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LIMITATIONS ON CP-VIOLATING EFFECTS IN STRANGE PARTICLE DECAYS

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ABSTRACT

The difference in the partial weak decays between strange particles and anti-particles is suppressed by the $\Delta I = \frac{1}{2}$ rule or centrifugal barrier effects. However, for the case of heavier quarks, this difference can be of the order of 10^{-3} .

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The CP non-conservation in nature, in view of its close connection with the baryon asymmetry and the grand unification, represents an important tool for the understanding of physics beyond the standard model. From our present knowledge of the production and decay of c and b quark states in known and planned accelerators and storage rings, it will be extremely difficult to determine the source of CP violation in heavy quark decays. Consequently, the neutral kaon system and the hyperon decays still represent the most promising means of investigating the breakdown of the CP invariance.

In a properly chosen convention there are two parameters describing the CP non-conservation in the neutral-kaon system: a small complex number ϵ specifying the CP impurity of the observed eigenstates K_S^0 and K_L^0 , which is a measure of the CP violation in the mass matrix, and the amplitude ϵ' measuring the violation of the CP symmetry in the decay matrix. The quantity ϵ' arises from the interference between the $\Delta I = 1/2$ (two-pion isospin zero amplitude) and the $\Delta I = 3/2$ (two-pion isospin two amplitude) weak currents and is related to the complexity of the coupling constants. Although the ratio $|\epsilon'/\epsilon|$ is required in order to quantify the source of CP violation, its magnitude is suppressed, mainly because of the $\Delta I = 1/2$ rule, and thus is experimentally difficult to measure. Therefore, theoretical attempts to look for other CP-violating phenomena different from those of ϵ and ϵ' are very welcome. Such effects may appear in the dominant isospin decay amplitude and thus may not be suppressed by the $\Delta I = 1/2$ rule. Indeed recent theoretical ideas [1-3] have given rise to the possibility of a new effect in the difference of the partial decay rates between particles and antiparticles. Based on this theoretical context arguments for future accelerators [4] and experiments [5] have been discussed. In this letter we draw the attention of experimentalists to the implication of CPT invariance for such a new effect in the strange particle decays (kaons and Λ -hyperons).

It has been argued [1-3] that a new CP-violating parameter D_K (D_Λ) measured by the asymmetry

$$D_K^{+-} = \frac{|A(K^0 \rightarrow \pi^0 \pi^0)|^2 - |A(\bar{K}^0 \rightarrow \pi^0 \pi^0)|^2}{|A(K^0 \rightarrow \pi^0 \pi^0)|^2}, \quad D_\Lambda = \frac{|A(\Lambda \rightarrow N\pi)|^2 - |A(\bar{\Lambda} \rightarrow \bar{N}\pi)|^2}{|A(\Lambda \rightarrow N\pi)|^2} \quad (1)$$

may appear because of the simultaneous complexity of the coupling constants and the complexity of the amplitudes arising from a possible absorptive part. The only relevant absorptive part can, however, be obtained from a "Penguin" type graph G (fig. 1) whenever the quark line in the loop can be put on its mass shell, resulting in a time-like gluon four-momentum. It is important to notice that such an effect would arise from an interference in the dominant isospin amplitude and therefore the asymmetries in eq. (1) would not be suppressed by the $\Delta I = 1/2$ rule and thus be of order ϵ . At the quark level this amplitude has a non-zero absorptive part for the case of a u-quark in the phase-space region $4m_u^2 \leq q^2 \leq (m_K - 2m_\pi)^2$, with m_u , m_π , and m_K being the mass of the u-quark, of the pion, and of the kaon, respectively, and q^2 the gluon momentum. In this framework the absorptive part of the diagram G can be estimated to be the operator

$$\frac{G_F}{\sqrt{2}} \frac{\alpha_s}{12\pi} (-i\pi) U_{su} U_{ud}^* \left(\bar{s}_L \gamma^\mu \frac{\lambda^a}{2} d_L \right) \left(\bar{u}_L \gamma_\mu \frac{\lambda^a}{2} u_L + \bar{d}_L \gamma_\mu \frac{\lambda^a}{2} d_L \right) \quad (2)$$

