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Charmed-meson lifetime ratios and production in e^+-e^- collisions*

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Two separate charmed-particle issues are discussed in the context of charm production in e^+-e^- collisions. One has to do with the kinds of measurements that might serve to establish the relative lifetimes of the charmed mesons D^+, D^0, F^+. The other concerns the isotopic properties of the production process.

I. LIFETIME RATIOS

It is probable that weakly unstable charmed hadrons are too short lived to allow direct observation of their tracks (or gaps, in the neutral case) in conventional detectors, except perhaps for photographic emulsions.[1] Although direct determination of the lifetimes will therefore be difficult, it would be interesting enough to at least know the ratios of lifetimes of different charmed particles. We shall discuss how this might be done for the case where these particles are produced in e^+-e^- collisions. The required measurements are demanding. However, to our knowledge, there are no simpler ways (short of direct lifetime determinations).

It is utterly trivial conceptually to see what kinds of measurements would be needed. We call attention to the reasoning not because it is subtle but because information on lifetime ratios is of such interest. Indeed the reasoning involves nothing more than application of the meaning of "branching ratio"—this taken together with simple theoretical observations based on the Glashow-Iliopoulos-Maiani (GIM) scheme[2] of the weak interactions. We focus on the charmed mesons D^+, D^0, F^+ (and their conjugates). They form a triplet under SU(3), D^+ and D^0 forming a doublet under SU(2). In the GIM scheme the dominant effects in semileptonic decay are mediated by an *isoscalar* charged current obeying the selection rule $\Delta S/\Delta C = 1$. (Inclusive tests for this isoscalar property have been described recently.[3]) This implies that the inclusive semileptonic rates for D^+ and D^0 decay are equal up to corrections of order $\tan^2\theta_C \approx 0.05$. With $l = e$ or μ,

$$\Gamma_l(D^+ \to l^+ + \nu_l + \bar{K} + \cdots) = \Gamma_l(D^0 \to l^+ + \nu_l + \bar{K} + \cdots) \equiv \Gamma_l(D)\,.$$

We shall turn to exclusive semileptonic channels later on, for the F as well as D particles.

Now consider the reaction

$$e^+ + e^- \to D^+ + D^-\,.$$

Suppose that the D^- particle is identified, and its momentum measured, through observation of its decay into a particular hadronic channel, e.g., $D^- \to K^+\pi^-\pi^-$. From measurements of the D^- particle alone (the beam energy being known) one can select for the D^+D^- production events in question. We speak of this, here and later on, as the matter of kinematically "establishing" the wanted reaction. Now select the subset of events in which the detected D^- particle is accompanied in the final state by a charged lepton l^+, accompanied by any number of ordinary hadrons (for present purposes these hadrons need not be observed). These are the events in which the D^+ has decayed semileptonically. This yields the D^+ semileptonic branching ratio $B_l(D^+) \equiv \Gamma_l(D^+)/\Gamma(D^+)$, where $\Gamma(D^+)$ is the net decay rate (nonleptonic plus semileptonic) of the D^+ particle.

In the same way, consider the reaction

$$e^+ + e^- \to D^0 + \bar{D}^0\,,$$

where $\bar{D}^0$ is identified and its momentum measured through observation of its decay into a particular hadronic channel, e.g., $\bar{D}^0 \to K^+ + \pi^-$. From the kinematics one again establishes the two-body reaction and then determines the fraction of these events in which the D^0 particle has decayed semileptonically (as signaled by detection of a lepton l^+ in the final state). This yields the branching ratio $B_l(D^0) = \Gamma_l(D^0)/\Gamma(D^0)$. If we now accept the GIM prediction that $\Gamma_l(D^+) = \Gamma_l(D^0) \equiv \Gamma_l(D)$ we determine the inverse lifetime ratio from

$$\frac{\Gamma(D^+)}{\Gamma(D^0)} = \frac{B_l(D^0)}{B_l(D^+)}\,.$$

We stress that this information has to come from study of the reactions $e^+ + e^- \to D + \bar{D}$, rather than from the more prominent reactions $e^+ + e^- \to D + \bar{D}^*$ or $D^* + \bar{D}^*$ or from inclusive processes. One can convince oneself that these latter reactions cannot easily be exploited for present purposes, without making more demanding measurements.

The procedures discussed above for the D^+ and D^0 semileptonic branching ratios $B_l(D^+)$ and $B_l(D^0)$ can obviously be applied as well, in the reaction $e^+ + e^- \to F^+ + F^-$, to determine the semileptonic branching ratio $B_l(F^+)$ of the still undiscovered F particle. Indeed, here one can also proceed inclusively. Consider the inclusive reaction $e^+ + e^- \to F^- + X$, where F^- is identified and measured through its decay into some specific nonleptonic channel, e.g., $F^- \to K^0 + K^-$. Suppose one selects events where the "missing mass" of X lies below the $(\overline{D} + K)$ mass. For these events one can be sure that the observed F^- was accompanied in production by F^+, plus perhaps other ordinary hadrons. The semileptonic branching ratio $B_l(F^+)$ is then determined by observing the fraction of events in which there is a lepton l^+ in the final state.

