Weak decays of charmed hadrons*

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SU(3) relations among various two-body channels in weak decays of charmed hadrons are worked out in the framework of the four-quark model of the weak interactions. Effects analogous to K^0, $\bar{K}^0$ mixing are discussed for charmed mesons. A certain dominance possibility, analogous to octet dominance for charm-conserving weak reactions, is noted.

The notion that there may be one or more new degrees of freedom in hadronic physics—denoted, singly or collectively, by the word *charm*—was motivated initially in connection with problems in the physics of weak interactions.[1] The case for charm has lately received indirect support through the discovery[2] of narrow boson resonances at 3.1 GeV and 3.7 GeV. According to one widely discussed interpretation these resonances, though they carry no net charm, are taken to be bound states of charmed quark-antiquark pairs. A less indirect case for charm now awaits the discovery of particles whose (associated) production and decay characteristics directly demand the introduction of new quantum numbers.

The most definite set of ideas about the role of charm in the weak interactions is embodied in the four-quark scheme of Bjorken, Glashow, Iliopoulos, and Maiani,[1] as this is incorporated into the Weinberg-Salam[3] gauge theory of the weak and electromagnetic interactions. Here there is introduced a single new charm quantum number, C, and this is the model we shall be considering. On the basis of this model, and in advance of the experimental discoveries noted above, Gaillard, Lee, and Rosner[4] prepared a remarkable, systematic survey of the expected phenomenology of charmed particle spectroscopy, production, and decays. Our purpose here is to add a few additional observations having to do with weak, nonleptonic decays of charmed particles. Gaillard, Lee, and Rosner have emphasized and exploited the SU(4) structure of the model, but since SU(4) symmetry is likely to be badly broken by the strong interactions any results that rest on this symmetry can only be qualitative. On the other hand, as we report here, for certain simple decay reactions SU(3) considerations alone suffice to provide quantitative predictions that can serve as powerful tests of the model. Although SU(3) itself is far from being an exact symmetry of the strong interactions, it ought to be good enough to be fairly decisive for the matters discussed here.

If charmed particles exist at all they are likely to form families with all the richness and complexity of ordinary hadron spectroscopy, but for present purposes it is only the low-lying states, stable against strong and electromagnetic decays, that are of interest. For the singly charmed mesons we leave open the spin-parity properties of the lowest (hence stable) states, although one may anticipate that the lowest-mass mesons are 0^-, the next lowest 1^-. Even if the mass separation were small, the heavier would decay electromagnetically into the lighter with rates greatly exceeding rates for weak decay. For both cases, however, we expect a triplet structure with respect to SU(3). Following the notation of Gaillard, Lee, and Rosner, the names and quark content for $C=+1$ are $D^0=(\mathcal{P}',\bar{\mathcal{P}})$, $D^+=(\mathcal{P}',\bar{\mathfrak{N}})$, $F^+=(\mathcal{P}',\bar{\lambda})$, where $\mathcal{P}$, $\mathfrak{N}$, λ are the usual quarks, $\mathcal{P}'$ the charmed ($C=+1$, $Q=\frac{2}{3}$) quark. The corresponding $C=-1$ antiparticles are $\bar{D}^0, D^-, F^-$. When we wish to distinguish between the 0^- and 1^- alternatives we write $D(0^-)$ or $D(1^-)$, etc. As for the $C=1$ baryons we may expect that the lowest-lying levels belong either to the 6 or $\bar{3}$ representations of SU(3), probably with spin-parity $\frac{1}{2}^+$. It is an open question whether even the lowest-lying charmed baryons are stable against strong decay into an ordinary baryon and a charmed meson.

In the weak-interaction model under consideration the weak neutral current is charm-conserving, so that the charm-changing interactions are mediated exclusively by exchange of charged, intermediate vector bosons. The effective Lagrangian for $\Delta C=\pm 1$ nonleptonic processes has the quark structure

$$\mathcal{L}=(\bar{\mathcal{P}}\mathcal{P}')\left[\bar{\lambda}\mathfrak{N}\cos^2\theta_C-\left(\frac{\bar{\mathfrak{N}}\mathfrak{N}-\bar{\lambda}\lambda}{\sqrt{2}}\right)\sqrt{2}\,\sin\theta_C\cos\theta_C-\bar{\mathfrak{N}}\lambda\sin^2\theta_C\right]+\text{H.c.}, \tag{1}$$

