PHYSICAL REVIEW LETTERS

VOLUME 46 | 18 MAY 1981 | NUMBER 20

Importance of the $K\eta$ and $K\eta'$ Decay Modes in Understanding Charmed and Other Meson Decays

Harry J. Lipkin[(a)]

Fermi National Accelerator Laboratory, Batavia, Illinois 60510, and Argonne National Laboratory, Argonne, Illinois 60439

(Received 3 November 1980)

The $D^0 \to \bar{K}^0\eta$ decay mode is shown to be suppressed by a large factor insensitive to η-η' mixing and SU(3)-symmetry breaking in all transitions via intermediate states with flavor quantum numbers of a $q\bar{q}$ pair, e.g., SU(3) octet, but to be roughly equal to the $\bar{K}^0\pi^0$ and $\bar{K}^0\eta'$ when produced via exotic $qq\bar{q}\bar{q}$ channels. The relative decay rates to $\bar{K}^0\eta$, $\bar{K}^0\eta'$, and $\bar{K}^0\pi^0$ distinguish between models producing the additional $q\bar{q}$ pair in weak or strong vertices.

PACS numbers: 13.25.+m, 12.30.-s, 14.40.Pe

Nonleptonic decays of charmed mesons appear to be complicated and not to fit any simple model.[1-10] Attempts to understand these decays either by symmetries or dynamics involve fitting a number of branching ratios with several independent amplitudes, either with different symmetry properties or arising from different diagrams. Assumptions that any one particular symmetry amplitude or diagram is dominant have not been successful, and complications from strong final-state interactions and SU(3)-symmetry breaking are difficult to include.[5]

This paper presents an alternative approach of combining weak-interaction models with known features of strong-interaction phenomenology to find striking signatures which can distinguish between different classes of models. The peculiar flavor symmetry properties of the $K\eta$ and $K\eta'$ channels provide such a signature, namely the *suppression of the* $D^0 \to \bar{K}^0\eta$ *decay by an order of magnitude in any transition via intermediate states with SU(3) octet flavor quantum numbers; e.g., a single quark-antiquark pair and one or more gluons.* This suppression is rigorous in the SU(3)-symmetry limit, even in the presence of strong final-state interactions, and is insensitive to η-η' mixing and SU(3)-symmetry breaking. The $K\eta$ and $K\eta'$ decay modes are normally overlooked because they are theoretically complicated by mixing and experimentally difficult to observe. However, the suppression effect is so striking that it is of interest to search for this decay mode in experiments and to analyze data for upper limits if it is not seen.

The basis of the suppression is easily seen in both SU(3) and quark-diagram descriptions, which are mathematically equivalent in the SU(3)-symmetry limit. The even-parity $K\eta_8$ states are "almost exotic" even though their isospin and hypercharge quantum numbers, $I=\frac{1}{2}$ and $Y=1$, are not exotic. Their SU(3) classification has 90% of the wave function in the exotic $\underline{27}$ representation and only 10% in the octet. The $K\eta_1$ state, on the other hand, is 100% pure octet. Thus the $K\eta_8$ decay mode is suppressed by an order of magnitude in any transition via octet intermediate states. This has been noted in the strong decays of even-parity K^* resonances and in experimental analyses of s-wave $K\pi$ scattering.[11] Of particular interest for D^0 decays is the result that $K\eta'$ is the dominant inelastic channel for $K\pi$ scattering in the D-mass region with no evidence[11] for coupling to $K\eta$. This strongly suggests that any weak-interaction model which predicts a sup-

© 1981 The American Physical Society

pression of the $\bar{K}\eta$ decay mode retains this prediction even in the presence of strong final-state interactions; i.e., that the decoupling of $K\eta$ which is rigorous in the SU(3)-symmetry limit still holds in the real world as investigated by experimental $K\pi$ scattering.

