in part by the National Science Foundation (Cornell).
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[1]For a recent review see D. Sivers, S. J. Brodsky, and R. Blankenbecler, Phys. Rep. 23C, 1 (1976).
[2]F. W. Busser *et al.*, Phys. Lett. 46B, 471 (1973).
[3]J. W. Cronin *et al.*, Phys. Rev. D 11, 3105 (1975).
[4]S. M. Berman, J. D. Bjorken, and J. B. Kogut, Phys. Rev. D 4, 3388 (1971).
[5]For a somewhat different interpretation see R. C. Hwa, A. J. Spiessbach, and M. J. Teper, Phys. Rev. Lett. 36, 1418 (1976).
[6]R. Blankenbecler, S. J. Brodsky, and J. F. Gunion, Phys. Lett. 42, (1972), and Phys. Rev. D 6, 2652 (1972).
[7]R. Blankenbecler and S. J. Brodsky, Phys. Rev. D 10, 2973 (1974).
[8]R. Blankenbecler, S. J. Brodsky, and J. Gunion, Phys. Rev. D 12, 3469 (1975).
[9]L. N. Hand, Phys. Rev. 129, 1834 (1964).
[10]W. B. Atwood, private communication.
[11]A. Browman *et al.*, Phys. Rev. Lett. 35, 1313 (1975).
[12]V. Eckardt *et al.*, DESY Report No. 74/5, 1974 (unpublished).
[13]K. C. Moffeit *et al.*, Phys. Rev. D 5, 1603 (1972).
[14]H. Burfeindt *et al.*, Phys. Lett 43B, 345 (1973), and Nucl. Phys. B74, 189 (1974).
[15]W. Kaune *et al.*, Phys. Rev. D 11, 478 (1975).
[16]A. M. Boyarski *et al.*, SLAC Report No. SLAC-PUB-1694, 1975 (unpublished).
[17]C. J. Bebek *et al.*, Phys. Rev. Lett. 34, 759 (1975).
[18]J. D. Bjorken and J. Kogut, Phys. Rev. D 8, 1341 (1973).
[19]S. J. Brodsky and G. R. Farrar, Phys. Rev. Lett. 31, 1153 (1973).

Electromagnetic Mass Differences and Decay Rates of Charmed Mesons in the Charmed-Quark Model

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Using the harmonic-oscillator charmed-quark model, I have studied the electromagnetic mass differences and the decay rates of charmed mesons.

A new particle D^0 with a mass of 1.86 GeV has recently been discovered.[1] This particle has properties of a charmed meson.[1,2] In this note I study the properties of charmed mesons using the charmed-quark model. In a previous paper[3] the electromagnetic mass differences of baryons, the amplitudes for the processes $\gamma N \to N^* \to N\pi$, and the cross sections for the processes $eN \to eN^*$ were explained with remarkable success using explicit harmonic-oscillator wave functions with a radius $R^2 = 2.75\ \text{GeV}^{-2}$ consistently. In an analogous way I studied the electromagnetic properties of mesons[4] and found almost the same radius $R^2 = 2.74\ \text{GeV}^{-2}$ for the $q\bar{q}$ wave function.

Following Refs. 3 and 4 I make the following assumptions on the charmed mesons: (a) The electromagnetic mass differences of charmed mesons are caused (i) by the mass difference (Δm_e) between the u quark and the d quark, (ii) by the Coulomb force between the quark and the antiquark, and (iii) by the magnetic hyperfine interaction. (b) The gyromagnetic ratios of quarks are 1. Therefore, the magnetic moment equals charge/2× mass. From the magnetic moments of baryons we get $\mu_q = \mu_p = 2.793e/2m_p$, hence $m_q \sim 336$ MeV for the u quark and for the d quark. (c) From the mass spectrum of mesons (ψ, D^0, ρ, π, etc.), I estimate the mass of the charmed quark (m_c) to be about 1300 MeV.

