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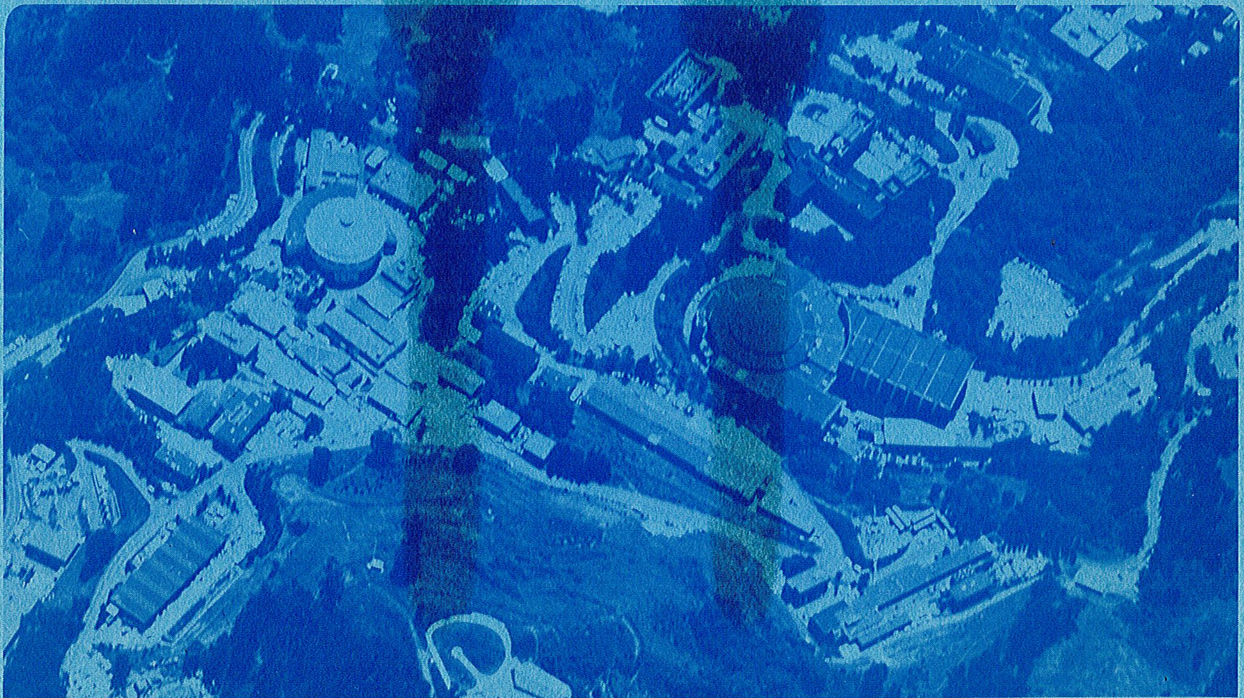

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SOFT-GLUON EFFECTS IN CHARMED-MESON DECAYS

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Recent experiments suggest significant enhancements of nonleptonic decays of the D^0 meson, such as $\tau(D^+)/\tau(D^0) = 3\sim10$ and $BR(D^0\to K^-\pi^+)/BR(D^0\to\bar{K}^0\pi^0) \gtrsim 1$, which cannot be explained by charm-quark decay mechanisms alone.[1] The observed nonleptonic enhancements are presumably dynamical, having their origins in quantum chromodynamics (QCD). In particular, in D^0- and F^+-meson decays, QCD effects are expected to activate W-exchange processes ("quark-annihilation" processes), as shown in Figs. 2 & 3, which by themselves are strongly suppressed because of helicity mismatch. For example, the D^0 meson, on gluon emission, can flip its spin so that the subsequent weak decay proceeds without helicity suppression. Hard-gluon emission from the D^0 meson, evaluated perturbatively,[2-4] enhances the D^0 decay rate (by ~ 20%). Soft-gluon emission[3,5] is an equally likely source of enhancements in charmed-meson decays, and indeed seems to be the dominant one.[5]