where θ_C is the Cabibbo angle. The terms multiplied respectively by the factors $\cos^2\theta_C$, $\sqrt{2}\sin\theta_C\cos\theta_C$, and $\sin^2\theta_C$ form a U-spin triplet and produce transitions which change strangeness and charm according to $\Delta S/\Delta C=+1, 0, -1$. Since $\sin^2\theta_C \ll 1$ these lie in the order of decreasing strength. With respect to SU(3) the effective Lagrangian decomposes into pieces which, for $\Delta C=+1$, transform like $\underline{\overline{15}}$ and $\underline{6}$, and for $\Delta C=-1$, like $\underline{15}$ and $\underline{\overline{6}}$. We may imagine a color tripling of the four quarks, but for the purposes of this paper the color indices can be suppressed.

We shall discuss the following topics: (1) various two-body, weak, nonleptonic decays of the charmed mesons; (2) effects of $D^0, \overline{D}^0$ mixing; (3) two-body decays of charmed baryons. The SU(3) considerations employed here can be applied to a wider class of decay reactions, but the cases selected for emphasis look already to be interesting and in some instances perhaps even experimentally practicable.

TWO-BODY MESON DECAYS

(i) Let us first consider the set of D^0 transitions into a pair of ordinary *charged* mesons belonging to a definite pair of SU(3) octets, e.g., the octet containing the vector mesons $K^{*\pm}, \rho^\pm$ and the pseudoscalar octet containing $K^\pm, \pi^\pm$. For inequivalent octets we are dealing with a set of eight transitions, and U-spin considerations imply that the amplitudes are related by two reduced matrix elements, to within definite Cabibbo factors. Insofar as we can ignore effects of SU(3) symmetry breaking and effects arising from D^0, $\overline{D}^0$ mixing we find for the decay rates

$$\begin{aligned}&\Gamma(\rho^+ + K^-):[\Gamma(K^{*+}+K^-)=\Gamma(\rho^+ + \pi^-)]:\Gamma(K^{*+}+\pi^-)=\cos^4\theta_C:\cos^2\theta_C\sin^2\theta_C:\sin^4\theta_C\,,\\ &\Gamma(K^{*-}+\pi^+):[\Gamma(K^{*-}+K^+)=\Gamma(\rho^- + \pi^+)]:\Gamma(\rho^- + K^+)=\cos^4\theta_C:\cos^2\theta_C\sin^2\theta_C:\sin^4\theta_C\,.\end{aligned} \tag{2}$$

Of course, $\overline{D}^0$ decays satisfy similar relations, with the obvious interchanges $K^{*+}\leftrightarrow K^{*-}$, $K^+\leftrightarrow K^-$, etc.

Symmetry-violating phase-space and centrifugal-barrier effects arising from mass differences among the members of a given SU(3) multiplet can be taken into account in the usual way. If the charmed particle is much more massive than the final-state particles these effects will not be too significant, but in any case we suppose they are allowed for and we do not emphasize them in the following discussion. We ignore the remaining intrinsic effects of SU(3) symmetry breaking, including η-η' mixing.

For the case of D^0 decay into a pair of equivalent octets we deal with a set of four reactions. For the example of two pseudoscalars we have

$$\Gamma(K^- + \pi^+):[\Gamma(K^+ + K^-)=\Gamma(\pi^+ + \pi^-)]:\Gamma(K^+ + \pi^-)=\cos^4\theta_C:\cos^2\theta_C\sin^2\theta_C:\sin^4\theta_C\,. \tag{3}$$

The effects of $D^0, \overline{D}^0$ mixing have already been discussed by Gaillard, Lee, and Rosner and will be further elaborated below. The problem is that a state which initially is pure D^0, say, becomes a mixture of D^0 and $\overline{D}^0$ at later times. For the present we merely anticipate the results of the later discussion; namely, the mixing effects are expected to be unimportant for $\Delta S/\Delta C=+1$ and $\Delta S/\Delta C=0$ processes, but they could, *a priori*, be significant for the highly suppressed $\Delta S/\Delta C=-1$ processes. Just for this reason these $\Delta S/\Delta C=-1$ processes will be very interesting, though enormously demanding experimentally. In fact, we shall argue that mixing effects may be small even for the $\Delta S/\Delta C=-1$ transitions. However, in the present section we ignore mixing altogether.

