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Nonleptonic decays of charmed D mesons and the pole approximation

Azuma Toda
Department of Applied Physics, Tohoku Gakuin University, Tagajo 985, Japan
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We investigate the decay modes of $D \to \bar{K}\pi$ and $D \to \bar{K}\pi\pi$ on the basis of the conventional quark-diagram approach. The matrix element of $\langle P$ or $V|(\bar{q}_1 q_2)|P\rangle$ type will be estimated by the pole approximation. The relevant coupling constants are given by an effective Lagrangian with chiral SU(4) $\times$ SU(4) symmetry. We vary the relative strength of (20-plet part)/(84-plet part) in the effective weak Hamiltonian and predict the decay rates of $D \to \bar{K}\pi$ and $D \to \bar{K}\pi\pi$ relative to $\Gamma(D^0 \to K^-\pi^+)$.

Nonleptonic decays of charmed mesons have been enriched by the recent experimental data,[1] though the number of events is still small. Now we have almost all the observed branching ratios for Cabibbo-favored decay modes of $D\to\bar{K}\pi$ and $D\to\bar{K}\pi\pi$, and also know the experimental ratio of

$$R \equiv \Gamma(D^+)/\Gamma(D^0) \,, \tag{1}$$

where $\Gamma(D^a)$ denotes the total decay rate of D^a meson ($a=0$ or $+$).[1] This new aspect greatly stimulates our theoretical interest in those nonleptonic decay modes, which is one motivation of this paper. Weak decays of charmed mesons have been described by many authors[2] on the assumption that these weak decays occur through the decay of the charm quark c with the noncharm antiquark acting as a spectator. In this paper, we will more closely examine the conventional quark-diagram approach for nonleptonic decays of charmed D mesons.[3-5]

The effective Hamiltonian for the decay $c\to s+u+\bar{d}$ is

$$H_w = \frac{G_F}{\sqrt{2}}\,\frac{\cos^2\theta_C}{2}\left[(c_+ + c_-)(\bar{u}d)(\bar{s}c) + (c_+ - c_-)(\bar{s}d)(\bar{u}c)\right] + \text{H.c.}, \tag{2}$$

where $(\bar{q}_i q_j)$ denotes a color-singlet $V-A$ current and the coefficients $c_\pm$ are the renormalization effects due to hard-gluon exchange.[6] $c_\pm$ have two remarkable properties,[3,7]

$$c_+ < 1 < c_- \quad \text{and} \quad c_- c_+^2 = 1, \tag{3}$$

where the former holds in a reasonable range of the coupling constant and the masses appearing in quantum-chromodynamic calculation, while the latter is independent of these parameters.[8]

We exclusively investigate the decay modes of $D\to\bar{K}\pi$ and $D\to\bar{K}\pi\pi$ although we can apply our approach to other decay modes of D mesons, and to F mesons as well. Three types of quark diagrams, (a), (b), and (c), can contribute to nonleptonic decay processes of D mesons (Fig. 1).[5] The decay mode $D\to\bar{K}\pi$ directly corresponds to these diagrams. For $D\to\bar{K}\pi\pi$, however, we assume that D mesons decay into three channels[9]: (i) $D\to\bar{K}\rho$ followed by $\rho\to\pi\pi$, (ii) $D\to\bar{K}^*\pi$ followed by $\bar{K}^*\to\bar{K}\pi$, and (iii) the "direct decay" with constant amplitudes. Then $D\to\bar{K}\rho$ and $\bar{K}^*\pi$ are presumed to proceed through the quark diagrams of Fig. 1. We neglect soft-gluon corrections at the weak vertex and write the decay amplitudes for two-body decays $D\to PP$ and $D\to PV$ (P is $\bar{K}$ or π, and V is $\bar{K}^*$ or ρ) in the factorized form,[3] e.g.,