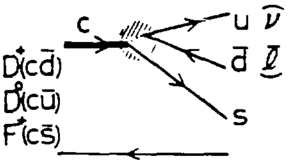
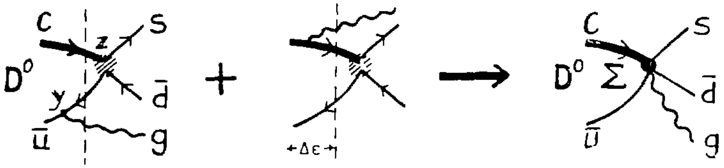


Fig. 1 Charm-quark decay mechanism.

In this talk I would like to study this soft-gluon effect in charmed-meson decays by a nonperturbative method that has theoretical foundations in QCD. The basic tool is a multipole expansion in QCD.[6] The analysis is divided into three steps.



(a_1) (a_2) (b)

Fig. 2 Nonleptonic decays of D^0 via quark annihilation with emission of soft gluons which eventually turn into light hadrons.

(I) Virtual color-fluctuation of charmed mesons.

A pair of c and $\bar{u}$ quarks, that constitutes the D^0 meson, changes its color upon emission or absorption of gluons surrounding it. (I call these gluons soft gluons below.) Correspodingly, let us describe the D^0-meson state $|D^0\rangle$ as a color-singlet $^1S_0$ $c\bar{u}$ constituent-quark pair $|c\bar{u}\rangle$ surrounded by a color-singlet 0^+ soft-gluon cloud (of lowest energy) $|0)$:

$$|D^0\rangle = |cu\rangle \otimes |0) \quad . \tag{1}$$

The spatial spread of the gluon cloud that induces the virtual color-fluctuation will be of the order of $1/\Delta\varepsilon = (100-200\ \text{MeV})^{-1}$, typical spatial spread of ordinary hadrons or a scale characterized by color confinement in QCD. Since the gluon cloud $|0)$ consists of soft-gluon color fluctuations (of vacuum quantum numbers) extending over the typical hadronic size, it may approximately be regarded as the gluonic vacuum.

(II) Separation of long-distance and short-distance phenomena by use of the QCD multipole expansion

Fig. 2a represents the W-exchange process for nonleptonic decays of D^0, accompanied by a soft gluon which eventually turns into light hadrons. Soft-gluon emission is a long-distance

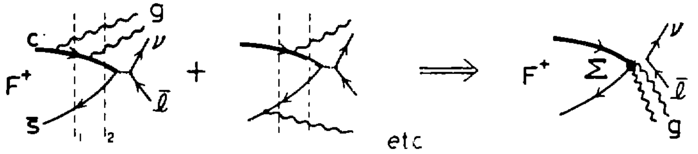


Fig. 3 Annihilation of F^+ into semileptonic channels with emission of soft gluons forming a color-singlet.

phenomenon characterized by the energy difference $\Delta\varepsilon$ associated with the virtual color-fluctuation. On the other hand, $c\bar{u}$ annihilation by the weak current is a short-distance phenomenon characterized by the spatial spread of the c quark $1/m_c$. It will therefore be a reasonable approximation to factorize the soft-gluon and annihilation parts in the decay amplitude:

$$\mathcal{M} = (\text{annihilation}) \cdot (\mathcal{G} \,|\, \mathcal{O}(E,H) \,|\, 0) , \tag{2}$$

where $|\mathcal{G})$ denotes the soft-gluon state. The multipole technique is useful for the determination of the operator $\mathcal{O}(E,H)$ consisting of the soft-gluon color fields E and H: Let us look at Fig. $2a_1$. The gluon field at $\vec{y}$, being soft, may be expanded in multipoles around the quark-annihilation position $\vec{z}$. Then the whole reaction is described by a series of local interactions at $\vec{z}$, as illustrated in Fig. 2b (and in Fig. 3 for the case of semileptonic decays of F^+). These multipole soft-gluon interactions are cast into gauge-invariant form by use of a suitable gauge transformation.[5)] For the process in Fig. 2,

$$\mathcal{O}(E,H) = (1 + m_u/m_c) H^a - i(1 - m_u/m_c) E^a , \tag{3}$$

where only color-M1 and color-E1 interactions have been retained.

