Novel CPT violation for EPR correlated neutral mesons

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J.B, N. Mavromatos, J. Papavassiliou ,
Phys.Rev.Lett.92:131601,2004

J.B, N. Mavromatos, J. Papavassiliou,
and A. Waldron-Lauda ,
arXiv:hep-ph/0506025,
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EPR correlated states and particle physics

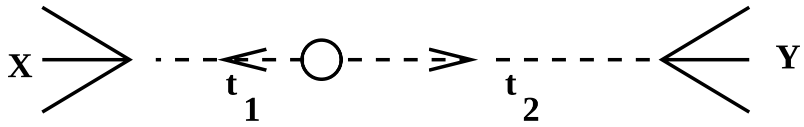
What are EPR correlations?

Einstein-Podolsky-Rosen (EPR) effect proposed originally as a **PARADOX** testing foundations of Quantum Theory.

Correlations between spatially separated events, instant transport of information? contradicts relativity?

NO, **NO PARADOX**

EPR has been confirmed EXPERIMENTALLY:
(i) pair of particles can be created in a definite quantum state,
(ii) move apart,
(iii) decay when they are widely separated (spatially).



EPR CORRELATIONS between different decay modes should be taken into account, when interpreting any experiment.

EPR and ϕ Factories

(Lipkin (1968), Dunietz, Hauser, Rosner (1987), Bernabeu, Botella, Roldan (1988))

It was claimed that due to EPR correlations, irrespective of CP, CPT violation, the FINAL STATE in ϕ decays is

$$e^+e^- \Rightarrow \phi \Rightarrow K_S K_L$$

WHY?

Entangled meson states: *Bose statistics* for the state $K^0\overline{K}^0$, to which ϕ decays, implies that the physical neutral meson-antimeson state must be *symmetric* under $C\mathcal{P}$, with C the charge conjugation and $\mathcal{P}$ the operator that permutes the spatial coordinates.

Assuming *conservation* of angular momentum, and a proper existence of the *antiparticle state* (denoted by a bar), one observes that: for $K^0\overline{K}^0$ states which are C-conjugates with $C = (-1)^\ell$ (with ℓ the angular momentum quantum number), the system has to be an eigenstate of $\mathcal{P}$ with eigenvalue $(-1)^\ell$.

Hence, for $\ell = 1$: $C = - \rightarrow \mathcal{P} = -$.

Bose statistics ensures that for $\ell = 1$ the state of two identical bosons is forbidden.

This correlation is transmitted to the decay channels, so that decays to the same final states at equal times are forbidden (Lipkin 1968). Hence initial entangled state $K^0\overline{K}^0$ in ϕ factory:

$$|i> = \frac{1}{\sqrt{2}}\left(|K^0(\vec{k}), \overline{K}^0(-\vec{k}) > -|\overline{K}^0(\vec{k}), K^0(-\vec{k}) >\right)$$
$$= C\left(|K_S(\vec{k}), K_L(-\vec{k}) > -|K_L(\vec{k}), K_S(-\vec{k}) >\right)$$

with $C = \frac{\sqrt{(1+|\epsilon_1|^2)(1+|\epsilon_2|^2)}}{\sqrt{2}(1-\epsilon_1\epsilon_2)} \simeq \frac{1+|\epsilon^2|}{\sqrt{2}(1-\epsilon^2)}$, and $K_S = \frac{1}{\sqrt{1+|\epsilon_1^2|}}(|K_+ > +\epsilon_1|K_- >)$, $K_L = \frac{1}{\sqrt{1+|\epsilon_2^2|}}(|K_- > +\epsilon_2|K_+ >)$, where ϵ_1, ϵ_2 are complex parameters, such that, if CPT invariance of the Hamiltonian is assumed (within a quantum mechanical framework), $\epsilon_1 = \epsilon_2$, otherwise $\delta \equiv \epsilon_1 - \epsilon_2$ parametrizes the CPT violation within quantum mechanics.

Convenient to use: the CP-violating parameters δ and $\epsilon \equiv |\epsilon|e^{i\phi_\epsilon} = \frac{\epsilon_1+\epsilon_2}{2}$ to parametrize CPT and T violation in a quantum mechanical framework.

It was claimed in the literature that the above form of $|i>$ holds independently of CPT violation. BUT, if CPT is violated ... The concept of antiparticle may be MODIFIED !