$$(8p_D^0 p_K^0 p_\pi^0)^{1/2}\langle \bar{K}^0\pi^+|H_w(0)|D^+\rangle = \frac{G_F}{\sqrt{2}}\cos^2\theta_C\big[X_+(2p_\pi^0)^{1/2}\langle\pi^+|(\bar{u}d)|0\rangle(4p_D^0 p_K^0)^{1/2}\langle\bar{K}^0|(\bar{s}c)|D^+\rangle + X_-(2p_K^0)^{1/2}\langle\bar{K}^0|(\bar{s}d)|0\rangle(4p_D^0 p_\pi^0)^{1/2}\langle\pi^+|(\bar{u}c)|D^+\rangle\big]\,, \tag{4}$$

and so on, where $X_\pm \equiv (2c_+ \pm c_-)/3$. The factors $X_\pm$ arise from the four-fermion vertex itself in H_w(2) and its Fierz-transformed one. We will estimate the matrix element of $\langle P$ or $V|(\bar{q}_1 q_2)|P\rangle$ type by the pole-approximation method.[10] The relevant pole diagrams are shown in Fig. 2.

The effective coupling constants in pole diagrams can be derived from an effective Lagrangian with chiral SU(4)$\times$SU(4) symmetry.[11,12] Let us write our effective Lagrangian for spin 1 and 0 fields in

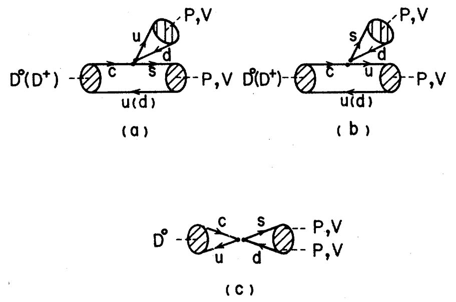

FIG. 1. Quark diagrams for two-body decays $D\to PP$ and $D\to PV$ (P is $\bar{K}$ or π, and V is $\bar{K}^*$ or ρ).

the following form:

$$L=-\tfrac{1}{4}\operatorname{Tr}[F_{\mu\nu}F^{\mu\nu}+G_{\mu\nu}G^{\mu\nu}] +\tfrac{1}{2}\operatorname{Tr}[(\Delta_\mu\sigma)^2+(\Delta_\mu\pi)^2] +\tfrac{1}{2}m_0{}^2\operatorname{Tr}[V_\mu V^\mu+A_\mu A^\mu]+\cdots\ , \tag{5}$$

where

$$\begin{aligned}
F_{\mu\nu}&\equiv\partial_\mu V_\nu-\partial_\nu V_\mu-i\frac{g}{\sqrt{2}}[V_\mu,V_\nu]-i\frac{g}{\sqrt{2}}[A_\mu,A_\nu],\\
G_{\mu\nu}&\equiv\partial_\mu A_\nu-\partial_\nu A_\mu-i\frac{g}{\sqrt{2}}[V_\mu,A_\nu]-i\frac{g}{\sqrt{2}}[A_\mu,V_\nu],\\
\Delta_\mu\sigma&\equiv\partial_\mu\sigma-i\frac{g}{\sqrt{2}}[V_\mu,\sigma]+\frac{g}{\sqrt{2}}\{A_\mu,\pi\},\\
\Delta_\mu\pi&\equiv\partial_\mu\pi-i\frac{g}{\sqrt{2}}[V_\mu,\pi]-\frac{g}{\sqrt{2}}\{A_\mu,\sigma\},
\end{aligned}\tag{6}$$

and V_μ, A_μ, σ, and π stand for vector, axial-vector, scalar, and pseudoscalar fields, respectively.[13] In (6), moreover, the matrix of a field is defined by $\Phi=\sum_{i=0}^{15}(\lambda_i/\sqrt{2})\Phi^i$. The local gauge transformations for those fields are

$$\begin{aligned}
&\delta_{(\alpha)}V_\mu=\frac{1}{g}\partial_\mu\alpha+\frac{i}{\sqrt{2}}[\alpha,V_\mu],\quad \delta_{(\alpha)}A_\mu=\frac{i}{\sqrt{2}}[\alpha,A_\mu],\\
&\delta_{(\beta)}V_\mu=\frac{i}{\sqrt{2}}[\beta,A_\mu],\quad \delta_{(\beta)}A_\mu=\frac{1}{g}\partial_\mu\beta+\frac{i}{\sqrt{2}}[\beta,V_\mu],
\end{aligned}\tag{7}$$