(ii) For discussion of the remaining two-body channels of D^0 decay and related two-body decays of D^+ and F^+ we now specialize to the situation where the final state involves a pair of pseudoscalar mesons. Although the results obtained above for D^0 decay into a pair of charged particles were independent of the spin-parity assignment of D^0, the pattern for the remaining modes of D^0 and of D^+ and F^+ decays *will* depend on this assignment. Thus, for the case 0^- the whole set of decays is determined by three independent reduced matrix elements, and for 1^-, by four reduced matrix elements. Again for the D^0 decays we tentatively ignore mixing, and again for all the processes we omit the corrections discussed above that ought to be applied to allow for SU(3) symmetry-breaking effects arising from mass differences within SU(3) multiplets. Straightforward SU(3) analysis leads to the rate formulas displayed in Tables I, II, and III, which refer respectively to D^0, D^+, and F^+ decays and which incorporate for D^0 the results already discussed above. There are separate entries for the case where the charmed mesons are 0^- (more generally, even spin) and 1^- (more generally, odd spin). For the antiparticles $\overline{D}^0$, D^-, and F^- one of course obtains identical results, with $K^+\leftrightarrow K^-$, $\pi^+\leftrightarrow\pi^-$, and $K^0\leftrightarrow\overline{K}^0$. The tables employ the notation

$$c\equiv\cos\theta_C,\quad s\equiv\sin\theta_C\,. \tag{4}$$

We have remarked already that the effective Lagrangian for charm-changing reactions transforms under SU(3) like a combination of $(\underline{6}+\underline{\bar{6}})$ and $(\underline{\overline{15}}+\underline{15})$. The tables reflect the joint contributions from both pieces. However, we may note that for pure $(\underline{6}+\underline{\bar{6}})$ we would have

$$A = C = -B, \quad \alpha = \beta, \quad \delta = \gamma\,, \tag{5}$$

and for pure $(\underline{\overline{15}}+\underline{15})$

$$B = C, \quad \alpha + \beta = 2\gamma, \quad \delta = -\gamma\,. \tag{6}$$

Now for charm-conserving, but strangeness-changing, nonleptonic reactions the effective Lagrangian contains pieces belonging to the 8- and 27-dimensional representations of SU(3). Empirically, the octet term seems to dominate. It has been suggested[5] that this may reflect that octets are the most singular terms in the short-distance expansion of the product of currents involved in the weak interactions. At short distances, however, the full SU(4) structure of the model under discussion should reveal itself as if SU(4) were an exact symmetry of the strong interactions. If this is so we can reason as follows. The product of currents that we are dealing with decomposes, with respect to SU(4), into pieces which transform like $\underline{1}$, $\underline{20}$, and $\underline{84}$. It is a special property of the model under discussion that there are no terms belonging to the 15-dimensional representation. Now SU(3) octets are contained in both the SU(4) $\underline{20}$ and $\underline{84}$, and the latter also contains the SU(3) $\underline{27}$. From octet dominance of the charm-conserving weak interactions we therefore infer, in the SU(4) setting and assuming that dominance effects reflect short-distance behavior, that the SU(4) $\underline{20}$ dominates over $\underline{84}$. However, the SU(3) $\underline{6}+\underline{\bar{6}}$ appears in the SU(4) $\underline{20}$, whereas the SU(3) $\underline{15}+\underline{\overline{15}}$ appears in the SU(4) $\underline{84}$. We therefore conclude that octet dominance for charm-conserving reactions implies $\underline{6}+\underline{\bar{6}}$ dominance for the charm-changing ones. Octet dominance at short distances has in fact been demonstrated, by Gaillard and Lee[6] and Altarelli and Maiani[7] in a color-tripled version of the model under discussion.

With $\underline{6}+\underline{\bar{6}}$ dominance one has an enormous simplification in the tables. In particular for the (more likely) 0^- case, all 26 decay reactions listed are described by a *single* reduced matrix element. We may note also that $\underline{6}+\underline{\bar{6}}$ dominance is in itself compatible with decay to "exotic," i.e., nonoctet, final states; e.g., $D^+(1^-)\to \bar{K}^0+\pi^+$, $D^+(0^-)\to\bar{K}^0+\rho^+$, etc.

TABLE I. D^0 decay rates.