Employing the harmonic-oscillator wave function for the $c\bar{q}$ system,

$$\psi = N \exp(-r^2/2R_0^2), \quad R_0 = \sqrt{2}R, \tag{1}$$

one gets

$$\begin{aligned} D^+ - D^0 &= -\Delta m_e + \frac{2}{3}\left(\frac{2}{\pi}\right)^{1/2}\frac{e^2}{R} + \frac{2}{3}\left(\frac{2}{\pi}\right)^{3/2} R^{-3}\pi\mu_p^2 \frac{m_q}{m_c}, \\ D^{*+} - D^{*0} &= -\Delta m_e + \frac{2}{3}\left(\frac{2}{\pi}\right)^{1/2}\frac{e^2}{R} - \frac{2}{9}\left(\frac{2}{\pi}\right)^{3/2} R^{-3}\pi\mu_p^2 \frac{m_q}{m_c}. \end{aligned} \tag{2}$$

Here D and D^* denote, respectively, the charmed pseudoscalar and vector mesons of isospin $\frac{1}{2}$.

At present we have no experimental data to determine the value of R directly. In previous papers[3,4] from electromagnetic properties of baryons and mesons I obtained

$$R_{qq} \approx R_{q\bar{q}} \approx 2R_{c\bar{c}}, \quad R_{q\bar{q}}^2 \approx 2.74\ \text{GeV}^{-2}. \tag{3}$$

Therefore, it seems most reasonable (see sections 6 and 7 of Ref. 4) to assume $R_{c\bar{q}} \simeq \frac{3}{4} R_{q\bar{q}}$.

Taking $\Delta m_e = -7.06$ MeV, which is obtained from the electromagnetic mass differences of mesons,[4] one gets

$$D^+ - D^0 = 12.5 \text{ MeV}, \quad D^{*+} - D^{*0} = 9.4 \text{ MeV}. \tag{4}$$

Notice that these results are consistent with the relations obtained by Lichtenberg,[5]

$$\begin{aligned} &D^+ > D^0, \quad D^+ - D^0 > K^0 - K^+, \\ &D^{*+} > D^{*0}, \quad D^+ - D^0 > D^{*+} - D^{*0}. \end{aligned} \tag{5}$$

Using the quark model but neglecting the hyperfine magnetic interaction, De Rújula[2] made the following rough estimates,

$$\begin{aligned} &D^+ - D^0 = 15 \pm 5 \text{ MeV}, \\ &D^{*+} - D^{*0} = 15 \pm 5 \text{ MeV}. \end{aligned} \tag{6}$$

However, the term coming from the magnetic hyperfine interaction is not negligible but comparable to other terms even if we assume a small magnetic moment for the charmed quark [$\mu_c = \frac{336}{1300}\mu_u$]. The difference

$$(D^+ - D^0) - (D^{*+} - D^{*0}) = 3.1 \text{ MeV}, \tag{7}$$

is caused only by the magnetic hyperfine interaction.

As the next step I consider the decay processes $D^* \to D\pi$. The decay rate, of course, depends on the mass difference between D^* and D. De Rújula[2] pointed out some evidences of $D^{*0}(2000)$ from his analysis of the recoil mass spectrum. Here I compute the decay rate by changing the mass difference $D^{*0} - D^0 \equiv \Delta$. Using the electromagnetic mass differences obtained above, one gets

$$\begin{aligned} &D^0 = 1865 \text{ MeV}, \quad D^+ = 1877.5 \text{ MeV}, \\ &D^{*0} = 1865 + \Delta \text{ MeV}, \quad D^{*+} = 1874.4 + \Delta \text{ MeV}. \end{aligned} \tag{8}$$

The charmed quark cannot couple with π. The (u,d)-π coupling is

$$\pm \frac{f_q}{m_\pi} (\vec{\sigma} \cdot \nabla)[\vec{\tau} \cdot \vec{\varphi}(\vec{x})], \tag{9}$$

where $f_q = \frac{3}{5} f_{\pi N}$, $f_{\pi N}{}^2/4 = 0.082$. The plus sign should be taken for the π emission by quarks and the minus sign for that by antiquarks.