and

$$\begin{aligned}
&\delta_{(\alpha)}\pi=\frac{i}{\sqrt{2}}[\alpha,\pi],\quad \delta_{(\alpha)}\sigma=\frac{i}{\sqrt{2}}[\alpha,\sigma],\\
&\delta_{(\beta)}\pi=\frac{1}{\sqrt{2}}\{\beta,\sigma\},\quad \delta_{(\beta)}\sigma=-\frac{1}{\sqrt{2}}\{\beta,\pi\},
\end{aligned}\tag{8}$$

where α and β are infinitesimal gauge functions. The first two terms in L (5) are invariant under these transformations (7) and (8), while the mass term (the third one) is not invariant unless α and

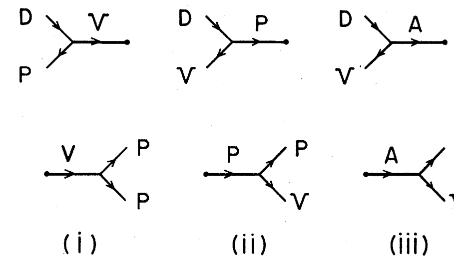

FIG. 2. Pole diagrams. (i) Vector-meson pole, (ii) pseudoscalar-meson pole, and (iii) axial-vector-meson pole. (P, V, and A stand for pseudoscalar, vector, and axial-vector mesons, respectively.)

β are constant. We also note that this mass term yields the vector and axial-vector currents as

$$J_\mu^i\equiv-\frac{\partial(\delta L_{VM})}{\partial(\partial^\mu\alpha^i)}=-\frac{m_0{}^2}{g}V_\mu^i \tag{9}$$

and

$$J_\mu^{(5)i}\equiv-\frac{\partial(\delta L_{VM})}{\partial(\partial^\mu\beta^i)}=-\frac{m_0{}^2}{g}A_\mu^i\ , \tag{10}$$

respectively, where L_{VM} is the mass term of L (5). The above currents correspond to the field algebra.[14]

We do not specify symmetry-breaking terms in the Lagrangian (5) in order to avoid ambiguous features connected with these breaking terms.[15] Thus we *effectively* introduce symmetry breaking into our scheme as

$$\sigma=\sigma_0+\sigma',\quad \sigma_0\equiv\langle\sigma\rangle_0\ , \tag{11}$$

where $\sigma_0^i\neq0$ for $i=0$, 8, and 15, and $\langle\cdots\rangle_0$ denotes a vacuum expectation value. Instead of m_0 and μ_0, if necessary, we will give physical masses for spin 1 and 0 mesons later on. (The mass of σ' must be regarded as large enough.) When $\sigma=\sigma_0+\sigma'$ is inserted into (5), the mixing term between A_μ and π arises from the Lagrangian. To get rid of this term, we define a new axial-vector field a_μ^i by

$$A_\mu^i=a_\mu^i+\xi_i\partial_\mu\pi^i\ , \tag{12}$$

where ξ_i is a free parameter. The coupling of $A_\mu\partial^\mu\pi$ type can then be eliminated by the following choice of ξ_i (Ref. 11):

$$\xi_i=gc_i/m_{Ai}{}^2\ , \tag{13}$$

where

$$m_{Ai}{}^2\equiv m_0{}^2+(gc_i)^2,\quad c_i\,\delta_{ij}=\frac{1}{2\sqrt{2}}\operatorname{Tr}(\{\lambda_i,\lambda_j\}\sigma_0).$$