	$D^0(0^-)$	$D^0(1^-)$
$K^-\pi^+$	$2\|A\|^2c^4$	$2\|\alpha\|^2c^4$
K^-K^+	$2\|A\|^2c^2s^2$	$2\|\alpha\|^2c^2s^2$
$\pi^-\pi^+$	$2\|A\|^2c^2s^2$	$2\|\alpha\|^2c^2s^2$
$K^+\pi^-$	$2\|A\|^2s^4$	$2\|\alpha\|^2s^4$
$\bar{K}^0\pi^0$	$\|B\|^2c^4$	$\|\beta-2\gamma\|^2c^4$
$\bar{K}^0\eta^0$	$\frac{1}{3}\|B\|^2c^4$	$\frac{1}{3}\|\beta+2\gamma\|^2c^4$
$\bar{K}^0K^0$	0	$8\|\gamma\|^2c^2s^2$
$\pi^0\pi^0$	$\|B\|^2c^2s^2$	0
$\eta^0\eta^0$	$\|B\|^2c^2s^2$	0
$\pi^0\eta^0$	$\frac{2}{3}\|B\|^2c^2s^2$	$\frac{8}{3}\|\beta-\gamma\|^2c^2s^2$
$K^0\pi^0$	$\|B\|^2s^4$	$\|\beta\|^2s^4$
$K^0\eta^0$	$\frac{1}{3}\|B\|^2s^4$	$\frac{1}{3}\|\beta-4\gamma\|^2s^4$

TABLE II. D^+ decay rates.

	$D^+(0^-)$	$D^+(1^-)$
$\bar{K}^0\pi^+$	$2\|A+B\|^2c^4$	$2\|\alpha+\beta-2\gamma\|^2c^4$
$\bar{K}^0K^+$	$2\|C\|^2c^2s^2$	$2\|\alpha-\gamma-\delta\|^2c^2s^2$
$\pi^0\pi^+$	$\|A+B\|^2c^2s^2$	$\|\alpha+\beta-2\gamma+2\delta\|^2c^2s^2$
$\eta^0\pi^+$	$\frac{1}{3}\|3A+3B-2C\|^2c^2s^2$	$\frac{1}{3}\|\alpha+3\beta-4\gamma\|^2c^2s^2$
$K^+\pi^0$	$\|C\|^2s^4$	$\|\alpha-\gamma+\delta\|^2s^4$
$K^+\eta^0$	$\frac{1}{3}\|C\|^2s^4$	$\frac{1}{3}\|\alpha-\gamma-3\delta\|^2s^4$
$K^0\pi^+$	$2\|A+B-C\|^2s^4$	$2\|\beta-\gamma+\delta\|^2s^4$

$D^0,\bar{D}^0$ MIXING

The states D^0 and $\bar{D}^0$ can mix through a sequence of two $\Delta S/\Delta C=0$ transitions or a sequence involving a $\Delta S/\Delta C=+1$ and a $\Delta S/\Delta C=-1$ transition. As a result the states of definite mass and lifetime are linear combinations, $(D^0\pm\bar{D}^0)/\sqrt{2}$, whose masses and inverse lifetimes we denote by $m_\pm$, $\lambda_\pm$. We shall ignore possible effects arising from CP

TABLE III. F^+ decay rates.

	$F^+(0^-)$	$F^+(1^-)$
$\bar{K}^0K^+$	$2\|A+B-C\|^2c^4$	$2\|\beta-\gamma+\delta\|^2c^4$
$\pi^0\pi^+$	0	$4\|\delta\|^2c^4$
$\eta^0\pi^+$	$\frac{4}{3}\|C\|^2c^4$	$\frac{4}{3}\|\alpha-\gamma\|^2c^4$
$K^0\pi^+$	$2\|C\|^2c^2s^2$	$2\|\alpha-\gamma-\delta\|^2c^2s^2$
$K^+\pi^0$	$\|A+B-C\|^2c^2s^2$	$\|\beta-\gamma-\delta\|^2c^2s^2$
$K^+\eta^0$	$\frac{1}{3}\|3A+3B-C\|^2c^2s^2$	$\frac{1}{3}\|2\alpha+3\beta-5\gamma+3\delta\|^2c^2s^2$
K^+K^0	$2\|A+B\|^2s^4$	$2\|\alpha+\beta-2\gamma\|^2s^4$