CPTV and EPR-correlations modification

If CPT is broken, e.g. via Quantum Gravity (QG) effects, then: CPT operator Θ is NOT defined and the antiparticle states cannot be reached.

Neutral mesons K^0 and $\overline{K}^0$ SHOULD NO LONGER be treated as IDENTICAL PARTICLES.

If, however, we separate the world into CPT-invariant and CPT-violating terms, the latter may be treated perturbatively

Bose Statistics in entangled states in ϕ factories implies now that $|i>$ can be written:

$$|i> = \frac{1}{\sqrt{2}}\left(|K^0(\vec{k}), \overline{K}^0(-\vec{k}) > -|\overline{K}^0(\vec{k}), K^0(-\vec{k}) >\right)$$
$$+ \frac{\omega}{\sqrt{2}}\left(|K^0(\vec{k}), \overline{K}^0(-\vec{k}) > +|\overline{K}^0(\vec{k}), K^0(-\vec{k}) >\right)$$

where $\omega = |\omega|e^{i\Omega}$. The complex parameter ω controls the amount of contamination by the "wrong" symmetry state. **We term such effects the ω-Effect**.

In terms of physical (mass) eigenstates, $K_{S,L}$:

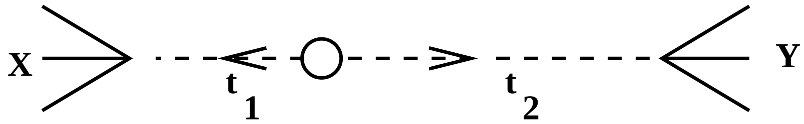
$$
\begin{aligned}
|i> \quad = \quad & C\Big[\Big(|K_S(\vec{k}), K_L(-\vec{k}) > - |K_L(\vec{k}), K_S(-\vec{k}) > \Big) \\
+ \quad & \omega \Big(|K_S(\vec{k}), K_S(-\vec{k}) > - |K_L(\vec{k}), K_L(-\vec{k}) > \Big) \Big]
\end{aligned}
$$

Notice the presence of $K_S K_S$ and $K_L K_L$ states; important when one considers decay channels.

Proceed now to Describe Experimental Tests of ω-Effect in ϕ factories...

ϕ Decays and the ω Effect

Consider the ϕ decay amplitude: final state X at t_1 and Y at time t_2 ($t = 0$ at the moment if ϕ decay)



Amplitudes:

$$A(X, Y) = \langle X|K_S\rangle\langle Y|K_S\rangle\, C\ (A_1 + A_2)$$

with

$$\begin{aligned} A_1 &= e^{-i(\lambda_L+\lambda_S)t/2}[\eta_X e^{-i\Delta\lambda\Delta t/2} - \eta_Y e^{i\Delta\lambda\Delta t/2}] \\ A_2 &= \omega[e^{-i\lambda_S t} - \eta_X\eta_Y e^{-i\lambda_L t}] \end{aligned}$$

the CPT-allowed and CPT-violating parameters respectively, and $\eta_X = \langle X|K_L\rangle/\langle X|K_S\rangle$ and $\eta_Y = \langle Y|K_L\rangle/\langle Y|K_S\rangle$.

The "intensity" $I(\Delta t)$: ($\Delta t = t_1 - t_2$)

$$I(\Delta t) \equiv \frac{1}{2}\int_{|\Delta t|}^{\infty} dt\, |A(X, Y)|^2$$

Tests of ω-Effect in ϕ factories

Most sensitive probe of ω-Effect : Identical final states $X = Y = \pi^+\pi^-$ (or $\pi^0\pi^0$).

The amplitudes of the CP violating decays $K_L \to \pi^+\pi^-$ are suppressed by factors of $\mathcal{O}(10^{-3})$, as compared to the principal decay mode of $K_S \to \pi^+\pi^-$. If $\omega = 0$, such decay rates would be suppressed, due to $K_S K_L$ correlation. BUT, if $\omega \neq 0$ this would not be the case, due to presence of $K_S K_S$ terms.

Relevant parameter for CPT violation in the intensity is thus ω/η_X, which enhances the potentially observed effect.

Sensitivity: Theoretically optimistic values for $\omega = \mathcal{O}(10^{-3} - 10^{-4})$ (c.f. QG decoherence effects: $\alpha/\Delta\Gamma$, $\alpha, \beta, \gamma = \mathcal{O}(E^2/M_P)$ (maximal Planckian effects)).