The coupling constants that we need are of $V\pi\pi$

and $AV\pi$ types. We now obtain these coupling constants from our effective Lagrangian (5) with Eqs. (11), (12), and (13) as

$$g\sum_{i,j,k} f_{ijk}(1-m_{Ai}^2\xi_i^2)\partial^\mu\pi^i V_\mu^j\pi^k + \tfrac{1}{2}g\sum_{i,j,k} f_{ijk}\,\xi_j\,\xi_k\,\Box V_\mu^i\pi^j\partial^\mu\pi^k \quad (14)$$

and

$$g\sum_{i,j,k} f_{ijk}[\,\xi_j\Box V_\mu^i\pi^j a^{\mu k}+(\xi_j-\xi_i)\Box a_\mu^i\pi^j V^{\mu k}\,], \quad (15)$$

for $V\pi\pi$ and $AV\pi$ couplings, respectively, where $\Box$ is the D'Alembertian operator and f_{ijk} is the structure constant of SU(4). If we permit a rough approximation of $\xi_i\simeq\xi$ and $m_{Ai}^2\simeq m_A^2$, the couplings (14) and (15) become

$$-i\frac{g}{\sqrt{2}}\{\mathrm{Tr}([\pi_r,\partial^\mu\pi_r]V_\mu)+\tfrac{1}{2}\xi^2 Z\,\mathrm{Tr}([\pi_r,\partial^\mu\pi_r]\Box V_\mu)\} \quad (16)$$

and

$$-i\frac{g}{\sqrt{2}}\xi Z^{1/2}\mathrm{Tr}([\pi_r,a^\mu]\Box V_\mu)\ , \quad (17)$$

respectively, where

$$\pi_r\equiv Z^{-1/2}\pi,\quad Z^{-1}=1-m_A^2\xi^2\,.$$

These results correspond to the $\kappa=0$ case of Gasiorowicz and Geffen in SU(2)×SU(2).[11]

As an extension of Eqs. (9) and (10), we assume that owing to symmetry breaking, the effective weak current takes the form of

$$J_\mu^{(i)}=-\frac{\tilde{m}_i^2}{g}(V_\mu^{(i)}+a_\mu^{(i)}), \quad (18)$$

TABLE I. Decay rates relative to $\Gamma(D^0\to K^-\pi^+)$. $\tilde{\Gamma}\equiv\Gamma(D\to\bar{K}\pi$ or $\bar{K}\pi\pi)/\Gamma(D^0\to K^-\pi^+)$. $\tilde{\Gamma}_{\rm exp}$ = the experimental data (Ref. 1), where we use $R=0.2$ for D^+ decay modes. Values of $\tilde{\Gamma}$ in parentheses are for $c_0\neq0$ and $c_2\neq0$ (Ref. 20). (a) $X_-/X_+=-0.17$, $c_0=c_2=0$ ($|c_0|^2=0.58$, $|c_2|^2=0.36$). (b) $X_-/X_+=-0.43$, $c_0=c_2=0$ ($|c_0|^2=0.58$, $|c_2|^2=0.13$).

Decay mode	$\tilde{\Gamma}$ (a)	$\tilde{\Gamma}$ (b)	$\tilde{\Gamma}_{\rm exp}$
$D^+\to\bar{K}^0\pi^+$	0.57	0.15 [a]	0.15 ± 0.03
$D^0\to\bar{K}^0\pi^0$	0.030	0.19	0.80 ± 0.38
$D^+\to K^-\pi^+\pi^+$	0.0013 (0.36 [a])	0.23 (0.36 [a])	0.36 ± 0.09
$D^+\to\bar{K}^0\pi^+\pi^0$	2.2 (2.3)	1.9 (2.0)	1.2 ± 0.7
$D^0\to K^-\pi^+\pi^0$	2.6 (2.7)	2.8 (2.8)	2.7 ± 0.9
$D^0\to\bar{K}^0\pi^+\pi^-$	0.062 (1.2 [a])	0.068 (1.2 [a])	1.2 ± 0.3
$D^0\to\bar{K}^0\pi^0\pi^0$	0.019 (0.64)	0.12 (0.71)	

[a] Input (see text and Ref. 20).

where $\tilde{m}_i$ is the parameter with the dimension of mass and i stands for the symbolic quantum number (except parity) of ρ, K^*, D^*, or F^* meson. (E.g., $J_\mu^{(\rho)}$ is composed of ρ and A_1 field-currents.) The decay amplitudes for $D\to\bar{K}\pi$, $D\to\bar{K}\rho$, and $D\to\bar{K}^*\pi$ are then given, as in the Appendix.

