

POSSIBILITY OF *CP* VIOLATION IN SEMI-STRONG INTERACTIONS

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The recently observed [1] decay $K_{02} \rightarrow 2\pi$ can be interpreted in two essentially different manners. Either, a) one has to do with an apparent *CP* violation due to the presence of some external field [2], in which case a velocity dependence of the decay rate would show up, or b) one has to do with some real *CP* violation due to some interaction as yet unspecified. In the latter case, the following possibilities emerge:

- i) the decay is entirely due to a new type of very weak interaction;
- ii) the *CP* violation is inherent in weak interactions;
- iii) the *CP* violation is due to perturbation by some interaction on an otherwise normal weak process.

The difference between these points of view is mainly a difference in suspected order of magnitude of the coupling constant of the *CP* violating interaction. In case i) one would expect a coupling constant small with respect to that of the weak interactions, and no prediction on any further properties, like $\Delta I = \frac{1}{2}$ can be made [3]. In case ii) the usual weak interaction selection rules are supposedly holding also for this mode of decay [4], so the K_{02} rate in $\pi^+\pi^-$ or $\pi^0\pi^0$ is according to the $\Delta I = \frac{1}{2}$ rule. As has been pointed out [5], no firm conclusions can be drawn on the magnitude of the coupling constant of the *CP* violating part, and it could be as large as the weak interaction coupling constant itself.

In this note we intend to entertain possibility iii). First we note that the coupling constant involved, by the same argument as in the case of ii), is undetermined. However, it should be at least of the order 1/500, in view of the observed branching ratio. This implies that this interaction should have a strength at least comparable with electromagnetic interactions. But the fundamental electromagnetic interaction is *CP* invariant thus it cannot be the electromagnetic interaction itself.

Obviously, by the introduction of an ad hoc

new interaction with some "good" properties, one can explain the $K_{02} \rightarrow 2\pi$ decay. What we want to point out in this paper is that already an interaction exists which could lead to some predictions which could be experimentally verified. As we will see some difficulties exist but we consider these difficulties as being not extremely serious. The interactions in question are the so-called semi-strong interactions, i. e., *SU3* violating interactions.

If the interplay of semi-strong and weak interactions is responsible for the *PC* violation in weak interactions, the semi-strong interactions must violate *PC*. However, *P* in this case must be conserved to a very high degree of accuracy as is seen from the measurement of the electric dipole moment of the neutron. Moreover these interactions conserve the isospin quite accurately as is seen from the isospin multiplet structure of the elementary particles, from the charge independence of nuclear forces, as seen for example from the reaction $d+d \rightarrow He+\pi_0$. From *PCT* one has then to deduce that medium strong interactions violate *C* and *T* respectively. Thus we will inspect now the evidence for *C* and *T* invariance of this interaction. To be more specific, we will also make the usual assumption that it transforms like the eighth component of an octet (although it is conceivable that the *C* violating part of the *SU3* violating interactions behaves differently). Let us first consider the question of order of magnitude of the coupling constant. The only information on this point is given by the mass differences between partners in an *SU3* multiplet. We may compare those mass differences with the electromagnetic mass differences. Let us consider the baryon multiplet. The charged-uncharged baryon mass differences are of second order in e , and are of the order of 1 (for p-n) to 5 or 6 (for Σ and Ξ) MeV. Typical mass differences within the octet are of order 75 - 150 MeV, and if we assume that the *SU3* breaking interactions do not have a complete-

ly 90° phase difference with the strong interactions, these differences are of the first order in f (= the coupling constant for the SU_3 breaking interaction). Thus f may be estimated to be 5-10 times the electromagnetic coupling constant. Roughly speaking one expects therefore 10% perturbation effects on processes involving strong interacting particles. It requires some stretching of the imagination (although we are in better position than in many models already proposed) to explain the small $K_0^2 \rightarrow 2\pi$ branching ratio, but we will not enter a discussion on this point. As we take the SU_3 breaking interaction to be I spin conserving, the CP violating decay should also obey the $\Delta I = \frac{1}{2}$ rule of weak interactions.