sandwiched between initial $|K^0\rangle$ and final $|\pi\pi\rangle$ states, where G_F is the Fermi coupling constant, α_s the strong coupling constant, and the factors U_{ij} are the Kobayashi-Maskawa matrix elements. Then the quantities D_K and D_Λ are given by

$$D_K = 4 \left[\text{Re } \Delta_K + \text{Re } \epsilon' \right], \quad D_\Lambda = \text{Re } \Delta_\Lambda + \text{Re } \epsilon'_\Lambda, \quad (3)$$

where Δ_K (Δ_Λ) is of the order of ϵ and is related to the absorptive part of the "Penguin" diagram involving u-quarks [eq. (2)]. If this argument is correct, then in particular the quantity D_K could be measured to an accuracy of 10^{-5} , two orders of magnitude better than D_Λ , using the intense source of tagged K^0 and $\bar{K}^0$ beams at LEAR, as described elsewhere [6].

However, the CPT invariance implies striking limitations to such an effect in the strange particle decays. We repeat some remarks of Pais and Treiman [7,8] and Carter and Sanda [9] concerning the constraints imposed by CPT symmetry and

their implications for observing CP violation. The CPT symmetry requires the total widths of a particle P and of its antiparticle $\bar{P}$ to be equal

$$\sum_i \Gamma(P \rightarrow F_i) \stackrel{\text{CPT}}{=} \sum_i \Gamma(\bar{P} \rightarrow \bar{F}_i) , \quad (4)$$

where F_i is a final state into which P can decay and $\bar{F}_i$ is the corresponding CP-conjugate state. Further, if one organizes the states F_i into subgroups $\{F_i\}_\alpha$, $\{F_i\}_\beta$, etc., such that the states within each subgroup couple to one another via strong final-state interactions, but that there are no such interactions between states in different subgroups, then the partial width of P for each subgroup must be equal to the width of $\bar{P}$ for the corresponding subgroup of conjugate states owing to CPT. For the case of strange particles the different subgroups can be labelled by the isospin quantum number I:

$$\sum_i \Gamma[P \rightarrow (I=j)_i] \stackrel{\text{CPT}}{=} \sum_i \Gamma[\bar{P} \rightarrow (I=j)_i] , \quad (5)$$

with $j = 0, 1, 2, 3$ for kaons, and $j = 1/2, 3/2$ for Λ 's. If a subgroup contains only a single state, then comparison of decays in that channel and its conjugate can provide no information about CP symmetry. For the strange particle decays each isospin subgroup [eq. (5)] contains only a single state, i.e. $i = 1$:

$$|0\rangle = \frac{\sqrt{2}}{\sqrt{3}} |\pi^+\pi^-\rangle - \frac{\sqrt{1}}{\sqrt{3}} |\pi^0\pi^0\rangle$$

$$|1\rangle = \frac{\sqrt{2}}{\sqrt{5}} |\pi^+\pi^-\pi^0\rangle + \frac{\sqrt{3}}{\sqrt{5}} |\pi^0\pi^0\pi^0\rangle$$

$$|2\rangle = \frac{\sqrt{1}}{\sqrt{3}} |\pi^+\pi^-\rangle + \frac{\sqrt{2}}{\sqrt{3}} |\pi^0\pi^0\rangle$$

$$|3\rangle = \frac{\sqrt{3}}{\sqrt{5}} |\pi^+\pi^-\pi^0\rangle - \frac{\sqrt{2}}{\sqrt{5}} |\pi^0\pi^0\pi^0\rangle$$

$$|\frac{1}{2}\rangle = -\frac{\sqrt{2}}{\sqrt{3}} |\pi^-p\rangle + \frac{\sqrt{1}}{\sqrt{3}} |\pi^0n\rangle$$

$$|\frac{3}{2}\rangle = \frac{\sqrt{1}}{\sqrt{3}} |\pi^-p\rangle + \frac{\sqrt{2}}{\sqrt{3}} |\pi^0n\rangle$$