This branching ratio is interesting in its own right. However, it cannot be used, by comparing it with $B_l(D^+)$ or $B_l(D^0)$, to relate the net F particle lifetime to the D particle lifetimes. The GIM scheme does not lead to a definite relation connecting the inclusive semileptonic rate of F to that of D^+ or D^0. There is more to be done, however, if one reverts to the exclusive production reactions $e^+ + e^- \to D + \overline{D}$ and $e^+ + e^- \to F + \overline{F}$; and if one looks at certain exclusive semileptonic decay channels. In the following discussion we suppose that one of the charmed particles in each reaction is detected in nonleptonic decay and that kinematics are exploited to establish the production reaction in question. One then studies specific semileptonic decays of the other charmed particle.

With respect to SU(3), the $\Delta S/\Delta C = 1$ semileptonic current in the GIM scheme transforms like the third component of a triplet. To the extent that SU(3) symmetry is a good approximation for the strong interactions, this permits the interesting possibility of getting at the F/D lifetime ratios. From SU(2) considerations one finds the semileptonic equality[4]

$$\Gamma_l(D^+ \to \overline{K}^0 + l^+ + \nu_l) = \Gamma_l(D^0 \to K^- + l^+ + \nu_l) \equiv \Gamma_l(D \to \overline{K} + l^+ + \nu_l)\,.$$

From SU(3) properties of the GIM scheme, one finds

$$\Gamma_l(F^+ \to \eta + l^+ + \nu_l) = \tfrac{2}{3}\Gamma_l(D \to \overline{K} + l^+ + \nu_l)\,.$$

[SU(3)-breaking effects, insofar as they arise from mass differences, may not be too serious here because the η-K mass difference is rather small and the same is expected for the F-D mass difference.] This last equation provides a basis for determining the F/D lifetime ratios. For example, study $e^+ + e^- \to D^+ + D^-$, where D^- is detected via a specific nonleptonic mode and where one records the fraction of events $B_l(D^+ \to \overline{K}^0 + l^+ + \nu_l)$ in which the D^+ particle decays in the indicated way. Similarly, from $e^+ + e^- \to F^+ + F^-$ determine $B_l(F^+ \to \eta + l^+ + \nu_l)$. The F^+/D^+ net decay rate ratio is then given by

$$\frac{\Gamma(F^+)}{\Gamma(D^+)} = \frac{2}{3}\,\frac{B_l(F^+ \to \eta + l^+ + \nu_l)}{B_l(D^+ \to \overline{K}^0 + l^+ + \nu_l)}\,.$$

Of course there is the practical difficulty of detecting the η or K^0 and making sure that no additional decay products escaped detection.

As to the order of magnitude of the *inclusive* semileptonic branching ratios, on the basis of a charm interpretation of dilepton events discovered in neutrino reactions one infers a μ-leptonic branching ratio of roughly 10 percent, where this number is some weighted average over the various kinds of charmed particles produced in these reactions.[5] Evidence for final-state leptons has also been reported for the inclusive reactions $e^+ + e^- \to l$ + hadrons.[6] Here one is presumably dealing with a mixture of sources: heavy leptons and charmed hadrons.

In the preceding discussion we have exploited the predictions of the GIM scheme for semileptonic decay of charmed hadrons. As for weak nonleptonic processes, these are dominated by interactions which transform like an isovector and which obey the rule $\Delta S/\Delta C = 1$. For the D particles this means that D^+ decays nonleptonically mainly into $I = \frac{3}{2}$ states, whereas D^0 can decay to both $I = \frac{3}{2}$ and $I = \frac{1}{2}$ states. It is easy to see, then, that the hadronic rates obey the inequality (up to $\tan^2\theta_C$ corrections)

$$0 \le \frac{\Gamma_h(D^+ \to \overline{K} + \cdots)}{\Gamma_h(D^0 \to \overline{K} + \cdots)} \le 3\,.$$

On the simplest kind of independent quark-model reasoning one might argue that the *total* hadronic decay rates of D^+ and D^0 are in fact equal, the rate being determined by the common process of charmed-quark "decay": $c \to s + u + \overline{d}$. However, this reasoning may well be too naive. With respect to SU(3), the nonleptonic Hamiltonian in the GIM scheme transforms like a mixture of $6 + \overline{6}$ and $15 + \overline{15}$. It has been argued[7] that the $6 + \overline{6}$ component may dominate, in a manner similar to octet dominance for $\Delta C = 0$, $\Delta S = \pm 1$ transitions. This consideration does not provide definite relations among the D^+, D^0, F^+ lifetimes, but it does yield interesting relations among rates to simple exclusive channels. Indeed, one of the general points of interest in obtaining the lifetime ratios (in the ways discussed here, or otherwise) is the need to convert *exclusive* decay *rate* predictions into branching-ratio predictions; it is the branching ratios that are closer to experiment.