The $\bar{K}^0\eta$ decay mode is unhindered in D^0 decays described by diagrams of the general form shown in Fig. 1, where the weak decay leads to a nontrivial four-quark state with exotic $\overline{27}$ components. However, $\bar{K}^0\eta$ is suppressed in the SU(3) limit by an order of magnitude in all diagrams that have the general form shown in Fig. 2 with a pure octet intermediate state of a single quark-antiquark pair and one or more gluons. Many models include dominant diagrams that have the general form of Fig. 2, and therefore predict the suppression $\bar{K}^0\eta$. One example is the annihilation diagram.

In the quark picture the $\bar{K}\eta$ suppression is easily seen in Fig. 2, where the $q\bar{q}$ pair produced by the gluon can be either $d\bar{d}$ or $s\bar{s}$. The two amplitudes producing the $\bar{K}\eta$ state via the $d\bar{d}$ or $s\bar{s}$ components of the η interfere destructively because of the negative phase in the η wave function. This gives exactly the same suppression factor as the mathematically equivalent SU(3) treatment. However, the quark picture also indicates the direction of the corrections for η-η' mixing and SU(3) breaking. The destructive interference is not complete because the $s\bar{s}$ component in the η_8 wave function is larger than the $d\bar{d}$ component and the two contributions do not exactly cancel. However, the dominant effects of mixing and SU(3)-symmetry breaking both reduce the $s\bar{s}$ contribution and suppress the $\bar{K}\eta$ decay even further by making the cancellation more nearly complete. Thus the decoupling of the $\bar{K}\eta$ channel is stable against effects of mixing and symmetry breaking, as indicated experimentally by the $K\eta$ scattering results.[11]

For a more quantitative description of these effects we consider in detail the decays $D^0 \to \bar{K}^0 P^0$, where P^0 is a neutral pseudoscalar meson, π^0, η, or η'. There is one quark-antiquark pair in the initial state and two pairs in the final state. There are only two mechanisms for the creation of the additional pair, one weak and one strong, shown in Figs. 1 and 2. The box denotes any arbitrary set of diagrams.

(1) *The additional pair is created directly in the weak decay of the charmed quark* $c \to su\bar{d}$, with no further pair annihilation and re-creation in final-state interactions. In this case the final state has the quark constituents $(s\bar{d})$ $(u\bar{u})$ and the neutral pseudoscalar P^0 is created via its $u\bar{u}$ component.

(2) *The additional pair is created by a strong gluon.* This includes both the diagrams where the weak transition leads to a single $q\bar{q}$ state and the additional pair is created by gluons either before or after the weak transition, and the diagrams where a $u\bar{u}$ pair created in a weak transition via the mechanism (1) above is annihilated into one or more gluons and a new $q\bar{q}$ pair is created.

The transition amplitude for the mechanism (1) can be written

$$\langle \bar{K}^0 P^0 | W_1 | D^0 \rangle = \langle P^0 | P_u \rangle \langle \bar{K}^0 P_u | W_1 | D^0 \rangle, \qquad (1)$$

where P_u, P_d, and P_s denote the neutral pseudoscalar meson states with the quark constituents $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$, respectively. Equation (1) expresses the observation that transitions via this mechanism must go by the $u\bar{u}$ state.

The transition amplitude for the mechanism (2) can be written

$$\langle P_1 P_2 | W_2 | D^0 \rangle = \langle P_1 P_2 | G | (s\bar{d}) \rangle \langle (s\bar{d}) | W | D^0 \rangle, \quad (2)$$

where P_1 and P_2 are any two pseudoscalar mesons, charged or neutral, G is the operator which denotes the transition from a single $q\bar{q}$ pair to two pairs by strong gluon interactions, and W describes the weak transition from the initial D^0 state to an intermediate $(s\bar{d})$ state, including effects of strong gluon interactions. The state denoted by the flavor quantum numbers $(s\bar{d})$ may contain an arbitrary number of flavor singlet gluons in addition to the $(s\bar{d})$ pair. Equation (2) expresses the essential feature of mechanism (2);

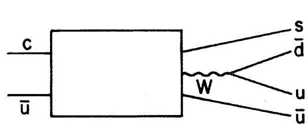

FIG. 1. Weak pair creation.