violation. The mixing amplitudes are proportional to $\cos^2\theta_C \sin^2\theta_C$. On the other hand, the diagonal elements of the $D^0, \bar{D}^0$ mass matrix, owing to the smallness of the Cabibbo angle, should be dominated by $\Delta S/\Delta C = +1$ amplitudes proportional to $\cos^4\theta_C$. As noted by Gaillard, Lee, and Rosner one therefore expects mixing effects to be small, in the sense that $|\Delta\lambda/\lambda| \approx \tan^2\theta_C$, and presumably also $|\Delta m/\lambda| \approx \tan^2\theta_C$, where $\Delta\lambda = \lambda_+ - \lambda_-$, $\Delta m = m_+ - m_-$, $\lambda = (\lambda_+ + \lambda_-)/2$. In this situation an initially produced D^0, say, will make transitions to the dominant $S=-1$ final states, and even to the $S=0$ states, without receiving much contribution from the admixed $\bar{D}^0$. On the other hand, $S=+1$ final states, which prefer a $\bar{D}^0$ over a D^0 origin, can be expected on the above reasoning to receive comparable contributions from both sources. That is, for an initially produced D_0, decay to $S=+1$ final states, although rare, should be sensitive to the effects of mixing.

As we shall now discuss, however, the effects of mixing are expected to be even smaller than is indicated by the above estimates: Namely, if SU(3) were an exact symmetry of the strong interactions, mixing effects in the weak-interaction model under discussion would vanish altogether. Indeed this model was originally designed, in part, to suppress $K^0, \bar{K}^0$ mixing, which would vanish altogether in the limit of exact SU(4) symmetry. It also forbids $D^0, \bar{D}^0$ mixing in the more nearly realistic limit of exact SU(3) symmetry. One sees this from the effective Lagrangian by considering the sequences $D^0 \to \bar{\mathfrak{N}} + \lambda \to \bar{D}^0$, $D^0 \to \bar{\lambda} + \lambda \to \bar{D}^0$, $D^0 \to \bar{\mathfrak{N}} + \mathfrak{N} \to \bar{D}^0$, and $D^0 \to \bar{\lambda} + \mathfrak{N} \to \bar{D}^0$. Up to a common proportionality factor the transition amplitudes are respectively $-\cos^2\theta_C \sin^2\theta_C$, $\cos^2\theta_C \sin^2\theta_C$, $\cos^2\theta_C \sin^2\theta_C$, and $-\cos^2\theta_C \sin^2\theta_C$, and the sum vanishes. We therefore expect that $\Delta\lambda/\lambda$ and $\Delta m/\lambda$ are even smaller than $\tan^2\theta_C$, suppressed additionally by a factor which measures SU(3) symmetry breaking.[8]

Since charmed mesons will pretty surely have lifetimes too small to permit direct measurements of the kind that have been carried out on the K_S, K_L system, one can at best hope to get information on mixing only through indirect methods, by integrating count rates over time. For example, consider the final states $K^- + \pi^+$ and $K^+\pi^-$ produced from decay of a charmed state which is initially D_0. In the absence of mixing, the branching ratio according to our earlier results is

$$\frac{K^+ + \pi^-}{K^- + \pi^+} = \frac{\sin^4\theta_C}{\cos^4\theta_C} \approx \sin^4\theta_C\,. \tag{7}$$

With mixing, the denominator remains essentially unchanged, but for the numerator we have

$$\frac{\lambda}{4}\int dt\left[(c^2 - s^2)^2 e^{-\lambda_+ t} + e^{-\lambda_- t} - 2(c^2 - s^2)e^{-\lambda t}\cos(\Delta m t)\right], \tag{8}$$

where $c \equiv \cos\theta_C$, $s = \sin\theta_C$. Treating s^2, $\Delta\lambda/\lambda$, and $\Delta m/\lambda$ as being of the same order, we then find to lowest order

$$\frac{K^+ + \pi^-}{K^- + \pi^+} = \sin^4\theta_C\left[1 + \frac{\Delta\lambda}{2\lambda\sin^2\theta_C} + \frac{1}{8}\left(\frac{\Delta\lambda}{\lambda\sin^2\theta_C}\right)^2 + \frac{1}{2}\left(\frac{\Delta m}{\lambda\sin^2\theta_C}\right)^2\right]. \tag{9}$$

Our expectation is that the bracketed quantity is close to unity.

