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CP VIOLATION AND COSMOLOGICAL FIELDS

O. Nachtmann

CERN - Geneva

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1. - INTRODUCTION

The rather surprising fact that the decay properties of the neutral K mesons can provide information on the gravitational interaction of these particles was first discovered by Good ¹⁾ long before CP violation. He realized that the very observation of a short and long lived component implied that the gravitational energies of K^0 and $\bar{K}^0$ could not be very different. So the $\bar{K}^0$ cannot fall upwards as was proposed sometimes for antiparticles. The discovery of CP violation ²⁾ brought increased interest to this field. A number of suggestions were made to explain the observed CP violation by the action of some unknown cosmological field ³⁾⁻⁶⁾. Most of these explanations have now been ruled out by experiment. But we can take another point of view, as Professor Thirring did last year here in Schladming ⁷⁾, namely to ask what information we can get from existing experiments on cosmological fields. We will explore this below in a simple field theoretical model. But before we will review the propagator method for defining the mass matrix as given by Sachs ^{8),9)}.

We use units $\hbar = c = 1$, metric $g_{00} = -g_{11} = -g_{22} = -g_{33} = 1$.

2. - THE MASS MATRIX AND ITS INVARIANCE PROPERTIES

In the approach of Sachs, one assumes the existence of fields describing the K mesons. Now we find it convenient to work with Hermitian fields ϕ_1, ϕ_2 corresponding to the CP eigenstates K_1, K_2 which are the following linear combinations of K^0 and $\bar{K}^0$

$$K_1 = \frac{1}{\sqrt{2}} (K^0 - \bar{K}^0)$$
$$K_2 = \frac{1}{\sqrt{2}} (K^0 + \bar{K}^0)$$

An expansion of these fields in terms of creation and annihilation operators would be

$$\begin{aligned}\phi_1(x) &= \sum \frac{i}{\sqrt{2\omega V}} (e^{ikx} a_1^+(k) - e^{-ikx} a_1(k)) \\ \phi_2(x) &= \sum \frac{1}{\sqrt{2\omega V}} (e^{ikx} a_2^+(k) + e^{-ikx} a_2(k))\end{aligned}\quad (2.1)$$

where $a_{1,2}^+$ create the states $K_{1,2}$ respectively *).

It is useful to list the transformation properties of these fields under the operations CP, T and $\Theta = \text{CPT}$:

- Table I -

A	CP A (CP)^{-1}	$(\text{TAT}^{-1})^+$	$(\Theta \text{ A } \Theta^{-1})^+$
$\phi_1(\vec{x}, t)$	$\phi_1(-\vec{x}, t)$	$\phi_1(\vec{x}, -t)$	$\phi_1(-\vec{x}, -t)$
$\phi_2(\vec{x}, t)$	$-\phi_2(-\vec{x}, t)$	$-\phi_2(\vec{x}, -t)$	$\phi_2(-\vec{x}, -t)$
$a_1(\vec{k})$	$a_1(-\vec{k})$	$-a_1^+(-\vec{k})$	$-a_1^+(\vec{k})$
$a_2(\vec{k})$	$-a_2(-\vec{k})$	$-a_2^+(-\vec{k})$	$a_2^+(\vec{k})$

The essential tool in the further analysis is the propagator, defined by

*) The factor i in the expansion for ϕ_1 corresponds to the phase conventions given in ¹⁰⁾.

$$\begin{aligned}\Delta_{ij}(x-x') &= i \langle 0 | T(\phi_i(x), \phi_j(x')) | 0 \rangle \\ &= \int \frac{dk}{(2\pi)^4} e^{-ik(x-x')} \Delta_{ij}(k^2) \\ i, j &= 1, 2\end{aligned}\quad (2.2)$$

If we turned off all interactions, the propagator would have the simple structure

$$\Delta(k^2) = \frac{1}{m_0^2 - k^2} \quad (2.3)$$

where m_0 is the common mass of $K_{1,2}$ and Δ is understood to be a multiple of the unit 2×2 matrix.

