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SOFT-GLUON EFFECTS IN CHARMED-MESON DECAYS

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Recent experiments suggest significant enhancements of non-leptonic decays of the $D^0$ meson, such as $\tau(D^+)/\tau(D^0) = 3 \sim 10$ and $\text{BR}(D^0\rightarrow K^-\pi^+)/\text{BR}(D^0\rightarrow K^0\pi^0) > 1$, 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 $\sim 20\%$). Soft-gluon emission$^3,5$ is an equally likely source of enhancements in charmed-meson decays, and indeed seems to be the dominant one.$^5$

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.
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.) Correspondingly, 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) $|0\rangle$:

$$|D^0\rangle = |c\bar{u}\rangle \otimes |0\rangle$$  \hspace{1cm} (1)

The spatial spread of the gluon cloud that induces the virtual color-fluctuation will be of the order of $1/\lambda_c = (100-200 \text{ MeV})$, typical spatial spread of ordinary hadrons or a scale characterized by color confinement in QCD. Since the gluon cloud $|0\rangle$ 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...
phenomenon characterized by the energy difference $\Delta E$ associated with the virtual color-fluctuation. On the other hand, $c\bar{c}$ 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:

\[ \mathcal{M}_2 = \langle \text{annihilation} \rangle \cdot \langle c' | \mathcal{O}(E,H) | 0 \rangle, \]  

where $| c' \rangle$ 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. The gluon field at $\mathbf{y}$, being soft, may be expanded in multipoles around the quark-annihilation position $\mathbf{z}$. Then the whole reaction is described by a series of local interactions at $\mathbf{z}$, 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. For the process in Fig. 2,

\[ \mathcal{O}(E,H) = (1 + m_d/m_c)H^a - i(1 - m_u/m_c)E^a, \]  

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

\[ \sum_{g} |G| \frac{1}{(M_D - E)^2} (g) \sim \frac{1}{(\Delta E)^2} 1 \]  

where the energy denominator has been replaced by its typical average value \( \Delta E \).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

\[ \langle 0 | \mathcal{O}^{(E,H)}_{(E,H)} \mathcal{O}^{(E,H)} | 0 \rangle \]  

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

\[ \mathcal{V} = \langle 0 | (A^\mu A^\nu) \mathcal{F}_{\mu\nu} | 0 \rangle \sim 0.012 \text{ GeV}^4 \]  

a quantity phenomenologically known from the charmonium sum rules of Shifman et al. 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

\[ \frac{\Gamma^{\text{sg}}_{(NL)}}{\Gamma_{(c+all)}} = 12 \left( \frac{M_D}{m_c} \right)^3 \left( \frac{f_D}{m_c} \right)^2 \left( 1 + \frac{m_u^2}{m_c^2} \right) \mathcal{V} / (m_u^4 E^2) \]
where \( m_u = 0.34 \text{ GeV} \) and \( m_c = 1.65 \text{ GeV} \) have been used. An empirical scaling law gives an estimate of the D-meson decay constant\(^4\)

\[
f_D/\sqrt{2} \approx 150 \text{ MeV}.
\]  \( (8) \)

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

\[
\Delta \varepsilon \approx M_D^* - M_D \approx 140 \text{ MeV}, \hspace{1cm} (9)
\]

or from the "binding energy"

\[
\Delta \varepsilon \approx m_c + m_u - M_D \approx 120 \text{ MeV}. \hspace{1cm} (10)
\]

Using eq. (8) and \( \Delta \varepsilon \approx 140 \text{ MeV} \) (120 MeV), one gets an estimate

\[
\tau(D^+)/\tau(D^0) \approx 2.5 \ (3.0). \hspace{1cm} (11)
\]

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

6) For references on the multipole expansion, see ref. 5).

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