It is interesting also to consider the effects of mixing in semileptonic decays, for example, into the states $K^- + \mu^+ + \nu$ and $K^+ + \mu^- + \bar{\nu}$. The former arises only from D^0, the latter from $\bar{D}^0$. To lowest order in $\Delta\lambda/\lambda$ and $\Delta m/\lambda$, the ratio of counts coming from a state which is initially D^0 is given by

$$\frac{K^+ + \mu^- + \bar{\nu}}{K^- + \mu^+ + \nu} = \frac{1}{8}\left(\frac{\Delta\lambda}{\lambda}\right)^2 + \frac{1}{2}\left(\frac{\Delta m}{\lambda}\right)^2. \tag{10}$$

The tiny branching ratio effects that we have been considering, both for the nonleptonic and semileptonic channels, would clearly lie beyond experimental reach for some time to come, even if charmed particles were soon to be discovered. Nevertheless, it is interesting that one *can*, at least in principle, get at lifetime and mass differences through the effects illustrated above, even for very short-lived objects.

BARYON DECAYS

The low-lying singly charmed baryons presumably lie in the SU(3) representations $\underline{\bar{3}}$ or $\underline{6}$. It is not at all clear that the lowest multiplets of either kind are stable against strong decay into an ordinary baryon and charmed meson. Nevertheless, allowing for the possibility we note a few of the SU(3) relations among two-body decays. The list could be extended, but the examples selected are among the simplest.

First, for the $\underline{6}$ multiplet consider the doubly charged baryon C_1^{++} with quark content $(\mathcal{P}'\mathcal{P}\mathcal{P})$. One readily finds that

$$\Gamma(C_1^{++} \to \Sigma^+ + \pi^+) : [\Gamma(C_1^{++} \to \Sigma^+ + K^+) = \Gamma(C_1^{++} \to p + \pi^+)] : \Gamma(C_1^{++} \to p + K^+) = \cos^4\theta_C : \cos^2\theta_C\sin^2\theta_C : \sin^4\theta_C\,. \tag{11}$$

Also in the 6 multiplet consider $S^0 \equiv (\mathcal{P}'\lambda\mathfrak{N})$, for which we find

$$\begin{aligned} &\Gamma(S^0 \to n + \bar{K}^0) = \Gamma(S^0 \to \Xi^0 + K^0),\ \ \Gamma(S^0 \to \Lambda + \pi^0) = \Gamma(S^0 \to \Sigma^0 + \eta^0), \\ &\Gamma(S^0 \to p + K^-) = \Gamma(S^0 \to \Sigma^+ + \pi^-),\ \ \Gamma(S^0 \to \Sigma^- + \pi^+) = \Gamma(S^0 \to \Xi^- + K^+), \end{aligned} \tag{12}$$

and

$$\frac{\Gamma(S^0 \to p + \pi^-)}{\Gamma(S^0 \to \Sigma^+ + K^-)} = \frac{\Gamma(S^0 \to \Sigma^- + K^+)}{\Gamma(S^0 \to \Xi^- + \pi^+)} = \frac{\sin^4\theta_C}{\cos^4\theta_C}\,. \tag{13}$$

Next consider the $\bar{3}$ baryon triplet and, in particular, the baryon A^0 with quark content $(\mathcal{P}'\lambda\mathfrak{N})$. Here one finds

$$\begin{aligned} &\Gamma(A^0 \to \Lambda + \eta^0) = \Gamma(A^0 \to \Sigma^0 + \pi^0), \\ &\Gamma(A^0 \to n + \bar{K}^0) = \Gamma(A^0 \to \Xi^0 + K^0), \\ &\Gamma(A^0 \to \Sigma^+ + K^-) : [\Gamma(A^0 \to \Sigma^+ + \pi^-) = \Gamma(A^0 \to p + K^-)] : \Gamma(A^0 \to p + \pi^-) = \cos^4\theta_C : \cos^2\theta_C \sin^2\theta_C : \sin^4\theta_C; \\ &\Gamma(A^0 \to \Xi^- + \pi^+) : [\Gamma(A^0 \to \Sigma^- + \pi^+) = \Gamma(A^0 \to \Xi^- + K^+)] : \Gamma(A^0 \to \Sigma^- + K^+) = \cos^4\theta_C : \cos^2\theta_C \sin^2\theta_C : \sin^4\theta_C\,. \end{aligned} \tag{14}$$

Note added in proof. After this paper was completed we learned of a related discussion by Altarelli, Cabibbo, and Maiani,[9] who independently noted the argument for $6+\bar{6}$ dominance and considered some of the implications for charmed hadron decays.

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