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New Puzzles in Nonleptonic B and D Decays

H.J. LIPKIN

Department of Particle Physics, Weizmann Institute, Rehovot 76100, Israel

and

School of Physics and Astronomy, Tel-Aviv University,

Tel-Aviv 69978, Israel

and

High Energy Physics Division, Argonne National Laboratory

Argonne, IL 60439-4815, USA

Exclusive charged B decays show an unexplained enhancement in low-lying channels which must be reversed in other channels to equalise charged and neutral lifetimes. One suggested explanation involves decay modes with excited mesons like the a_1. The anomalous behaviour of decay modes of D and B mesons into final states containing the η and η' mesons is discussed.

1 Systematics in charged and neutral quasi-two-body $B \to$ charm decays

The surprising enhancement of $B^{\pm}$ decays to low-lying exclusive channels[1] was first noted and explained with a hadron spectroscopy approach[2]. The enhancement required a *constructive* interference between color suppressed and color favored contributions, in contrast with previous predictions[1]. The enhancement could not be general because the B^o and $B^{\pm}$ lifetimes are nearly equal. The final states where constructive interference is observed all involve nodeless s-wave quark-model wave functions. The relative phase of the suppressed and favored diagrams depends upon hadron form factors whose signs can be reversed by the presence of nodes or orbital angular momentum in the wave functions. This wave function dependence can be checked experimentally by looking for systematic differences in the interference in final states containing excited quark-model wave functions in both B and D decays; e.g. $B \to Da_1$.

The analysis followed from noting that all diagrams for $B \to D+X$ decays could be grouped into three topologically distinct classes, denoted for historical reason as T, S and W. The final charmed antiquark can only combine to make the final D with (T) the spectator antiquark, (S) an antiquark from the weak vertex or (W) an antiquark created by gluons. The amplitudes T, S and W are defined as the sums of all possible diagrams satisfying the corresponding topological conditions. They are not calculated from strong interaction models. Their contributions including all FSI are considered as phenomenological parameters to be determined by experiment. They were shown to have definite

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isospin properties which related their contributions to final states within the same isospin multiplets.

Recently the conventional description has been modified[1] to include an additional energy-dependent (fudge?) factor that explains the surprising enhancement. But the assumption[1,3] that standard model B-decay is well understood and described by calculating the right diagrams can be questioned in view of still unexplained[3,4] long-standing regularities and paradoxes in simple experimental hadron physics. That $\sigma_{tot}(\pi p) = (2/3)\sigma_{tot}(pp) \pm 7\%$ up to highest energies tells us the pion is 2/3 of a proton, even though some theorists call pions Goldstone bosons and protons skyrmions. Other remarkable successes of the constituent quark model show that the relevant degrees of freedom describing static properties and low lying excitations are asymptotically free relativistic quasiparticles having quark charges, Dirac magnetic moments and an effective mass with exactly the same value for predicting hadron masses, magnetic moments and hyperfine splittings. As long as QCD calculations have not yet succeeded to explain these striking experimental facts, one does well to take standard QCD calculations for B and D decays with a few grains of salt and look for other approaches to understanding weak decay data; e.g. effects of hadron resonances[5] and form factors[2].

2 Puzzles in Decays to Final States Containing η and η' Mesons

2.1 Puzzles in $B^\pm \to K^\pm\eta'$ Decays

The recently reported high branching ratios led to suggestions for new types of diagrams. However, the standard penguin diagram predicts[6,7]

$$\tilde{\Gamma}(B^\pm \to K^\pm\eta') : \tilde{\Gamma}(B^\pm \to K^\pm\eta) : \tilde{\Gamma}(B^\pm \to K^\pm\pi^o) = 3 : 0 : 1 \qquad (1a)$$

$$\tilde{\Gamma}(B^\pm \to K^{*\pm}(890)\eta') : \tilde{\Gamma}(B^\pm \to K^{\pm *}\eta) : \tilde{\Gamma}(B^\pm \to K^{*\pm}\pi^o) = (1/3) : (8/3) : 1 \qquad (1b)$$

$$\frac{\tilde{\Gamma}(B^\pm \to K^\pm\eta') + \tilde{\Gamma}(B^\pm \to K^\pm\eta)}{\tilde{\Gamma}(B^\pm \to K^\pm\pi^o)} \leq 3 \qquad (1c)$$