Owing to the limited phase space a second channel is forbidden, i.e. the isospin zero state from the four-pion decay. The presence of such an effect Δ_K (Δ_Λ) in the strange particle decays would simply violate CPT invariance in the absence of many hadronic decay channels which possess equal quantum numbers conserved by strong interactions. Indeed, for the hyperons there is only one set of channels, namely the nucleon-pion channel. Although in the neutral-kaon system there are two sets of channels, the two- and the three-pion channel, the situation is similar. The two-pion state does not communicate via strong interactions with the three-pion state and, consequently, CPT invariance should hold for each decay channel separately. Thus for strange particle decays CPT invariance requires equal partial decay rates for the same isospin amplitude. The only difference in the partial decay rates can arise from the interference of different isospin or different spin amplitudes, resulting in an effect suppressed by the $\Delta I = 1/2$ rule or the centrifugal barrier. As a matter of fact it can be roughly estimated that the p-wave decay amplitude for Λ 's is suppressed by a factor of 1/14 relative to the s-wave decay amplitude.

In a diagrammatic approach, at the quark level described in refs. 1-3, the cut in fig. 1 must be interpreted as a physical one, i.e. the quark states should be identified with physical particles. In the situation of only one hadronic channel, this physical cut is, however, already taken into account in the final-state strong interactions. The imaginary part of the graph G (fig. 1) giving rise to this new effect is

$$\text{Im } G = \sum_n \langle \pi\pi | X_n \rangle_s \langle X_n | K^0 \rangle_w ,$$

where the quark lines at the cut are replaced by a sum over all possible intermediate states X_n (strong interactions eigenstates). The subscript n labels the states X by quantum numbers conserved by strong interactions. The amplitude $\langle X_n | K^0 \rangle_w$ denotes the weak transition $K^0 \rightarrow X_n$ while $\langle \pi\pi | X_n \rangle_s$ denotes the transition of the X_n state to a $\pi\pi$ final state via emission of a time-like gluon. Of all

physical states only the 2π ($I = 0$) state contributes, since we actually deal with a $\Delta I = 1/2$ operator, so that

$$\text{Im}(G) = \langle \pi\pi | \pi\pi(I=0) \rangle_s \langle \pi\pi(I=0) | K^0 \rangle_w ,$$

where $\langle \pi\pi(I=0) | K^0 \rangle_w$ is the ordinary weak transition amplitude for $K^0 \rightarrow 2\pi(I=0)$, which in the literature is denoted usually by A_0 . The amplitude $\langle \pi\pi | \pi\pi(I=0) \rangle_s$ is part of the strong amplitude for $\pi\pi(I=0) \rightarrow \pi\pi(I=0)$, which is $e^{i\delta_0}$ with δ_0 being the strong isospin zero phase shift. Thus, the $\text{Im}(G)$ has already been taken into account by writing the total amplitude as $e^{i\delta_0} \langle \pi\pi(I=0) | \bar{K}^0 \rangle_w$ and gives no further contribution other than the phase δ_0 . The real part of the diagram G (fig. 1) does contribute and renormalizes the $\Delta I = 1/2$ effective Hamiltonian giving the well-known "Penguin" effects, which have been extensively studied in the literature [10,11].

Consequently the quantity Δ_K (Δ_Λ) is certainly not of the order of ε , but in the best case is of the order of $\alpha\varepsilon$, where α is the coupling of the electromagnetic interaction violating isospin invariance.

Thus, the difference in the partial decay rates is suppressed by the $\Delta I = 1/2$ rule and is hence only of the order of ε' :

$$D_K = 4 \text{ Re } \varepsilon' , \quad D_\Lambda = \text{Re } \varepsilon'_\Lambda$$

with

$$\frac{\varepsilon'}{10} < \varepsilon_\Lambda \leq \varepsilon' .$$

Summarizing, we conclude that any CP-violating effect in the decay matrix of strange particles is suppressed by the $\Delta I = 1/2$ rule or centrifugal barrier effects, owing to the limited phase space in these systems and the CPT invariance. On the contrary, such an effect in heavy-quark systems can be appreciably large and in agreement with CPT invariance. In fact, in these systems because the momentum transfer of the time-like gluon in fig. 1 can be quite large the cut on the light-quark loop represents a sum over many physical intermediate states allowed by the large phase space [12].

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Fig. 1 : The "penguin" diagram