The propagator in presence of interaction can be calculated in principle ¹¹⁾ and is given by

$$\Delta(k^2) = [m_0^2 + \Pi^*(k^2) - k^2]^{-1} \quad (2.4)$$

$\Pi^*(k^2)$ is the sum of all proper self-energy diagrams. Since in our case the coupling is weak, it is sufficient to approximate $\Pi^*(k^2)$ by a constant: $\Pi^*(m_0^2 + i\varepsilon)$. So the propagator reads finally ^{*)}:

$$\Delta(k^2) = [W - k^2]^{-1} \quad (2.5)$$

$$W = m_0^2 + \Pi^*(m_0^2 + i\varepsilon) \quad (2.6)$$

^{*)} If we take into account strong interactions, $\Delta(k^2)$ of (2.5) is understood to be the pole term of the propagator.

W, of course, is a 2x2 matrix containing transitions from K_1 to K_2 .

It has been shown in Refs. 8),9) that the mass matrix m governing the decay of $K_{1,2}$ is given by the square root of W

$$m = W^{1/2} = m_0 + \frac{1}{2m_0} \pi^*(m_0^2 + i\varepsilon) \quad (2.7)$$

If we construct the propagator from the fields ϕ_1, ϕ_2 we will get m in the following basis :

$$m = \begin{pmatrix} \langle iK_1 | m | iK_1 \rangle & \langle iK_1 | m | K_2 \rangle \\ \langle K_2 | m | iK_1 \rangle & \langle K_2 | m | K_2 \rangle \end{pmatrix} \quad (2.8)$$

Any invariance of the theory will reflect itself in an invariance of the propagator and therefore also of the mass matrix m . Let us for example assume CPT invariance. Then, Table I tells us that

$$\begin{aligned} \Delta_{ij}(x-x') &= \theta(t-t') i \langle 0 | \phi_i(x) \phi_j(x') | 0 \rangle \\ &\quad + \theta(t'-t) i \langle 0 | \phi_j(x') \phi_i(x) | 0 \rangle \\ &= \theta(t-t') i \langle 0 | \theta \phi_i(-x) \phi_j(-x') \bar{\theta}' | 0 \rangle \\ &\quad + \theta(t'-t) i \langle 0 | \theta \phi_j(-x') \phi_i(-x) \bar{\theta}' | 0 \rangle \\ &= \theta(t-t') i \langle 0 | \phi_j(-x') \phi_i(-x) | 0 \rangle \\ &\quad + \theta(t'-t) i \langle 0 | \phi_i(-x) \phi_j(-x') | 0 \rangle \\ &= \Delta_{ji}(x-x') \end{aligned}$$

From this and from corresponding arguments for CP and T, follow the relations for the mass matrix given below in Table II.

- Table II -

Invariance	Relation for m
CP	$\langle iK_1 m K_2 \rangle = \langle K_2 m iK_1 \rangle = 0$
T	$\langle iK_1 m K_2 \rangle = -\langle K_2 m iK_1 \rangle$
θ	$\langle iK_1 m K_2 \rangle = \langle K_2 m iK_1 \rangle$

3. - LAGRANGIAN MODEL FOR INTERACTION OF K MESONS WITH COSMOLOGICAL FIELDS

Let us write down the most general Lagrangian for the interaction of two K mesons with scalar, vector and tensor fields

$$\begin{aligned}
 \mathcal{L}(x) = & \frac{1}{2} f_{ik} : \phi_i(x) \phi_k(x) : \\
 & + \frac{1}{2} f_{ik}^{\mu} : \phi_{i,\mu}(x) \phi_k(x) : \\
 & + \frac{1}{2} f_{ik}^{\mu\nu} : \phi_{i,\mu}(x) \phi_{k,\nu}(x) :
 \end{aligned} \tag{3.1}$$

The double points mean as usual normal ordering. Summation over $i, k = 1, 2$ is implied. The f 's are supposed to be cosmological fields generated by the surrounding heavy objects as the earth, the sun or the galaxy and are taken as constants. It must, however, be

emphasized that it is difficult to go beyond the external field approximation. It was shown in Ref. ⁶⁾ that quantization of a long range vector field will lead to an enormous production rate if the field is not coupled to a conserved current. The same argument can be used to conclude that the gravitational coupling must be universal. Still it may be useful to ask how well this is borne out by experiment, disregarding paradoxes which arise on the quantum level.

