 \to \gamma\gamma$.

A CPT violating effect due to interference of points 3 and 0 would be muon polarization perpendicular to the plane of decays $K_L^0 \to \mu^+\nu_\mu\pi^-$ and $K_L^0 \to \mu^-\bar{\nu}_\mu\pi^+$. The correlation $\mathbf{s}_\mu[\mathbf{k}_\mu \times \mathbf{k}_\pi]$ is C even, P even, but T odd. Hence it is CPT odd. However "a fake T violation" could be caused by the final state muon-pion scattering [25, 26] at point 0 with phase $\delta \sim \alpha/\pi$. The experimental upper limit for such polarization is 0.5% [27].

Note that the same transverse polarization in the decays $K^+ \to \mu^+\nu_\mu\pi^0$ and $K^- \to \mu^-\bar{\nu}_\mu\pi^0$ cannot be faked a simple final state electromagnetic scattering.

In the lagrangian language the CPT-violating terms violate hermiticity. Thus a nonvanishing mass difference between particles and antiparticles (point 1) can be caused by an additional mass term which has opposite signs for particle and antiparticle. This term is antihermitian.

A similar situation is with point 2 illustrated above by the helicity of photons in π^0 decay. The P odd and TC even spin-momentum correlation in this case is produced by interference of the point 0 amplitude $\varphi F\tilde{F}$ which is hermitian with parity violating antihermitian amplitude φFF.

The T odd but CP-even term in the amplitude of $K_{\mu 3}$ decay (point 3) can interfere with the "bare" point 0 only if the former is antihermitian (has a real coefficient).

As an example of manifestation of point 7 let us consider the electric dipole moments of a particle and its antiparticle, say, e^- and e^+, or ν_e and $\bar{\nu}_e$.

If P and T are broken, while C is conserved (vertex 6), the electric dipole moments are nonvanishing, however their sum must vanish, because they (similarly to charges and to the ordinary magnetic dipole moments described by vertex 0) must have opposite signs. This can be easily seen from the negative C parity of the photon.

If we now consider vertex 7, we see that it must be not only P and T odd but also C odd. This requires a term in the lagrangian which gives not only the same absolute value, but also the same sign to the electric dipole moments of a particle and its antiparticle. If both vertices 7 and 6 are present, then $d_{\nu_e} \neq d_{\bar{\nu}_e}$. Similar inequalities would be valid for all leptons and quarks and hence hadrons.

The effects caused by interference of terms 1-7 will be discussed elsewhere.

The antihermitian terms in lagrangian must break unitarity of S-matrix. But testing unitarity is more difficult than searching for CPT violating phenomena discussed above.

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Concluding remarks

I do not belive that CPT is broken.

But Galileo: Measure whatever can be measured!

In the framework of Lorentz invariance: 4 ways of breaking CPT.

The price: antihermitian terms.

Maybe: wormholes, quantum gravity, branes

Barenboim and Lykken (unpublished) also preserve Lorentz-invariance, but they want more of QFT and hence break locality. (My terms are local.) They are inspired by LSND result.

I am inspired only by Galileo.