Let us now consider the pion-nucleon interaction Lagrangian. According to the theorem by Soloviev [6], generalized to SU_3 invariant interactions by Pais [7], P and CPT are enough to guarantee C and T invariance for interactions like

$$ig(\bar{N}\gamma^5\tau N)\pi$$

because the addition of the Hermitian conjugate cancels the imaginary part of g . This argument is valid also in SU_3 context, when one considers the couplings $g_1(\bar{B}BM)$ and $g_1(B\bar{B}M)$, where \bar{B} , B , M are the usual antibaryon, baryon and meson octets.

We may now write down the SU_3 breaking part \mathcal{L}'_1 of the interaction Lagrangian \mathcal{L}_1 by introducing a spurion that behaves as the eighth component of an octet. We have 9 couplings (with one relation among the coefficient which is not of interest to us here):

$$\begin{aligned} \mathcal{L}'_1 = & a_1(\bar{B}SMB) + a_2(\bar{B}MBS) + a_3(\bar{B}BSM) + \\ & + a_4(\bar{B}SBM) + a_1^*(\bar{B}MSB) + a_3^*(\bar{B}BMS) + \\ & + a_7(\bar{B}M)(BS) + a_7^*(\bar{B}S)(BM) + a_9(\bar{B}B)(MS). \end{aligned}$$

Hermiticity requires the reality of a_2 , a_4 and a_9 , apart from the explicitly indicated relations above. From the above formula one deduces that all couplings involving pions and the η are C conserving, apart from the terms

$$\begin{aligned} & \frac{1}{\sqrt{6}} (a_1 + a_2 + a_3 + a_4 + a_1^* + a_3^* + 6a_7)(\bar{\Sigma} \Lambda) \pi \\ & + \frac{1}{\sqrt{6}} (a_1 + a_2 + a_3 + a_4 + a_1^* + a_3^* + 6a_7^*)(\bar{\Lambda} \Sigma) \pi \end{aligned}$$

i. e., this coupling violates C through a_7 only. The couplings involving kaons do not have any

special property in this respect.

Thus, from the above we do expect significant CP violating effects only if strange particles play a significant role (which of course may also be through virtual effects).

Inspecting now the existing evidence on CP or T violation in strong interactions we observe that T violation in usual experimental arrangements is not an easily measurable effect in view of final state interactions. The limit on T is of the order of 10%. But we must consider those strong interacting systems that are an eigenstate of C . These systems are the 3S_1 or 1S_0 proton-antiproton system, and the existing unstable particles. The $p\bar{p}$ data are certainly not sufficiently accurate for this purpose. The most (and in fact the only - see the table for some examples) serious case is the decay of the η particle, supposedly going via an electromagnetic process [8]

$\eta \rightarrow \pi^+ \pi^- \pi^0$	27 %
$\pi^+ \pi^- \gamma$	5.5 %
$3 \pi^0$	31 %
$\pi^0 2\gamma$	
2γ	35 %

If I spin is conserved no $3\pi^0$ mode should be present and the Dalitz plot of the 3π system should be different from that which is observed. The above rates are of order e^4 in the electromagnetic interactions (why the e^2 process $\pi^+ \pi^- \gamma$ is so small is not clear), as follows from the large $\eta \rightarrow 2\gamma$ rate, while a C violating process through the SU_3 breaking interactions could be of order f^2 , i. e., a factor 10^3 - 10^4 larger. However, as pointed out above such effects may be suppressed in interactions not involving strange particles. Moreover, the isospin conservation implies a large angular momentum barrier; as is well known the simplest wave function involves 6 derivatives (i, j, k are isospin indices)

$$\eta \frac{\partial^3 \pi^i}{\partial x_\mu \partial x_\nu \partial x_\lambda} - \frac{\partial^2 \pi^j}{\partial x_\mu \partial x_\nu} \frac{\partial \pi^k}{\partial x_\lambda} \epsilon_{ijk}.$$

This, in connection with the small phase space for the 3π mode could give a very important suppression for this transition, in contrast to the C conserving I spin violating transition that involves only S waves in the final state. For this reason we do not consider the η decay modes as strong evidence for C conservation by the SU_3 breaking interactions.