Now, since $\mathcal{L}$ must be Hermitian, the f 's have to be real. We get further restrictions on the f 's by using the symmetry properties of the normal ordered products and by discarding total divergence expressions from the Lagrangian (3.1).

Since $:\phi_i(x) \phi_k(x):$ is symmetric in i, k , f_{ik} can also be taken to be symmetric

$$f_{ik} = f_{ki} = f_{ik}^* \quad (3.2)$$

In the second term of (3.1), we can use the identity

$$\begin{aligned} :\phi_{i,\mu}(x) \phi_k(x): &= \frac{1}{2} : [\phi_{i,\mu}(x) \phi_k(x) - \phi_{k,\mu}(x) \phi_i(x)]: \\ &+ \frac{1}{2} \frac{\partial}{\partial x^\mu} : \phi_i(x) \phi_k(x): \end{aligned} \quad (3.3)$$

The divergence can be discarded. Because of the antisymmetry in i, k of the first term in (3.3), we can choose f_{ik}^μ to satisfy

$$f_{ik}^\mu = - f_{ki}^\mu = f_{ik}^{\mu *} \quad (3.4)$$

By analogous reasoning, we find, for $f_{ik}^{\mu\nu}$

$$f_{ik}^{\mu\nu} = f_{in}^{\nu\mu} = f_{ki}^{\mu\nu} = f_{ik}^{\mu\nu *} \quad (3.5)$$

In this model the Feynman diagrams are of course very simple and we find for the self-energy matrix Π^*

$$\begin{array}{ll}
 \begin{array}{c} \xrightarrow{K} \text{---} \times \text{---} \\ p \quad S \end{array} & -i \Pi_{ik}^* \\
 \begin{array}{c} \xrightarrow{K} \text{---} \times \text{---} \\ p \quad V \end{array} & i f_{ik} \\
 \begin{array}{c} \xrightarrow{K} \text{---} \times \text{---} \\ p \quad T \end{array} & - f_{ik}^{\mu} p_{\mu} \\
 & i f_{ik}^{\mu\nu} p_{\mu} p_{\nu} \quad (3.6)
 \end{array}$$

where S, V, T stand for scalar, vector and tensor.

The mass matrix is according to (2.7)

$$m = \begin{pmatrix} M_1^{(0)} + \epsilon_{11} & \epsilon_{12} \\ \epsilon_{21} & M_2^{(0)} + \epsilon_{22} \end{pmatrix} \quad (3.6)$$

$M_1^{(0)}$ and $M_2^{(0)}$ are the eigenvalues of the mass matrix when the cosmological fields are turned off. For simplicity we have assumed CP invariance in this case. The ϵ_{ik} are given below

$$\begin{aligned}
 \epsilon_{11} &= - \frac{1}{2m_0} f_{11}^{\mu\nu} p_{\mu} p_{\nu} \\
 \epsilon_{22} &= - \frac{1}{2m_0} f_{22}^{\mu\nu} p_{\mu} p_{\nu} \\
 \epsilon_{12} &= - \frac{1}{2m_0} \{ f_{12} + i f_{12}^{\mu} p_{\mu} + f_{12}^{\mu\nu} p_{\mu} p_{\nu} \} \\
 \epsilon_{21} &= - \frac{1}{2m_0} \{ f_{21} + i f_{21}^{\mu} p_{\mu} + f_{21}^{\mu\nu} p_{\mu} p_{\nu} \} \quad (3.7)
 \end{aligned}$$

The terms with f_{11} and f_{22} have been absorbed in $M_1^{(0)}$ and $M_2^{(0)}$. p^{μ} is the four-momentum of the K meson in the laboratory system.

If we now compare the symmetry properties of the f 's (3.2), (3.4), (3.5) with the invariance requirements for m under T and CPT (Table II), we find that scalar and tensor fulfil CPT but violate T whereas vector coupling fulfils T but violates CPT . Translating the relations of Table II to the basis $K^0, \bar{K}^0$ this means that in the scalar and tensor case we get

$$\langle K^0 | m | K^0 \rangle = \langle \bar{K}^0 | m | \bar{K}^0 \rangle$$

So these interactions do not give rise to different masses for particle and antiparticle.