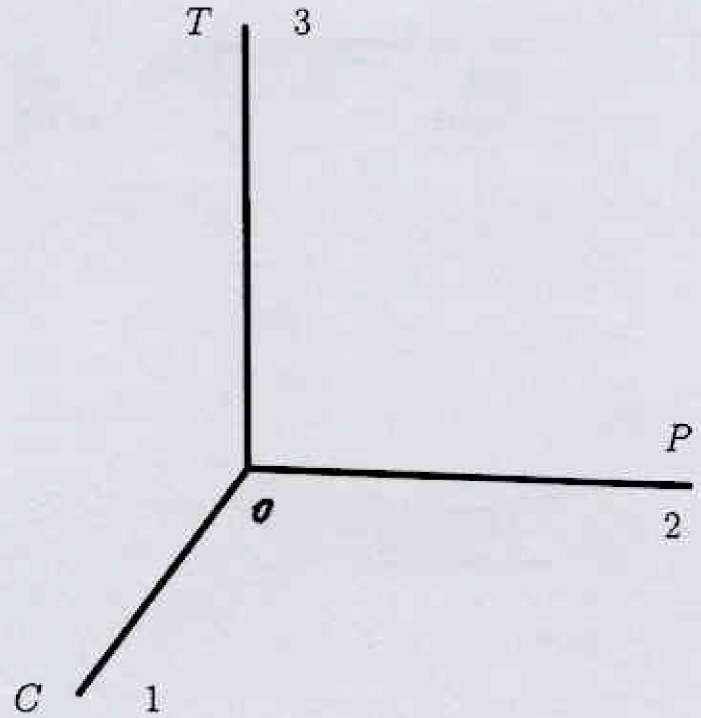

Fig.1

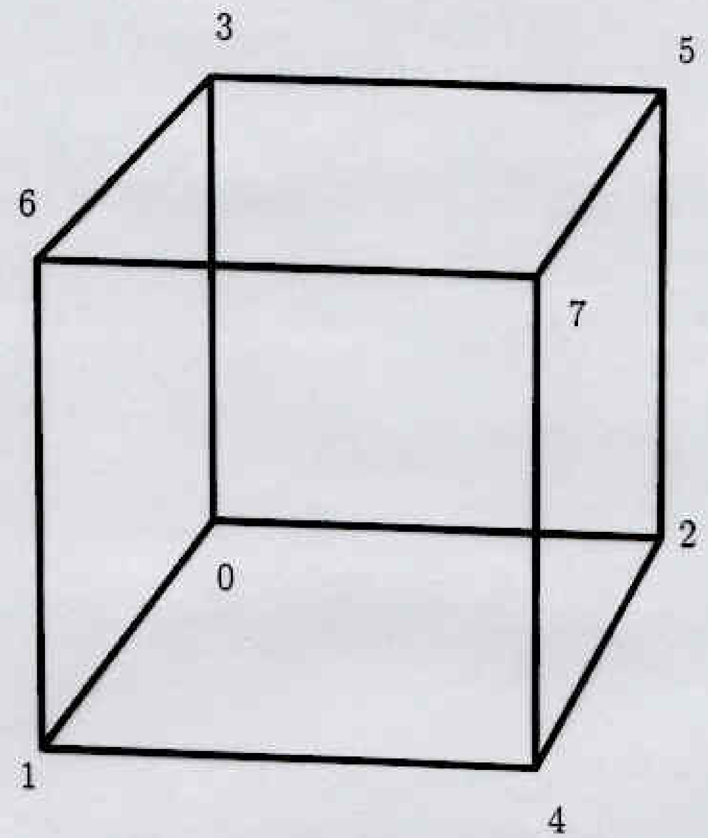

Fig.2

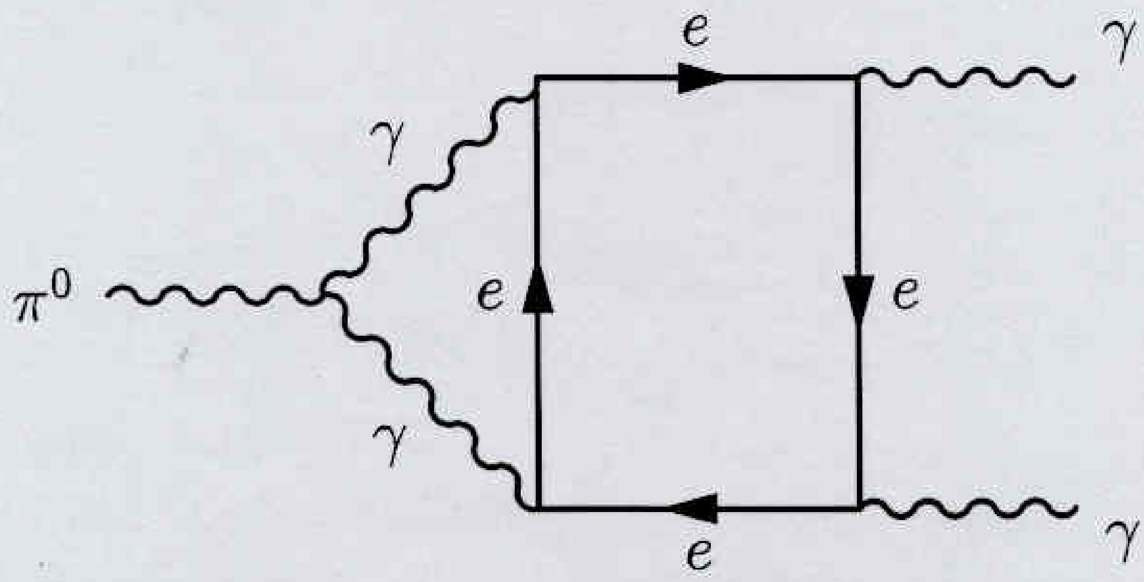

Fig.3

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