II. PRODUCTION RATIOS

We turn now to an altogether different issue that arises when one is contemplating charm production in e^+-e^- collisions. In these collision processes final states containing a pair of charmed particles, accompanied perhaps by one or more ordinary hadrons, can generally be induced by parts of the electromagnetic current formed either of ordinary quarks or of charmed quarks. The former contains both isoscalar and isovector pieces, whereas the latter is pure isoscalar. It is usually assumed,[8] however, that the charmed-quark part of the current dominates for charmed-hadron production. This conjecture about the dynamics of charmed-particle production implies a substantial suppression of charmed-quark pairs produced from the vacuum. It seems very interesting to test this hypothesis, also since it has important implications for the dynamics of charm production in hadronic collisions. It might well be that the hypothesis does work at regions of moderate energy and that it progressively fails at higher energy regions. For this reason we shall pay particular attention to the energy-dependent aspects of the conjecture.

According to this isoscalar production hypothesis, the production of charm in e^+e^- collisions should take place mainly in states of zero isotopic spin. As an immediate illustration, we observe that this rule implies forbiddenness of the reactions

$$e^+ + e^- \to F^+ + F^- + \pi^0\,,$$

$$e^+ + e^- \to F^+ + F^- + \rho^0\,.$$

Of course the practical difficulty arises again that at least two of the three final-state particles have to be detected and measured to kinematically "establish" the reaction. Another set of tests, somewhat less decisive, is the following. Consider the reaction $e^+ + e^- \to D^+ + D^-$, where D^+ is detected and measured by its nonleptonic decay to a specific channel, e.g., $D^+ \to K^-\pi^+\pi^+$. Let B^+ be the branching ratio for D^+ decay into this channel, and let $\sigma_{+-}(E)$ be the production cross section for beam energy E. The rate of these events (D^- is allowed to decay as it pleases) determines $\sigma_{+-}(E)B^+$. Now determine the fraction B^- of events in which D^- is detected in decay to the conjugate channel ($D^- \to K^+\pi^-\pi^-$). If CP invariance holds, as we shall assume for present purposes,[9] then $B^- = B^+ = B^\pm$ and one thus determines both $B^\pm$ and $\sigma_{+-}(E)$. Now proceed in the same way for the reaction $e^+ + e^- \to D^0 + \bar{D}^0$, where D^0 is detected and measured in decay to a specific channel, e.g., $D^0 \to K^-\pi^+$. Let B^0 be the branching ratio for this mode (equally for $\bar{D}^0 \to K^+\pi^-$) and let $\sigma_{00}(E)$ be the production cross section. Again one determines B^0 and thus $\sigma_{00}(E)$ by determining the fraction of events in which $\bar{D}^0$ decays to the conjugate mode.

If the two $D\bar{D}$ production reactions take place exclusively in the isoscalar state the cross sections $\sigma_{+-}(E)$ and $\sigma_{00}(E)$ must be equal; and this constitutes a test of the isoscalar production hypothesis. The test is not quite decisive, however, for it happens that the cross-section equality would also hold if production takes place exclusively in the $I=1$ state. If one found that $\sigma_{+-}(E) \neq \sigma_{00}(E)$ the isoscalar hypothesis would be ruled out. If the cross sections were found to be equal, either pure $I=0$ or pure $I=1$ production would survive as possibilities, with a strong presumption in favor of $I=0$.

These tests require that both D and $\bar{D}$ be detected, in decay to conjugate channels. A less demanding, but less conclusive test of the isoscalar hypothesis could be based on detection of only *one* of the D particles in each reaction. Then one measures the combinations $\sigma_{+-}B^\pm$ and $\sigma_{00}B^0$, hence the ratio

$$R(D,\bar{D}) = \left(\frac{\sigma_{+-}}{\sigma_{00}}\right)\left(\frac{B^\pm}{B^0}\right).$$