NB: with $|\omega| \sim 10^{-3} - 10^{-4}$ the ω-effects are comparable to $|\eta_{+-}| \sim 10^{-3}$;

A precision of 10^{-3} in $I(\Delta t)$, which is needed in order to observe ϵ' effects, would probe **sensitivities up to $|\omega| \sim 10^{-6}$ in ϕ factories.**

ω-effect & Intensities

We calculate the impact of the ω-term on the intensity

$$I(\Delta t) = \frac{1}{2}\int_{|\Delta t|}^{\infty} dt\, |A(\pi^+\pi^-,\pi^+\pi^-)|^2$$
$$= |\langle\pi^+\pi^-|K_S\rangle|^4 |C|^2 |\eta_{+-}|^2 \Big[I_1 + I_2 + I_{12}\Big]$$

Setting $\Delta M = M_S - M_L$ and $\eta_{+-} = |\eta_{+-}|e^{i\phi_{+-}}$, we obtain

$$I_1(\Delta t) = \frac{e^{-\Gamma_S \Delta t} + e^{-\Gamma_L \Delta t} - 2e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\cos(\Delta M \Delta t)}{\Gamma_L + \Gamma_S}$$

$$I_2(\Delta t) = \frac{|\omega|^2}{|\eta_{+-}|^2}\frac{e^{-\Gamma_S \Delta t}}{2\Gamma_S}$$

$$I_{12}(\Delta t) = -\frac{4}{4(\Delta M)^2 + (3\Gamma_S + \Gamma_L)^2}\frac{|\omega|}{|\eta_{+-}|} \times$$
$$\Big[2\Delta M\Big(e^{-\Gamma_S \Delta t}\sin(\phi_{+-} - \Omega) -$$
$$e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\sin(\phi_{+-} - \Omega + \Delta M \Delta t)\Big)$$

$$-(3\Gamma_S + \Gamma_L)\Big(e^{-\Gamma_S \Delta t}\cos(\phi_{+-} - \Omega) -$$
$$e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\cos(\phi_{+-} - \Omega + \Delta M \Delta t)\Big)\Big]$$