We now proceed to predict the decay rates for $D\to\bar{K}\pi$ and $D\to\bar{K}\pi\pi$ in terms of our decay amplitudes (A1), (A2), (A3), and (A6). As already mentioned, D mesons are assumed to decay into $\bar{K}\pi\pi$ through three channels,[9] so that we write the decay rate $\Gamma(D\to\bar{K}\pi\pi)$ in the following form:

$$\tilde{\Gamma}(D^+\to K^-\pi^+\pi^+)=|c_2|^2+\tfrac{2}{3}(\bar{K}^{*0}\pi^+)\ ,$$

$$\tilde{\Gamma}(D^+\to\bar{K}^0\pi^+\pi^0)=\tfrac{1}{4}|c_2|^2+(\bar{K}^0\rho^+)+\tfrac{1}{3}(\bar{K}^{*0}\pi^+)\ ,$$

$$\tilde{\Gamma}(D^0\to K^-\pi^+\pi^0)=\tfrac{1}{4}|c_2|^2+(K^-\rho^+)+\tfrac{1}{3}(K^{*-}\pi^+)+\tfrac{2}{3}(\bar{K}^{*0}\pi^0)\ , \quad (19)$$

$$\tilde{\Gamma}(D^0\to\bar{K}^0\pi^+\pi^-)=|\sqrt{2}\,c_0+\frac{1}{3\sqrt{2}}c_2|^2+(\bar{K}^0\rho^0)+\tfrac{2}{3}(K^{*-}\pi^+),$$

$$\tilde{\Gamma}(D^0\to\bar{K}^0\pi^0\pi^0)=|-c_0+\tfrac{1}{3}c_2|^2+\tfrac{1}{3}(\bar{K}^{*0}\pi^0)\ ,$$

where $\tilde{\Gamma}(D\to\bar{K}\pi\pi)/\Gamma(D^0\to K^-\pi^+)$. $(\bar{K}\rho)$ and $(\bar{K}^*\pi)$ stand for the contributions [normalized by the decay rate $\Gamma(D^0\to K^-\pi^+)$] from $D\to\bar{K}\rho$ and $D\to\bar{K}^*\pi$, respectively, and c_0 and c_2 arise from the direct decays with 2π final states of the isospin $I=0$ and 2, respectively. In order to make numerical estimates, we set several simplified relations in the decay amplitudes (A1), (A2), and (A3) as follows:

$$g_V\simeq g,\quad g_A\simeq-m_\rho g\,,\quad g=\frac{m_\rho}{\sqrt{2}\,f_\pi}\quad \text{(Ref. 16)},$$

$$f_F\simeq f_D\simeq f_K=1.28f_\pi, \quad (20)$$

$$\tilde{m}_i^2=m_i^2\quad (i=\rho,\ K^*,\ D^*,\ F^*)$$

where m_i is the physical mass of i meson. (These relations may well serve our analysis of the branching ratios since the errors of their data are large as yet.[1]) From Eqs. (A1), (A2), (A3), and (A6), using (20) also, we obtain the decay rates for $D\to\bar{K}\pi$ and $D\to\bar{K}\pi\pi$ as shown in Table I. Though the value of X_-/X_+ is intrincically predicted by QCD, QCD does not give a definite value to X_-/X_+ on account of the ambiguity due to the coupling constant and the masses appeared in its calculation.[3,6] In Table I, we have presented our results for the two different values of X_-/X_+. While $X_-/X_+=-0.17$ corresponds to the usual value,[3] $X_-/X_+=-0.43$ is an anomalous value,[17] which was fixed from the value of $\tilde{\Gamma}(D^+\to\bar{K}^0\pi^+)$ when $R=0.2$.[18] The main difference between the two results is due to the cancellation effect at the above values of X_-/X_+. The result (b) is in better agreement with the recent data[1] than the result (a). When R becomes much smaller than 1, $\tilde{\Gamma}(D^+ \to \bar{K}^0\pi^+)$ in case (a) clearly disagree with the data. We note that the amplitudes for $D \to \bar{K}^*\pi$ are small as compared with $D \to \bar{K}\rho$. Thus it may be allowed to neglect the contributions from $D \to \bar{K}^*\pi$. We find that $D \to \bar{K}\pi\pi$ needs at least the direct decay amplitudes c_0 (2π final state of $I = 0$). The recent data of $\tilde{\Gamma}(D^0 \to \bar{K}^0\pi^0)$ is considerably larger than our prediction, which is common to other models.[3-5] This fact seems to need subsequent experiments on $D^0 \to \bar{K}^0\pi^0$.