To get the states with exponential decay law, we have to construct the (non-orthogonal) eigenstates of m

$$\begin{aligned} m |K_S\rangle &= M_S |K_S\rangle \\ m |K_L\rangle &= M_L |K_L\rangle \end{aligned} \tag{3.8}$$

$$\begin{aligned} |K_S\rangle &= |K_1\rangle + \varepsilon_1 |K_2\rangle \\ |K_L\rangle &= |K_2\rangle + \varepsilon_2 |K_1\rangle \end{aligned} \tag{3.9}$$

$$M_S = M_1^{(0)} + \varepsilon_{11} \tag{3.10}$$

$$M_L = M_2^{(0)} + \varepsilon_{22}$$

$$\begin{aligned} \varepsilon_1 &= \frac{i \varepsilon_{21}}{M_S - M_L} \\ \varepsilon_2 &= \frac{i \varepsilon_{12}}{M_S - M_L} \end{aligned} \tag{3.11}$$

Let us recall the definition of the observable quantities η_{+-}, η_{00} (see Ref. ¹⁰)

$$\eta_{\pi^+\pi^-} = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} \quad (3.12)$$

Since we have assumed CP invariance in the absence of cosmological fields, only the K_1 component of K_L can decay into 2π 's and we get

$$\eta_{+-} = \eta_{00} = \varepsilon_2 \quad (3.13)$$

If there are other sources of CP violation the resulting η will be the sum of all contributions. Below, we list $\eta_{\pi^+\pi^-}$ and $\Delta_m = \text{Re}(M_L - M_S)$ for S, V, T

$$\eta_{\pi^+\pi^-} = |\eta_{\pi^+\pi^-}| e^{i\varphi_{\pi^+\pi^-}}$$

- Table III -

	S	V	T
$\eta_{+-} = \eta_{00}$	$\frac{f_{12}}{m_0(\Gamma_S - 2i\Delta_m)}$	$\frac{if_{12}^{\mu} p_{\mu}}{m_0(\Gamma_S - 2i\Delta_m)}$	$\frac{f_{12}^{\mu\nu} p_{\mu} p_{\nu}}{m_0(\Gamma_S - 2i\Delta_m)}$
$\varphi_{+-} = \varphi_{00}$	$\pi/4, -3\pi/4$	$3\pi/4, -\pi/4$	$\pi/4, -3\pi/4$
Δ_m	$\Delta_m^{(0)}$	$\Delta_m^{(0)}$	$\Delta_m^{(0)} + \frac{f_{11}^{\mu\nu} - f_{22}^{\mu\nu}}{2m_0} p_{\mu} p_{\nu}$

In calculating $\varphi_{+-} = \varphi_{00}$ we have used $\Delta_m = \frac{1}{2}\Gamma_S$
 Γ_S : decay rate of the short lived component.

4. - UPPER LIMITS FOR COSMOLOGICAL FIELDS

According to Section 3, we will regard the f 's as static fields generated by cosmological objects. It will be convenient to compare these fields with the gravitational potential generated by the earth, sun, galaxy and universe, respectively.

ϕ : gravitational potential ($\sim \frac{\kappa M}{r}$)

f : gravitational coupling constant $f^2/8\pi = \kappa$

κ : Newton's gravitational constant

- Table IV -

	$m_0 \phi$		
earth	0.4	eV $\simeq 5 \cdot 10^4$	Γ_s
sun	6	eV $\simeq 8 \cdot 10^5$	Γ_s
galaxy	300	eV $\simeq 4 \cdot 10^7$	Γ_s
universe	500	MeV $\simeq 6 \cdot 10^{13}$	Γ_s

a - The scalar case

Looking at the Lagrangian (3.1), we realize that we could as well interpret f_{ik} as coupling constants. This would then be a superweak model in the sense of Wolfenstein^{12),13)}. Therefore, we see that a superweak model and a cosmological model with scalar coupling could only be distinguished if emission of real quanta of the cosmological field were observed.