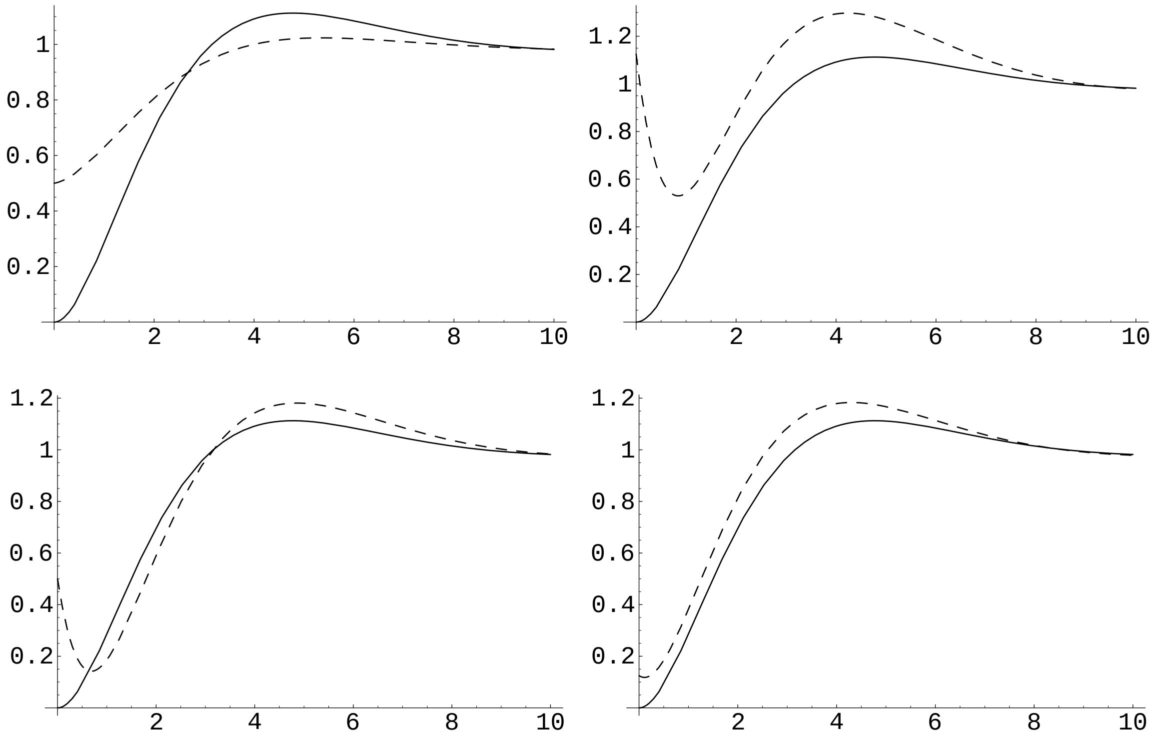


Figure 1: Characteristic cases of the intensity $I(\Delta t)$, with $|\omega| = 0$ (solid line) vs $I(\Delta t)$ (dashed line) with (from top left to right) : (i) $|\omega| = |\eta_{+-}|$, $\Omega = \phi_{+-} - 0.16\pi$, (ii) $|\omega| = |\eta_{+-}|$, $\Omega = \phi_{+-} + 0.95\pi$, (iii) $|\omega| = 0.5|\eta_{+-}|$, $\Omega = \phi_{+-} + 0.16\pi$, (iv) $|\omega| = 1.5|\eta_{+-}|$, $\Omega = \phi_{+-}$. Δt is measured in units of τ_S (the mean life-time of K_S) and $I(\Delta t)$ in units of $|C|^2|\eta_{+-}|^2|\langle\pi^+\pi^-|K_S\rangle|^4\tau_S$.

ω-Effect & C(even) Background

The C(even) background:

$$e^+e^- \Rightarrow 2\gamma \Rightarrow K^0\overline{K}^0 \quad (1)$$

$$|b> = |K^0\overline{K}^0(C(\text{even}) > =$$
$$\frac{1}{\sqrt{2}}\left(K^0(\vec{k})\overline{K}^0(-\vec{k}) + \overline{K}^0(\vec{k})K^0(-\vec{k})\right)$$

mimic ω-Effect. Can we disentangle ?

Order of Magnitude of C(even) Background mass smaller than $C(odd)$ resonant contribution:

Unitarity bounds (Dunietz *et al.* (1987), 2nd DAΦNE Handbook) one can estimate:

$$\frac{\sigma(e^+e^- \to K^0\overline{K}^0, J^P = 0^+)}{\sigma(e^+e^- \to \phi \to K_S K_L)} \sim 3.6 \times 10^{-10}$$

This is an important difference from the ω-Effect order of magnitude (in the optimistic case).

There are others, more important ...

Terms of the type $K_S K_S$ (which dominate over $K_L K_L$) coming from the ϕ-resonance as a result of ω-CPTV can be distinguished from those coming from the $C = +$ background because they interfere differently with the regular $C = -$ resonant contribution with $\omega = 0$).

Indeed, in the CPTV case, the $K_L K_S$ and $\omega K_S K_S$ terms have the same dependence on the center-of-mass energy s of the colliding particles producing the resonance, because both terms originate from the ϕ-particle. Their interference, therefore, being proportional to the real part of the product of the corresponding amplitudes, still displays a peak at the resonance. On the other hand, the amplitude of the $K_S K_S$ coming from the $C = +$ background has no appreciable dependence on s and has practically vanishing imaginary part.

Therefore, given that the real part of a Breit-Wigner amplitude vanishes at the top of the resonance , this implies that the interference of the $C = +$ background with the regular $C = -$ resonant contribution vanishes at the top of the resonance, with opposite signs on both sides of the latter. **This clearly distinguishes experimentally the two cases.**

Quantum Decoherence

The above formalism assumes that the time development still follows a unitary evolution in quantum mechanics. If there is a non-unitary decoherent Lindbland evolution (Commun.Math.Phys.48, 119 (1976)) , the density matrix $\rho(t)$ satisfies (Ellis, Hagelin, Nanopoulos, Srednicki, Lopez and Mavromatos).