where $\tilde{\Gamma}$ denotes the theoretical partial width without phase space corrections. We have assumed SU(3) symmetry with one of the standard mixings:

$$|\eta\rangle = \frac{1}{\sqrt{3}} \cdot (|P_u\rangle + |P_d\rangle - |P_s\rangle); \quad |\eta'\rangle = \frac{1}{\sqrt{6}} \cdot (|P_u\rangle + |P_d\rangle + 2\,|P_s\rangle) \qquad (2)$$

where $|P_f\rangle$ denotes a pseudoscalar $f\bar{f}$ state $|P_f\rangle \equiv \left|f\bar{f}\right\rangle_{0^-}$ and noted that the penguin diagram creates the two states $K^\pm P_u$ and $K^\pm P_s$, with a relative phase depending upon the orbital angular momentum L of the final state.

$$A(B^{\pm} \to K^{\pm} P_s) = (-1)^L \cdot (1-\epsilon) \cdot A(B^{\pm} \to K^{\pm} P_u) \tag{3}$$

where ϵ is a parameter describing SU(3) symmetry breaking and $K^{\pm}$ can also denote any K^* resonance. The sum rule inequality (1c) holds generally for all mixing angles and for all positive values of ϵ. This suggests that there is no point in inventing new mechanisms until it is clear that the observed $K^{\pm}\eta$ enhancement is greater than a factor of 3 over $K^{\pm}\pi^o$.

The dramatic reversal of the $\eta'/\pi^o/\eta$ ratio in the final states with $K^{*\pm}(890)$ occurs naturally in this penguin interference model and does not occur in any other suggestion for enhancing the η'. Present data indicate $K^{*\pm}(890)\eta'$ suppression. Better data showing significant suppression will rule out most other η' enhancement mechanisms.

A violation of the inequality (1c) would require an additional contribution. The Cabibbo favored charmed tree diagram $A(B^{\pm} \to K^{\pm} P_c \to K^{\pm}\eta')$ can contribute via hidden or intrinsic charm in the η' wave function and may contribute appreciably even though the charm in the η' is quite small.

We now estimate the effect of an additional contribution from the production of the η and η' via an additional diagram which in the SU(3) symmetry limit produces the states $|P_u\rangle$, $|P_d\rangle$ and $|P_s\rangle$ with equal amplitudes.

$$A(B^{\pm} \to K^{\pm}\eta) = \sqrt{2/3} \cdot \xi \cdot A(B^{\pm} \to K^{\pm}\pi^o) \tag{4a}$$

$$A(B^{\pm} \to K^{\pm}\eta') = \sqrt{1/3} \cdot (3+4\xi) \cdot A(B^{\pm} \to K^{\pm}\pi^o) \tag{4b}$$

$$A(B^{\pm} \to K^{*\pm}(890)\eta) = \sqrt{2/3} \cdot (2-\xi) \cdot A(B^{\pm} \to K^{*\pm}\pi^o) \tag{4c}$$

$$A(B^{\pm} \to K^{*\pm}(890)\eta') = -\sqrt{1/3} \cdot (1+4\xi) \cdot A(B^{\pm} \to K^{*\pm}\pi^o) \tag{4d}$$

where ξ defines the extra contribution strength. For $\xi = 0.5$

$$\tilde{\Gamma}(B^{\pm} \to K^{\pm}\eta') : \tilde{\Gamma}(B^{\pm} \to K^{\pm}\eta) : \tilde{\Gamma}(B^{\pm} \to K^{\pm}\pi^o) = (25/3) : (1/6) : 1 \tag{5a}$$

$$\tilde{\Gamma}(B^{\pm} \to K^{*\pm}(890)\eta') : \tilde{\Gamma}(B^{\pm} \to K^{\pm *}\eta) : \tilde{\Gamma}(B^{\pm} \to K^{*\pm}\pi^o) = 3 : (1.5) : 1 \tag{5b}$$

$$\tilde{\Gamma}(B^{\pm} \to K^{\pm}\eta') + \tilde{\Gamma}(B^{\pm} \to K^{\pm}\eta)/\tilde{\Gamma}(B^{\pm} \to K^{\pm}\pi^o) \leq (17/2) \tag{5c}$$

The inequality (5c) holds for all mixing angles and all $\epsilon \geq 0$. Thus a comparatively small contribution interfering constructively with the dominant penguin can give an appreciable enhancement. With ξ sufficiently large to give (25/3) for $(\tilde{\Gamma}(B^{\pm} \to K^{\pm}\eta') : \tilde{\Gamma}(B^{\pm} \to K^{\pm}\pi^o)$ and a 50:1 ratio favoring η' over η, the enhancement of η' over η is only a factor of two for the K^* final state. The drastic difference between the K and K^* branching ratios still persists if both the penguin and the extra contribution are present, in contrast to the case where the extra contribution is dominant. Thus the K^* data are important for determining the exact mechanism for the η' enhancement.