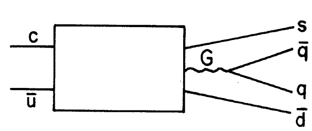

FIG. 2. Strong pair creation. G denotes any number of gluons.

namely that the transition proceeds via an intermediate $q\bar{q}$ state which must be $s\bar{d}$ to conserve charge and strangeness in the strong transition to the final state. The flavor dependence of the gluon matrix element is given by

$$\langle (s\bar{u})(u\bar{d})|G|(s\bar{d})\rangle = \langle (s\bar{d})(d\bar{d})|G|(s\bar{d})\rangle = (1/\xi)\langle (s\bar{s})(s\bar{d})|G|(s\bar{d})\rangle, \quad (3)$$

where ξ is an SU(3)-breaking parameter which is unity in the flavor SU(3) limit and is generally less than unity.[12] We consider amplitudes in which the additional $q\bar{q}$ pair produced is split between the two final mesons, in accordance with the Okubo-Zweig-Iizuka rule. Thus the $u\bar{u}$ amplitude contributes only to charged decay modes.

The gluon matrix element for the physical meson final states is then given by

$$\langle P_1P_2|G|(s\bar{d})\rangle = \sum_{q=u,d,s} \langle P_1|(s\bar{q})\rangle\langle P_2|(q\bar{d})(s\bar{q})(q\bar{d})|G|(s\bar{d})\rangle. \quad (4)$$

The overlaps between the quark states and the pseudoscalar mesons are assumed to be simply related, i.e., all mesons in the pseudoscalar nonet are assumed to have the same spatial wave functions:

$$\langle K^-|(s\bar{u})\rangle = \langle \bar{K}^0|(s\bar{d})\rangle = \langle P_s|(s\bar{s})\rangle = \langle \pi^-|(u\bar{d})\rangle = \langle P_d|(d\bar{d})\rangle = \langle P_u|(u\bar{u})\rangle. \quad (5)$$

This standard assumption in phenomenological quark models is supported by the success of SU(3) predictions for strong hadronic decays, and by the theoretical observation that overlap integrals between nodeless $q\bar{q}$ wave functions are very insensitive to radial size differences between the states. The neutral mesons are related to the P_u, P_s, and P_d states by the usual expressions,

$$|\pi^0\rangle = (1/\sqrt{2})|P_u - P_d\rangle, \quad (6a)$$

$$|\eta_8\rangle = (1/\sqrt{6})|P_u + P_d - 2P_s\rangle, \quad (6b)$$

$$|\eta_1\rangle = (1/\sqrt{3})|P_u + P_d + P_s\rangle, \quad (6c)$$

$$|\eta\rangle = \tfrac{1}{2}|P_u + P_d - \sqrt{2}P_s\rangle, \quad (7a)$$

$$|\eta'\rangle = \tfrac{1}{2}|P_u + P_d + \sqrt{2}P_s\rangle, \quad (7b)$$

where η_8 and η_1 are the SU(3) octet and singlet states and Isgur's mixing angle[13] has been used to define the physical η and η'. Our results are insensitive to the exact value of this mixing angle.

Substituting Eqs. (3)–(7) into Eqs. (1) and (2) gives the following results:

$$\langle \bar{K}^0\pi^0|W_1|D^0\rangle = \sqrt{3}\langle \bar{K}^0\eta_8|W_1|D^0\rangle = (\tfrac{3}{2})^{1/2}\langle \bar{K}^0\eta_1|W_1|D^0\rangle, \quad (8a)$$

$$\langle \bar{K}^0\pi^0|W_1|D^0\rangle = \sqrt{2}\langle \bar{K}^0\eta|W_1|D^0\rangle = \sqrt{2}\langle \bar{K}^0\eta'|W_1|D^0\rangle. \quad (8b)$$