Effects of the C and T violation proposed above would show up in non-leptonic weak decays,

in strange particle leptonic decays, in proton-antiproton reactions, etc.

In leptonic decays with $\Delta S = 0$ the strong interaction currents are supposedly belonging to a $I = 1$ multiplet, and in our model this remains like that. As is well known the C and T violation can proceed then only via currents of the second class. For $\Delta S = 0$ currents therefore our theory is giving the same results as Cabibbo's model [4]. For $\Delta S = 1$ leptonic decays the non-renormalization theorem of Fubini and Furlan [9] is valid for the vector part, thus we expect there small effects (1 %) only, in particular for $K_{\mu 3}$ decay.

In conclusion, let us state that apart from the difficulty connected with the η which can however be solved by an adequate model where the effects of barrier potential will be important, it is conceivable that the PC violation in weak interactions is due to a PC violation in medium strong interaction. It is then very important to re-examine again the problem of C and T conservation in strong interactions where effects possibly up to 10%, especially in strange particle physics, could be expected. Experiments of this kind should, in our opinion, be performed, and in particular the η decay should be very thoroughly re-examined. In weak interaction one expects then also effects of PC violation up to 10% in $\Delta S = 1$ transition, smaller in $\Delta S = 0$ for leptonic and non-leptonic decays. A very strong prediction of this model is the validity of the usual isospin selection rules also for PC violating effects in weak interactions.

Table
Consequences of C violation on some
observed reactions

$\pi_0 \rightarrow \gamma$	No, parity.
$\pi_0 \rightarrow 3\gamma$	Presumably small, at most $1/1000 \times \pi_0 \rightarrow 2\gamma$. It would probably be interesting to look for it.
$\pi_0 \rightarrow e^+e^-$	Only in second order in electromagnetic interactions.
$K_{01} \rightarrow e^+e^-, \mu^+\mu^-$	Only in second order in electromagnetic interactions in addition to first order in weak interactions.
$K_{02} \rightarrow e^+e^-, \mu^+\mu^-$	

$\omega_0 \rightarrow \pi^+\pi^-$	No, because of I spin and Bose statistics. No P wave with $I=0$ possible.
$\omega_0 \rightarrow 3\pi$	Unchanged.
$\rho_0^\pm \rightarrow \pi^+\pi^-$	Unchanged.
$\rho_0^\pm \rightarrow 3\pi$	Negligible, experimentally difficult to establish.
$\varphi_0 \rightarrow K_{01} K_{02}$	Unchanged, due to statistics.
$\varphi_0 \rightarrow K_{01} K_{01}$	
$\varphi_0 \rightarrow \pi\rho$	Unchanged.
$\varphi_0 \rightarrow \pi\omega$	No, I spin.

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References

- 1) J. H. Christenson, J. W. Cronin, V. L. Fitch and K. Turlay, Phys. Rev. Letters 13 (1964) 138.
- 2) J. S. Bell and J. K. Perring, Phys. Rev. Letters 13 (1964) 348.
J. Bernstein, N. Cabibbo and T. D. Lee, Physics Letters 12 (1964) 146.
S. Weinberg, Phys. Rev. Letters 13 (1964) 495.
- 3) L. Wolfenstein, Phys. Rev. Letters 13 (1964) 562.
- 4) N. Cabibbo, Physics Letters 12 (1964) 495.
- 5) R. G. Sachs, Phys. Rev. Letters 13 (1964) 286.
- 6) V. Soloviev, Zh. Eksperim. i. Teor. Fiz. 33 (1957) 537, 796, Soviet Physics JETP 6 (1958) 419, 613.
- 7) A. Pais, Phys. Rev. Letters 12 (1964) 432.
- 8) A. H. Rosenfeld, A. Barbaro Galtieri, W. H. Barkas, P. L. Bastien, J. Kirz and M. Roos, Rev. of Mod. Phys. 36 (1964) 977.
- 9) S. Fubini and G. Furlan, CERN preprint 9832/TH. 487. The Ademollo-Gatto proof does not hold as they use CP invariance. M. Ademollo and R. Gatto, Phys. Rev. Letters 13 (1964) 264.

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