(III) Evaluation of the soft-gluon effect in terms of a phenomenologically known gluonic vacuum condensate.

In the calculation of the decay rate, the sum over soft gluons may be approximated as follows

$$\sum_{\mathcal{G}} |\mathcal{G}) \frac{1}{(M_D - \varepsilon)^2} (\mathcal{G}| \quad \sim \quad \frac{1}{(\Delta\varepsilon)^2}\, \mathbb{1} \qquad (4)$$

where the energy denominator has been replaced by its typical average value $\Delta\varepsilon$. This procedure yields the vacuum matrix element of the gluonic operator

$$(0 \,|\, \mathcal{O}^{\dagger}(E,H)\; \mathcal{O}(E,H) \,|\, 0) \qquad (5)$$

Using Lorentz invariance of the QCD vacuum and some factorization hypothesis,[7)] this matrix element can be related to

$$\mathcal{V} = (0|\ (\alpha_s/\pi) F_{\mu\nu}[A]^2 |0) \ \sim\ 0.012\ \mathrm{GeV}^4 \qquad (6)$$

a quantity phenomenologically known from the charmonium sum rules of Shifman et al.[7)] The nonvanishing value of (6) is considered to be a consequence of strong soft-gluon interactions; i.e., it is predominantly saturated by soft-gluon color fluctuations. This will in turn justify the approximation eq.(4) which relies on the saturation of matrix elements involving soft-gluon operators by soft-gluon color fluctuations.

Results

The soft-gluon effect activates the quark-annihilation process for D^0 nonleptonic decays, with the decay rate

$$\frac{\Gamma^{sg}(NL)}{\Gamma(c\to all)} \simeq 12\ (M_D/m_c)^3 (f_D/m_c)^2 (1 + m_u^2/m_c^2)\, \mathcal{V}/(m_u \Delta\varepsilon)^2$$

$$\sim\ 0.7 \times (f_D/\Delta\varepsilon)^2 \qquad (7)$$

where $m_u = 0.34$ GeV and $m_c = 1.65$ GeV have been used. An empirical scaling law gives an estimate of the D-meson decay constant[4)]

$$f_D/\sqrt{2}\ \sim\ 150\ \text{MeV}. \qquad (8)$$

The energy difference $\Delta\varepsilon$ may be estimated from the $^3S_1 - {}^1S_0$ splitting of the D-meson system

$$\Delta\varepsilon\ \sim\ M_{D^*} - M_D\ \simeq\ 140\ \text{MeV}\ , \qquad (9)$$

or from the "binding energy"

$$\Delta\varepsilon\ \sim\ m_c + m_u - M_D\ \simeq 120\ \text{MeV}\ . \qquad (10)$$

Using eq.(8) and $\Delta\varepsilon \sim 140$ MeV (120 MeV), one gets an estimate

$$\tau(D^+)/\tau(D^0)\ \sim\ 2.5\ \ (3.0)\ . \qquad (11)$$

This result indicates that the soft-gluon effect could account for a significant portion of the $D^0 - D^+$ lifetime difference. The actual number in (11) depends on the unknown parameters f_D, $\Delta\varepsilon$, etc; it, nevertheless, is generally sizable for a reasonable range of these parameters. The above qualitative conclusion will therefore, I believe, survive a more elaborate analysis.

Some other consequences of the present analysis are the following:

(i) The enhancement of F^+ nonleptonic decays, though sizable, is smaller than that of D^0 decays.

(ii) Semileptonic decays of F^+ are significantly enhanced and lead to energetic leptons.

(iii) The soft-gluon effects decrease rapidly (like $1/m_c^3$ as $m_c \to \infty$) as quarks become heavier. Consequently, they are not very important for B-meson and T-meson decays.

References

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Acknowledgment

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