From the experimental point of view, a superweak model is not ruled out by the latest experiments.

- Table V -

Reference	$ \eta_{+-} $	φ_{+-}
14	$(1.92 \pm 0.04) \cdot 10^{-3}$	$(50 \pm 8)^{\circ}$
	$ \eta_{00} $	φ_{00}
15	$(2.3 \pm 0.3) \cdot 10^{-3}$	
16	$(2.2 \pm 0.4) \cdot 10^{-3}$	
17	$(3.2 \pm 0.7) \cdot 10^{-3}$	$(37 \pm 30)^{\circ}$

If we want over-all CP conservation, the cosmic field f_{12} must be odd under CP and also T. Therefore also its source will have to be odd under T, which leads to a vanishing thermodynamical expectation value for a stationary system. In other words, one cannot generate a T odd scalar field by a static distribution of matter in the universe. However, it is claimed in Ref. ⁵⁾ that, by considering more general types of universes, one can overcome this difficulty ^{*}).

Let us compare anyway the strength of a superweak interaction, if it is generated by a cosmic potential to the strength of gravitation. We set, by dimensional arguments (f is again the gravitational coupling constant) :

$$f_{12} = \frac{fs}{f} \phi m_o^2 \quad (4.1)$$

^{*}) I am grateful to Professor J.S. Bell for having drawn my attention to this point.

Inserting this in the expression for η_{+-} of Table III, we get

$$\left| \frac{f_s}{f} \right| = 2 \cdot \sqrt{2} \cdot 10^{-3} \frac{\Gamma_s}{m_0 \phi} \quad (4.2)$$

Assuming that only the earth, sun, etc., contribute to the scalar field we find the following orders of magnitude.

- Table VI -

	$ f_s/f $
earth	$\simeq 1.8 \cdot 10^{-7}$
sun	$\simeq 3.5 \cdot 10^{-9}$
galaxy	$\simeq 0.7 \cdot 10^{-10}$
universe	$\simeq 5 \cdot 10^{-14}$

We see that such a coupling would be even much weaker than gravitation, but would still have observable consequences on the elementary particle level.

b - The vector case

Such a coupling was proposed in Ref. 3) to explain the observed CP violation. As source of the vector field, the hypercharge current was used. This theory, however, would give an $|\eta_{+-}|$ dependent on the velocity of the K mesons in the laboratory system. Such a velocity dependence was looked for experimentally but was not found. Moreover we find from Table III that φ_{+-} for this case does not agree with the experimental value (Table V). So certainly this interaction is not responsible for the main part of observed CP violation. Experiments done on K mesons with laboratory energy up to 10 GeV/c¹⁸⁾ show a constant $|\eta_{+-}|$ to within 10 %. From this we conclude

$$\left| \frac{i f_{12}^{\mu} p_{\mu}}{m_0 \sqrt{2} \Gamma_s} \right| \leq 2 \cdot 10^{-4} \quad (4.3)$$

For f_{12}^{μ} we take analogously to (4.1)

$$f_{12}^{\mu} = \frac{f_v}{f} m_0 \phi \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (4.4)$$

We find, from (4.3), the following upper limits for $|f_v/f|$

$$\left| \frac{f_v}{f} \right| \lesssim 2 \cdot \sqrt{2} \cdot 10^{-4} \frac{\Gamma_s}{m_0 \phi \gamma} \quad (4.5)$$

$$\gamma = \frac{p_0}{m_0} = \frac{1}{\sqrt{1-v^2}}$$

- Table VII -

	$ f_v/f $
earth	$\lesssim 3 \cdot 10^{-10}$
sun	$\lesssim 2 \cdot 10^{-11}$
galaxy	$\lesssim 4 \cdot 10^{-13}$
universe	$\lesssim 2 \cdot 10^{-19}$

$\gamma \simeq 20$ for 10 GeV/c momentum.