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APPENDIX

In our model, the decay amplitudes for $D \to \bar{K}\pi$, $D \to \bar{K}\rho$, and $D \to \bar{K}^*\pi$ are given by

$$A(D^+ \to \bar{K}^0\pi^+) = G\left[X_+ f_\pi \left(\frac{\tilde{m}_{F^*}}{m_{F^*}}\right)^2 (m_D^2 - m_K^2) + X_- f_K \left(\frac{\tilde{m}_{D^*}}{m_{D^*}}\right)^2 (m_D^2 - m_\pi^2)\right],$$
$$A(D^0 \to K^-\pi^+) = G\left[X_+ f_\pi \left(\frac{\tilde{m}_{F^*}}{m_{F^*}}\right)^2 (m_D^2 - m_K^2) - X_- f_D \left(\frac{\tilde{m}_{K^*}}{m_{K^*}}\right)^2 (m_K^2 - m_\pi^2)\right], \tag{A1}$$

$$A(D^+ \to \bar{K}^0\rho^+) = G\left\{2X_+\left(-\frac{\sqrt{2}\,\tilde{m}_\rho^2}{g}\right)\frac{\tilde{m}_{F^*}^2}{m_{F^*}^2 - m_\rho^2} + X_- f_K\left[\left(\frac{g_A}{g_V}\right)\left(\frac{\tilde{m}_{D^*}}{m_{D_A}}\right)^2 + \sqrt{2}\, g f_D \frac{m_K^2}{m_D^2 - m_K^2}\right]\right\}(p_D \cdot \epsilon_\rho),$$
$$A(D^0 \to K^-\rho^+) = G\left\{2X_+\left(-\frac{\sqrt{2}\,\tilde{m}_\rho^2}{g}\right)\frac{\tilde{m}_{F^*}^2}{m_{F^*}^2 - m_\rho^2} + X_- f_D\left[\left(\frac{g_A}{g_V}\right)\left(\frac{\tilde{m}_{K^*}}{m_{K_A}}\right)^2 + \sqrt{2}\, g f_K \frac{m_D^2}{m_D^2 - m_K^2}\right]\right\}(p_D \cdot \epsilon_\rho), \tag{A2}$$

and

$$A(D^+ \to \bar{K}^{*0}\pi^+) = G\left\{2X_-\left(-\frac{\sqrt{2}\,\tilde{m}_{K^*}^2}{g}\right)\frac{\tilde{m}_{D^*}^2}{m_{D^*} - m_{K^*}^2} + X_+ f_\pi\left[\left(\frac{g_A}{g_V}\right)\left(\frac{\tilde{m}_{F^*}}{m_{F_A}}\right)^2 + \sqrt{2}\, g f_F \frac{m_\pi^2}{m_F^2 - m_\pi^2}\right]\right\}(p_D \cdot \epsilon_{K^*}),$$
$$A(D^0 \to K^{*-}\pi^+) = G\left\{X_+ f_\pi\left[\left(\frac{g_A}{g_V}\right)\left(\frac{\tilde{m}_{F^*}}{m_{F_A}}\right)^2 + \sqrt{2}\, g f_F \frac{m_\pi^2}{m_F^2 - m_\pi^2}\right] - X_- f_D\left[\left(\frac{g_A}{g_V}\right)\left(\frac{\tilde{m}_{K^*}}{m_{K_A}}\right)^2 + \sqrt{2}\, g f_K \frac{m_D^2}{m_D^2 - m_K^2}\right]\right\} \times (p_D \cdot \epsilon_{K^*}), \tag{A3}$$

where $G = (G_F/\sqrt{2})(g_V/g)\cos^2\theta_C$, ϵ_V denotes the polarization vector of V meson, and f_P is the decay constant of P meson. The effective coupling constants g_V and g_A are defined by