2.2 The $D_s \to \eta\pi$, $\eta'\pi$, $\eta\rho$ and $\eta'\rho$ puzzles.

The anomalously large η'/η ratio cannot come from a spectator tree diagram. But there is no clear indication of the nature of the additional contribution needed. The four channels for D_s decays with different parities and G-parities are not mixed by final state interactions. Positive G-parity is exotic for both parities and cannot have contributions that go via an intermediate state of a single quark-antiquark pair. $\rho - \eta$ is exotic and $\pi - \eta$ is not; yet both states seem to have the same anomalously large branching ratios and favor the η'. There seems to be a common mechanism independent of the quantum number of the final state. The required additional contribution cannot be a simple annihilation without additional gluons emitted before annihilation since this produces a G-parity eigenstate which is right for $\eta'\pi$, but wrong for $\eta'\rho$.

Annihilation with at least two gluons emitted from the initial state and interaction between these gluons and the $u\bar{d}$ state produced by an annihilation diagram could give a small amplitude which might interfere constructively with the η' amplitudes and destructively with the η amplitudes. However, this diagram must also show up in other G-forbidden even-π amplitudes. If sufficient data are obtained to place stringent upper limits on this diagram, this mechanism is excluded.

Annihilation with two gluons emitted from the initial state which then turn into an η' via a hairpin diagram will produce the η' rather than the η because gluons are SU(3) singlets. This mechanism can be compared with the radiative decay $J/\psi \to \eta'\gamma$ which is also dominated by a two-gluon hairpin diagram. However, one would also expect to see this diagram in the semileptonic decay $D_s \to \eta'\mu^+\nu_\mu$ where the η'/η ratio does not seem to be enhanced.

3 Other Puzzling Systematics in D_s Decays

3.1 The annihilation puzzle.

The observation of the purely leptonic annihlation decay $D_s \to W^+ \to \mu^+\nu_\mu$ implies the existence of the hadronic annihilation without gluons $D_s \to W^+ \to u\bar{d} \to (2n+1)\pi$ where the G parity of a J=0 $u\bar{d}$ state without additional gluons forbids the decay into an even number of pions.

It is therefore of interest to look for:

a. The forbidden $D_s \rightarrow 2n\pi$ decays. Even upper limits are of interest. Definite evidence would indicate some contribution other than the simple annihilation. Note that this goes beyond the search for the forbidden $\omega - \pi$ mode. Any state which ends up as an even number of pions is forbidden and its observation gives information about the existence of other annihilation-type diagrams including gluons or final-state rescattering.

b. The allowed D_s decays into states containing an odd number of pions. These decays must be there somewhere to be consistent with the observed leptonic decay.

c. Decays into states with several neutral pions may be difficult to detect. States with a single neutral pion can come from allowed odd-G decays into an η and an even number of charged pions. Thus it might be useful to examine all multipion decays with no more than one neutral and classify them as follows:

All D_s decays into an odd number of charged pions and nothing else.

All D_s decays into an odd number of charged pions and an η.

All D_s decays where no η is present into an odd number of charged pions and a single π^o.

The relative numbers of these three inclusive final states might give information on the validity of the G-parity selection rule.

3.2 Color Suppression not seen in $D_s \rightarrow VP$ and VV Decay Modes

There is no significant suppression of the "color-suppressed" KK^* and K^*K^* modes relative to the "color-favoured" $\phi\pi$ and $\phi\rho$. Comparing the VP and VV decays of the D^o and D_s, which differ only by spectator quark flavor, one sees definite color suppression in D^o decays in contrast to what is observed in D_s. How can changing the flavor of a spectator quark drastically change the degree of color suppression in tree diagrams where the spectator quark does not play an active role?

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