In the SU(3) limit, $\xi = 1$,

$$-\langle \bar{K}^0\pi^0|W_2|D^0\rangle = \sqrt{3}\langle \bar{K}^0\eta_8|W_2|D^0\rangle = (\tfrac{3}{8})^{1/2}\langle \bar{K}^0\eta_1|W_1|D^0\rangle. \quad (9a)$$

In general, for arbitrary values of ξ,

$$-\langle \bar{K}^0\pi^0|W_2|D^0\rangle = [\sqrt{2}/(1-\sqrt{2}\xi)]\langle \bar{K}^0\eta|W_2|D^0\rangle = [\sqrt{2}/(1+\sqrt{2}\xi)]\langle \bar{K}^0\eta'|W_2|D^0\rangle. \quad (9b)$$

Equations (8a) and (8b) show that the transitions to the $\bar{K}^0\pi^0$, $\bar{K}^0\eta$, and $\bar{K}^0\eta'$ states via mechanism (1) are roughly equal and insensitive to the mixing angle. However, Eqs. (9a) and (9b) show that the transition via mechanism (2) to the $\bar{K}^0\eta$ final state is strongly suppressed over a wide range of mixing angles and SU(3)-symmetry breaking. The ratio of the reduced transition probabilities (with phase space factored out) for the $\bar{K}\eta$ and $\bar{K}\eta'$ transitions is $\frac{1}{3}$ in the SU(3) limit with no mixing. Both mixing and SU(3) breaking make the suppression stronger. With the Isgur mixing angle, the suppression factor is $[(1-\sqrt{2}\xi)/(1+\sqrt{2}\xi)]^2$. This is less than $\frac{1}{9}$ for all values of ξ between $\sqrt{2}$ and $1/\sqrt{8}$. Thus the $\bar{K}\eta$ decay mode is suppressed at least by a factor of 9 relative to $\bar{K}\eta'$ when the probability of producing an $(s\bar{s})$ pair from the vacuum is anywhere between double and $\frac{1}{8}$ of the probability of producing a $(d\bar{d})$ pair.

Thus a measurement of the $\bar{K}^0\pi^0$, $\bar{K}^0\eta$, and $\bar{K}^0\eta'$ branching ratios in the D^0 decay should be able to distinguish between the two mechanisms.[14] Even an upper limit on the ratio of unobserved $\bar{K}^0\eta$ decays to $\bar{K}^0\pi^0$ decays is significant. It rules out mechanism (1) if it is well below the prediction (8a) of $\frac{1}{3}$.

This approach can be applied to any process which decays to $\bar{K}^0P^0$ or $\bar{K}^{*0}P^0$ states via an intermediate $s\bar{d}$ state. The results are a straightforward generalization of the well-known SU(3) predictions that the $K\eta_1$ and $K^*\eta_1$ decays are forbidden in transitions with F-type coupling and the $K\eta_8$ and $K^*\eta_8$ decays are suppressed by a factor of 3 relative to the π^0 decays with D-type coupling and suppressed by a factor of 8 relative to the η'

decays if the Okubo-Zweig-Iizuka rule is assumed in addition to D coupling. When SU(3) breaking and mixing described by Isgur's angle are included, the results analogous to Eqs. (9) are as follows:

$$-\langle \bar{K}^0\pi^0|G|(s\bar{d})\rangle = [\sqrt{3}/(1 \mp 2\xi)]\langle \bar{K}^0\eta_8|G|(s\bar{d})\rangle = [(\tfrac{3}{2})^{1/2}/(1 \pm \xi)]\langle \bar{K}^0\eta_1|G|(s\bar{d})\rangle, \tag{10a}$$

$$-\langle K^0\pi^0|G|(s\bar{d})\rangle = [\sqrt{2}/(1 \mp \sqrt{2}\xi)]\langle \bar{K}^0\eta|G|(sd)\rangle = [\sqrt{2}/(1 \pm \sqrt{2}\xi)]\langle K^0\eta'|G|(sd)\rangle, \tag{10b}$$

where the upper sign is used for transitions described by D-type coupling and the lower sign for F-type coupling. Whether the coupling is D or F depends in this case upon whether the amplitude is symmetric or antisymmetric under the interchange of the two final-state mesons. In the s-wave D^0 decays (9), the amplitude is symmetric and the upper sign of (10) is seen to be in agreement with the results (9). The results (10) hold for any $(s\bar{d})$ intermediate state and the K^0 can be replaced by any K^* resonance or other state with the same flavor quantum numbers.

