CONSTRAINTS ON THE OBSERVABILITY OF CP VIOLATION IN THE DECAYS OF CHARGE CONJUGATE HADRONS

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The decay rates of charge conjugate hadrons into channels related by CP may be different as a result of CP violation. However, CPT invariance requires the total decay rates of charge conjugate states to be equal. Thus any asymmetry in the decay to one pair of CP conjugate channels must be balanced by an opposite asymmetry elsewhere in order to give equal decay rates. For example, Carter and Sanda[1] have suggested a possible asymmetry between the decays

$$B^{-} \rightarrow K_S + K_S + X_n \tag{1a}$$

$$B^{+} \rightarrow K_S + K_S + \bar{X}_n , \tag{1b}$$

where X_n and $\bar{X}_n$ are any pair of CP conjugate states. To conserve CPT this symmetry must be compensated elsewhere. The question then arises of how this compensation takes place and what the relation is between the sets of compensating channels. This relation can be stated explicitly in the form of the following theorem:

Theorem: Any asymmetry between partial decay rates of states which go into one another under CPT must be balanced by an opposite asymmetry in a set of channels which are related to the original decay channels by a symmetry operation which is conserved in strong interactions and violated in weak interactions.

Proof: Consider the complete set of decay amplitudes for a pair of charge conjugate particles in a theory which has CP violation but conserves CPT. The additions of a "gedanken" final-state interaction to this model which is invariant under all the symmetries of strong interactions cannot introduce a violation of CPT. Thus the total decay rates of charge conjugate states must remain equal when such a final-state interaction is introduced.

Consider a final-state interaction which is a potential barrier with a range of ten fermis and which acts only in a single channel, together with all other channels related to it by strong-interaction symmetries. This suppresses the decay into a given set of channels related by symmetries, leaving all other decays unchanged. If this is not to destroy the initial equality of the total decay rates, the sum of the partial decay rates into the particular set of channels suppressed must be equal for the charge conjugate states, i.e., any asymmetry due to CP violation in one channel must be balanced by an opposite asymmetry within the set of states related by the symmetry.

The initial state is an eigenfunction of the mass operator which includes the strong interactions and therefore can be chosen to be an eigenstate of all strong interaction symmetries. If the symmetry defining the set of final states is conserved in the weak decay, there is only one channel in the final states related by this symmetry to which decay is allowed, and the charge conjugate decays must be symmetric to preserve CPT. If the symmetry is violated in weak interactions, e.g., conservation of strangeness, isospin, C or P, then final states which are not eigenstates of this symmetry can be produced in the decay and sets of states with opposite decay asymmetries can arise.

Corrolary: Violations of CP in decays of charge conjugate hadrons can be observed only in decay channels which are non-trivial coherent combination eigenstates of some symmetry conserved in strong interactions and violated in weak interactions.

A simple example of this theorem arises in the case of strangeness conservation, as in the case of the reactions (1). The K_S is a coherent state which is not a strangeness eigenstate. Decays which can go both into K^0X and $\bar{K}^0X$ modes can exhibit CP violation when observed in the K_SX and K_LX modes. Any asymmetry between decays of charge conjugate hadrons into K_Sx and $K_S\bar{X}$ modes would then be balanced by an opposite asymmetry in the decays to K_LX and $K_L\bar{X}$ modes, thus preserving the symmetry between total decay rates. In the example (1), the decay (1a) can go into different strangeness eigen channels.

$$B^- \to D^0\bar{K}^0X^- \to \bar{K}^0\bar{K}^0X^-Y^0 \tag{2a}$$

$$B^- \to \bar{D}\bar{K}^0X^- \to K^0\bar{K}^0X^+Y^0. \tag{2b}$$

The corresponding charge conjugate decays are

$$B^+ \to \bar{D}K^0X^+ \to K^0K^0X^+Y^0 \tag{3a}$$

$$B^+ \to DK^0X^+ \to \bar{K}^0K^0X^+Y^0. \tag{3b}$$

The corresponding decay rates into the charge conjugate strangeness eigenstates (2a) and (3a) are equal, and similarly for (2b) and (3b). But CP violation effects can appear in the relative phases and produce an asymmetry between the decays (1) into channels of mixed strangeness. This asymmetry is then compensated by decays into other channels where the K_S pairs in (4) are replaced by K_SK_L and K_LK_L pairs.

Decay rates into channels having different values of strangeness are related by factors of $\sin\theta_C$. In the cases relevant to this discussion, the two cases of K^0X and $\bar{K}^0X$ can either be both singly unfavored, or one can be favored and the other doubly unfavored. The above case involved two singly unfavored transitions.

An example of a favored and a doubly unfavored transition is in the decays

$$B^- \xrightarrow{F} D^0 \pi^- \xrightarrow{F} \bar{K}^0 M^0 \pi^- \tag{4a}$$

$$B^- \xrightarrow{F} D^0 \pi^- \xrightarrow{U2} K^0 M^0 \pi^- \tag{4b}$$

$$B^- \xrightarrow{U2} \bar{D}^0 \pi^- \xrightarrow{F} K^0 M^0 \pi^- \tag{4c}$$

and the conjugate decays

$$B^+ \xrightarrow{F} \bar{D}^0 \pi^+ \xrightarrow{F} K^0 M^0 \pi^+ \tag{5a}$$

$$B^+ \xrightarrow{F} \bar{D}^0 \pi^+ \xrightarrow{U2} \bar{K}^0 M^0 \pi^+ \tag{5b}$$

$$B^+ \xrightarrow{U2} D^0 \pi^+ \xrightarrow{F} \bar{K}^0 M^0 \pi^+, \tag{5c}$$

where M^0 is a neutral non-strange meson, state e.g., π^0, η or η', and F and U2 denote Cabibbo favored and doubly unfavored transitions. Observing the final states in the $K_S M^0 \pi^\pm$ modes can give asymmetries due to CP violation.

Note that the asymmetry in the decays (4) and (5) are of the same order in Cabibbo suppression as the decays (1). However the dominant decays (4a) and (5a) are favored whereas both (1a) and (1b) are singly unfavored. Thus, the CP isolation signal to background ratio is lower for (4) and (5) although the signals are of the same order.

This theorem is not quite as powerful as it may seem at first sight. Any hermitian operator which commutes with the strong interaction S-matrix defines a global U(1) symmetry. Thus in addition to the known symmetries there may be additional very peculiar symmetries not very easily found defined in this way. The known symmetries can be used to construct coherent states in which CP violation can be observed, as in Eqs. (1-5). But this does not exhaust the possibilities. Almost any state is a coherent linear combination of eigenstates of some peculiar U(1) symmetry of the type discussed above.

References

1. A. B. Carter and A. I. Sanda, Rockefeller U. preprint DOE/EY/2232B-203 (1980).