$$-i\frac{g_V}{\sqrt{2}}\,\mathrm{Tr}([\pi, \partial_\mu \pi]V^\mu) \tag{A4}$$

and

$$-i\frac{g_A}{\sqrt{2}}\,\mathrm{Tr}([\pi, a_\mu]V^\mu), \tag{A5}$$

respectively. It follows from the Hamiltonian (2) that our decay amplitudes satisfy the relations[19]

$$\sqrt{2}\,A(D^0 \to \bar{K}^0\pi^0) = A(D^+ \to \bar{K}^0\pi^+) - A(D^0 \to K^-\pi^+),$$
$$\sqrt{2}\,A(D^0 \to \bar{K}^0\rho^0) = A(D^+ \to \bar{K}^0\rho^+) - A(D^0 \to K^-\rho^+),$$
$$\sqrt{2}\,A(D^0 \to \bar{K}^{*0}\pi^0) = A(D^+ \to \bar{K}^{*0}\pi^+) - A(D^0 \to K^{*-}\pi^+). \tag{A6}$$

[1] The data is summarized by V. Luth and J. Kirkby, in *Proceedings of the 1979 International Symposium on Lepton and Photon Interactions at High Energies, Fermilab*, edited by T. B. W. Kirk and H. D. I. Abarbanel (Fermilab, Batavia, Illinois, 1980).

[2] For reviews, see M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. 47, 277 (1975); G. Altarelli, in *Proceedings of the 19th International Conference on High Energy Physics, Tokyo, 1978*, edited by S. Homma, M. Kawaguchi, and H. Miyazawa (Phys. Soc. of Japan, Tokyo, 1979), p. 411; M. K. Gaillard, in *Weak Interactions—Present and Future*, proceedings of SLAC Summer Institute on Particle Physics, 1978, edited by Marsha C. Zipf (SLAC, Stanford, 1978).

[3] J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B100, 313 (1975).

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

[5]Y. Abe, report, 1978 (unpublished).

[6]M. K. Gaillard and B. W. Lee, Phys. Rev. Lett. 33, 108 (1974); G. Altarelli and L. Maiani, Phys. Lett. 52B, 351 (1974).

[7]G. Altarelli, N. Cabibbo, and L. Maiani, Phys. Rev. Lett. 35, 635 (1975).

[8]For a phenomenological analysis, the importance of $c_- c_+^2 \doteq 1$ has been emphasized by Y. Koide, Phys. Rev. D 18, 1644 (1978).

[9]S. P. Rosen, Phys. Rev. Lett. 41, 3 (1978).

[10]See, for example, G. Feldman, P. T. Matthews, and A. Salam, Phys. Rev. 121, 302 (1961).

[11]S. Gasiorowicz and D. A. Geffen, Rev. Mod. Phys. 41, 531 (1969).

[12]Y. Takaiwa, Prog. Theor. Phys. 59, 1625 (1978).

[13]For spin-0 field, we may add $L_{MM} = -\frac{1}{2}\mu_0^2 \mathrm{Tr}(\sigma^2 + \pi^2)$ to L (5).

[14]N. Kroll, T. D. Lee, and B. Zumino, Phys. Rev. 157, 1376 (1967).

[15]See, for example, Ref. 11.

[16]K. Kawarabayashi and M. Suzuki, Phys. Rev. Lett. 16, 255 (1966); Riazuddin and Fayyazuddin, Phys. Rev. 147, 1071 (1966).

[17]The possibility of other value of X_-/X_+ was pointed out by M. Katuya and Y. Koide, Phys. Rev. D 19, 2631 (1979).

[18]The preliminary value is $R^{-1} > 5.8 \pm 1.5$. (Ref. 1).

[19]M. Peshkin and J. L. Rosner, Nucl. Phys. B122, 144 (1977).

[20]We have tentatively fixed c_0 and c_2 from the data of $\tilde{\Gamma}(D^0 \to \bar{K}^0\pi^+\pi^-)$ and $\tilde{\Gamma}(D^+ \to K^-\pi^+\pi^+)$, respectively, where the interference term between c_0 and c_2 has been ignored. For case (b), the data is not inconsistent with $c_0 \neq 0$ and $c_2 = 0$.