We see that we can be quite sure of the absence of a long range vector field.

c - The tensor case

From the point of view of gravitation, a tensor interaction is of course of the greatest interest. We may note that the interaction usually written down in gravitation ¹⁹⁾

$$f \psi_{\mu\nu} T^{\mu\nu} \quad (4.6)$$

with $T^{\mu\nu}$ the energy momentum tensor of the particles

$$T^{\mu\nu} = \phi'^{\mu} \phi'^{\nu} - \frac{g^{\mu\nu}}{2} (\phi'_{\lambda} \phi'^{\lambda} - m_0^2 \phi^2) \quad (4.7)$$

is completely equivalent to the tensor part of (3.1) as far as the mass matrix is concerned. This comes about because the part with $g^{\mu\nu}$ in (4.7) becomes proportional to $p^2 - m_0^2$ which gives 0 on the mass shell.

As in the previous cases, we can derive upper bounds for the non-diagonal coupling $f_{12}^{\mu\nu}$ if we assume it proportional to the gravitational field (see Ref. ¹⁹⁾ for the specific form)

$$f_{12}^{\mu\nu} = \frac{f_T}{f} \phi \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix} \quad (4.8)$$

$\eta_{\pm 0}^-$ is now even more strongly dependent on γ , so the same argument as for the vector case gives :

$$\left| \frac{f_T}{f} \right| \lesssim 2\sqrt{2} \cdot 10^{-4} \frac{\Gamma_s}{2m_0 \phi \gamma^2} \quad (4.9)$$

Now we can also test the diagonal couplings $f_{11}^{\mu\nu}$ and $f_{22}^{\mu\nu}$ by observing the dependence of the mass difference of K_L and K_S on the laboratory momentum. Table VIII below lists some experiments on Δm

- Table VIII -

Reference	Lab.momentum GeV/c	γ	Δm in units Γ_s
20	~ 2.7	5.5	0.44 ± 0.03
21	~ 0.8	1.9	0.42 ± 0.2
22	~ 4.5	9.0	0.48 ± 0.02
23	~ 1.0	2.2	0.42 ± 0.04
24			0.47 ± 0.02

We see that Δm is constant to about 10 % for γ up to 9.

We now set

$$f_{11}^{\mu\nu} = \frac{f_1}{f} \phi \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix} \quad (4.10)$$

$$f_{22}^{\mu\nu} = \frac{f_2}{f} \phi \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix} \quad (4.11)$$

where f_1 and f_2 can be interpreted as the deviations of the gravitational couplings of K_1 and K_2 from the universal coupling. This gives the following upper limit for $(f_1 - f_2)/f$:

$$\left| \frac{f_1 - f_2}{f} \right| \leq \frac{5 \cdot 10^{-2} \Gamma_s}{m_0 \phi \gamma^2} \quad (4.12)$$

The upper bounds for the off-diagonal and the difference of the diagonal couplings which one gets from (4.9) and (4.12) respectively, are listed below in Table IX.

- Table IX -

	$ f_T/f $	$ \frac{f_1-f_2}{f} $
earth	$\lesssim 5 \cdot 10^{-12}$	$\lesssim 1.2 \cdot 10^{-8}$
sun	$\lesssim 3 \cdot 10^{-13}$	$\lesssim 0.8 \cdot 10^{-9}$
galaxy	$\lesssim 6 \cdot 10^{-15}$	$\lesssim 1.6 \cdot 10^{-11}$
universe	$\lesssim 4 \cdot 10^{-21}$	$\lesssim 1.0 \cdot 10^{-17}$

These values have to be compared with the Eötvös-Dicke experiment ²⁵⁾ which gives

$$\left| \frac{\delta f}{f} \right| \leq 10^{-11} \quad (4.13)$$

for the difference of the gravitational couplings of protons and neutrons. Since the gravitational field extends certainly to the galaxy, we find that the universal gravitational coupling of K mesons is verified to the same accuracy as in the classical experiment for the diagonal coupling and four orders of magnitude better for the off-diagonal. We must, however, note that the Eötvös-experiment is sensitive to the field strengths whereas in the analysis of the K system the potential itself enters. Finally we have to say that, in the language of gravitational theory in both experiments, the so-called weak equivalence principle is tested.

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