$$\partial_t \rho(t) = i[\rho, H] + (\delta \not{H})\rho(t)$$

where $\delta \not{H}$ contains decoherent effcts

In an appropriate basis, where $\rho(t) = \frac{1}{2}\rho_\alpha \sigma_\alpha$, with $(\alpha = 0, 1, 2, 3,)$ and σ_α are the Pauli matrices ,

$$\partial_t \rho(t) = H_{\alpha\beta}\rho_\beta + (\delta \not{H})_{\alpha\beta}\rho_\beta$$

and

$$\delta \not{H}_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -2\alpha & -2\beta \\ 0 & 0 & -2\beta & -2\gamma \end{pmatrix}$$

so that α, β, γ parametrize these non-unitary decoherence in the time evolution

Identical final states

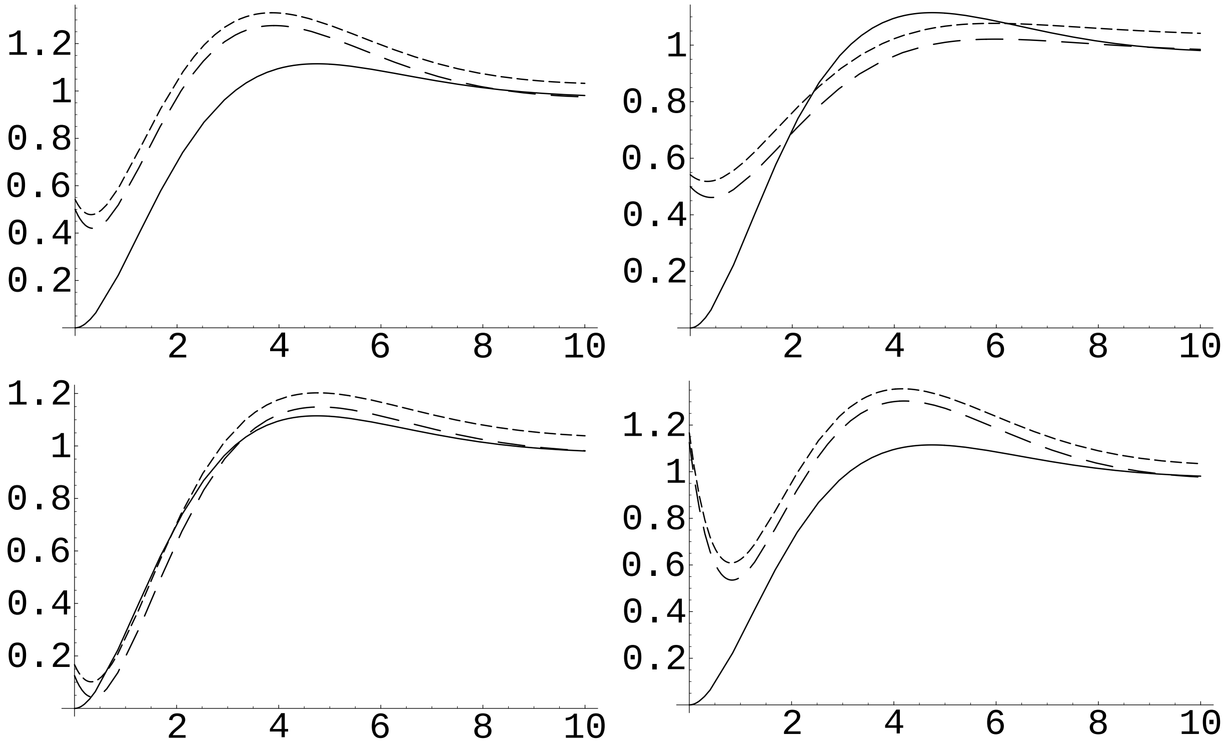


Figure 2:
solid : $\alpha = \beta = \gamma = \omega = 0$;
dashed : $\alpha, \beta, \gamma \neq 0, \ \omega \neq 0$;
long-dashed: $\alpha = \beta = \gamma = 0$, $\omega \neq 0$

CONCLUSIONS

– CPT Violation not only in the time evolution.

– What is the symmetry of the "initial" state $K^0\overline{K}^0$?
Bose statistics was implied iff K^0, $\overline{K}^0$ are indistinguishable .
If they are not , in perturbation theory $\Longrightarrow$ ω effect .

– The "wrong" symmetry induces by time evolution states like $|K_S K_S>$ or $|K_L K_L>$.

– For identical decay channels, $\pi^+\pi^-$,

· $A(\to \pi^+\pi^-, \pi^+\pi^-)|_{\Delta t=0} = 0$, iff $\omega = 0$.

· If $\omega \neq 0$, $A(\to \pi^+\pi^-, \pi^+\pi^-)|_{\Delta t=0} \sim \omega$.

– The intensity $I(\Delta t)$ sees a LINEAR ω/η EFFECT for $\Delta t \sim few\ \tau_S$.

– The ω effect can be disentangled from the non-unitary decoherent effects in time evolution (α, β, γ).