If the three-body decays $D^0 \to \bar{K}\pi P^0$ are dominated by the W_2 mechanism, then the $K^*(890)\eta$ channel should be enhanced and the $K^*(890)\eta'$ suppressed (but probably unobservable because of low phase space). However, for an s-wave $\bar{K}\pi$ system the $\bar{K}\pi\eta$ mode is suppressed and the $\bar{K}\pi\eta'$ enhanced. Thus if both decays are observed, the Dalitz plots for the two should be very different.

Application of these results to decays of strong K^* resonances may be of interest. Precise measurements of the suppression factors may give information on the mixing angles and SU(3) breaking.

[a]On leave from Department of Physics, Weizmann Institute of Science, Rehovot, Israel.

[1]For a general review, see C. Quigg, Z. Phys. C 4, 55 (1980).

[2]M. Suzuki, Phys. Lett. 85B, 91 (1979), and Phys. Rev. Lett. 43, 818 (1979); V. Barger and S. Pakvasa, Phys. Rev. Lett. 42, 1589 (1979); L.-L. C. Wang and F. Wilczek, Phys. Rev. Lett. 43, 816 (1979).

[3]N. Deshpande, M. Gronau, and D. Sutherland, Phys. Lett. 90B, 431 (1980); H. Fritzsch, Phys. Lett. 86B, 343 (1979); H. Fritzsch and P. Minkowski, Phys. Lett. 90B, 455 (1980).

[4]N. Cabibbo and L. Maiani, Phys. Lett. 73B, 418 (1978); D. Fakirov and B. Stech, Nucl. Phys. B133, 315 (1978); S. P. Rosen, Phys. Lett. 89B, 246 (1980).

[5]H. J. Lipkin, Phys. Rev. Lett. 44, 710 (1980); S. P. Rosen, Phys. Rev. Lett. 44, 41 (1980).

[6]J. F. Donoghue and B. R. Holstein, Phys. Rev. D 21, 1334 (1980).

[7]M. B. Einhorn and C. Quigg, Phys. Rev. D 12, 2015 (1975).

[8]R. L. Kingsley, S. B. Treiman, F. Wilczek, and A. Zee, Phys. Rev. D 11, 1919 (1975).

[9]J. F. Donoghue and L. Wolfenstein, Phys. Rev. D 15, 3341 (1977).

[10]K. Jagannathan and V. S. Mathur, Phys. Rev. D 21, 3165 (1980), and Nucl. Phys. B171, 78 (1980).

[11]P. Estabrooks *et al.*, Nucl. Phys. B133, 490 (1980); P. Estabrooks, Phys. Rev. D 19, 2678 (1979).

[12]H. Fritzsch and J. D. Jackson, Phys. Lett. 66B, 365 (1977); H. J. Lipkin, in *Deeper Pathways in High-Energy Physics*, edited by A. Perlmutter and L. F. Scott (Plenum, New York, 1977), p. 567.

[13]Nathan Isgur, Phys. Rev. D 12, 3770 (1975).

[14]Thomas G. Rizzo and Ling-Lie Chau Wang, Brookhaven National Laboratory Report No. BNL-27950 (to be published), have recently classified charm decays by quark diagrams. Their amplitudes b and c correspond exactly to transitions denoted here by W_1 and W_2. They also give the relations between these amplitudes and the SU(3) amplitudes of Refs. 1 and 2. Their remaining amplitudes a, d, e, and f do not contribute to Cabibbo-favored neutral decays and are not relevant to this discussion. In their terminology, the $\bar{K}^0\eta$ decay is strongly suppressed if the c amplitude is dominant. Thus the $\bar{K}^0\eta$ branching ratio measures directly the strength of the b amplitude.