If both the $I=0$ and $I=1$ currents contribute one would expect their relative contributions to vary with energy, so that $R(D,\bar{D})$ would vary with energy. It is a necessary, though not sufficient condition for validity of the isoscalar hypothesis that $R(D,\bar{D})$ be energy-independent. In exactly the same way one can study the more prominent reactions $e^+ + e^- \to D^+ + D^{-*}$ and $e^+ + e^- \to D^0 + \bar{D}^{0*}$, where D^+ is detected in the one case, D^0 in the other. With $\sigma^*_{+-}(E)$ and $\sigma^*_{00}(E)$ the two production cross sections, one determines

$$R(D^*,\bar{D}^*) = \left(\frac{\sigma^*_{+-}}{\sigma^*_{00}}\right)\left(\frac{B^\pm}{B^0}\right),$$

where we assume the same decay modes of D^+ and D^0 are employed here as for the $D\bar{D}$ reactions. Again, if the isoscalar hypothesis is correct, $R(D^*,\bar{D}^*)$ should be energy-independent; but in addition one must have that $R(D^*,\bar{D}^*) = R(D,\bar{D}) \equiv R$. If all these tests were passed the presumption would be strong that the production is pure $I=0$ or pure $I=1$ (with prejudice favoring the former), and on either choice one would learn, incidentally, the ratio $B^\pm/B^0 : B^\pm/B^0 = R$.

There is another test of the isoscalar hypothesis that suggests itself and that is seemingly simple; but it in fact will not work, for an annoying reason that is worth displaying. Consider the two inclusive reactions

$$e^+ + e^- \to D^+ + X\,,$$
$$e^+ + e^- \to D^0 + X\,,$$

where in each process one detects only the D particle in the "standard" nonleptonic modes. On the isoscalar hypothesis the production cross sections for the two reactions must be equal. Thus the ratio of events should be equal to the energy-independent quantity $B^\pm/B^0$. This latter can be determined from the two-body reactions in the manner already described (assuming that the same isoscalar hypothesis holds there). What fails in this simple reasoning is this: In the inclusive reactions some portion of the detected D particles will have arisen from nonweak decay of the higher D^* state (or states), e.g., from production of D^* followed by $D^* \to D + \pi$. There would be no harm in this if this "strong" decay respected isotopic-spin conservation. The phase space for $D^* \to D + \pi$ decays is, however, known to be small. This introduces substantial violations of isotopic-spin conservation and spoils the overall reasoning.

It is possible to avoid this difficulty by study of exclusive channels. Consider

$$e^+ + e^- \to D^+ + D^- + \pi^0\,,$$
$$e^+ + e^- \to D^0 + D^- + \pi^+\,,$$

supposing that one measures well enough to "establish" the reactions in question. We are interested here in the cross-section ratio $\sigma(\pi^+)/\sigma(\pi^0)$. With D^+ and D^0 detected in the "standard" modes one extracts the cross-section ratio from the data in terms of the branching-fraction ratio $B^\pm/B^0$. On the isoscalar hypothesis this latter can be extracted independently from the two-body reactions in the manner described earlier ($B^\pm/B^0 = R$). The isoscalar hypothesis for the three-body reactions leads to the prediction

$$\sigma(\pi^+)/\sigma(\pi^0) = 2\,.$$

For $I = 1$ the ratio could have any value; it is now a highly model-dependent matter. So the $I = 0$ prediction $\sigma(\pi^+)/\sigma(\pi^0) = 2$ constitutes a rather decisive test.

The various tests that we have discussed are in the main rather demanding for the present era, except for the two-body studies leading to the ratios $R(D, \bar{D})$ and $R(D^*, \bar{D}^*)$. Recall that a necessary though not sufficient consequence of the validity of the isoscalar hypothesis is that these quantities must be energy independent and equal. It should finally be noted that, for charmed-baryon pair production, the possibility exists to check the isoscalar hypothesis by purely inclusive methods.[10]

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[3]O. Nachtmann and A. Pais, Phys. Lett. 65B, 59 (1976).

[4]This equality is of course in itself a test of the semileptonic $\Delta I = 0$ rule inherent in the GIM scheme. A further example is the forbiddenness of $F^+ \to l^+ + \nu + \pi^0$ or ρ^0.

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[8]See, e.g., M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. 42, 277 (1973); A. De Rújula, H. Georgi, and S. L. Glashow, Phys. Rev. Lett. 37, 398 (1976); B. W. Lee, C. Quigg, and J. L. Rosner, Phys. Rev. D 15, 157 (1977).

[9]A discussion of possible CP breakdown in charmed-particle decays can be found in A. Pais and S. B. Treiman, Phys. Rev. D 12, 2744 (1975).

[10]Namely, by the application of similar arguments as were given previously to the reactions $e^+ + e^- \to C_1^{++} + X$, $C_1^+ + X$, $C_1^0 + X$, where the charmed baryons C_1 form an isotriplet. Each of these C_1 states decays strongly into the isoscalar charmed baryon plus a pion. The isoscalar hypothesis implies equality of these three inclusive cross sections.