In the nonrelativistic calculation there is an ambiguity coming from the choice of the reference frame.[6,7] However, in the process $D^* \to D\pi$ the recoil of the final D meson is small. I calculate the amplitude in the resonance rest frame (c.m. frame). The decay widths are found to be

$$\begin{aligned} \Gamma_{D^{*0} \to D^0\pi^0} &= \frac{1}{3}\frac{k^3}{2\pi}\left(\frac{f_q}{m_\pi}\right)^2 I_u(k)^2, \\ \Gamma_{D^{*0} \to D^+\pi^-} &= \frac{2}{3}\frac{k^3}{2\pi}\left(\frac{f_q}{m_\pi}\right)^2 I_u(k)^2, \\ \Gamma_{D^{*+} \to D^+\pi^0} &= \frac{1}{3}\frac{k^3}{2\pi}\left(\frac{f_q}{m_\pi}\right)^2 I_u(k)^2, \\ \Gamma_{D^{*+} \to D^0\pi^+} &= \frac{2}{3}\frac{k^3}{2\pi}\left(\frac{f_q}{m_\pi}\right)^2 I_u(k)^2, \end{aligned} \tag{10}$$

where

$$\begin{aligned} &I_u(k) = \exp\left[-\frac{1}{4}\left(\frac{m_c}{m_c + m_u}\right)^2 (R_0 k)^2\right], \\ &R_c = \tfrac{3}{4}(2 \times 2.74)^{1/2} \text{ GeV}^{-1}. \end{aligned} \tag{11}$$

We can also calculate decay rates of radiative decay processes $D^* \to D\gamma$ using the nonrelativistic interaction,

$$H_{\text{int}} = -i \sum_{i = q, \bar{q}} \mu_i \vec{\sigma}_i \cdot (\vec{k} \times \vec{A}). \tag{12}$$

The decay rates are given by

$$\begin{aligned} \Gamma_{D^{*0} \to D^0\gamma} &= \tfrac{4}{3}[\mu_u I_u(k) + \mu_c I_c(k)]^2] k^3, \\ \Gamma_{D^{*+} \to D^+\gamma} &= \tfrac{4}{3}[\mu_d I_u(k) + \mu_c I_c(k)]^2 k^3, \end{aligned} \tag{13}$$

where

$$I_c(k) = \exp\left[-\frac{1}{4}\left(\frac{m_u}{m_u + m_c}\right)^2 (R_0 k)^2\right]. \tag{14}$$

The plots of these predictions are given in Fig. 1. The most prominent feature of these decay rates is that $\Gamma_{D^{*0} \to D^0\gamma} \gg \Gamma_{D^{*+} \to D^+\gamma}$. Since $I_u(k) \sim I_c(k) \sim 1$ for $\Delta < 600$ MeV, one gets

$$\begin{aligned} &\Gamma_{D^{*0} \to D^0\gamma} / \Gamma_{D^{*+} \to D^+\gamma} \\ &\qquad \approx (\mu_u + \mu_c)^2 / (\mu_d + \mu_c)^2 \approx 25, \end{aligned} \tag{15}$$

for $\mu_c = (m_u/m_c)\mu_u$. Even if I assume a large magnetic moment of the charmed quark, e.g., $\mu_c = \mu_u$, I get $\Gamma_{D^{*0} \to D^0\gamma} / \Gamma_{D^{*+} \to D^+\gamma} \approx 16$ and the relation $\Gamma_{D^{*0} \to D^0\gamma} \gg \Gamma_{D^{*+} \to D^+\gamma}$ still holds.

For large Δ, the $D^* \to D\pi$ decay rate dominates but near the threshold of $D^* \to D\pi$, the $D^* \to D\gamma$ decay width becomes comparable to that for $D^* \to D\pi$,

$$\begin{aligned} &\Gamma_{D^{*0} \to D^+\pi^-} = \Gamma_{D^{*0} \to D^0\gamma} \text{ for } \Delta = 155.2 \text{ MeV}, \\ &\Gamma_{D^{*0} \to D^0\pi^0} = \Gamma_{D^{*0} \to D^0\gamma} \text{ for } \Delta = 139.2 \text{ MeV}, \\ &\Gamma_{D^{*+} \to D^0\pi^+} = \Gamma_{D^{*+} \to D^+\gamma} \text{ for } \Delta = 130.4 \text{ MeV}, \\ &\Gamma_{D^{*+} \to D^+\pi^0} = \Gamma_{D^{*+} \to D^+\gamma} \text{ for } \Delta = 138.5 \text{ MeV}. \end{aligned} \tag{16}$$

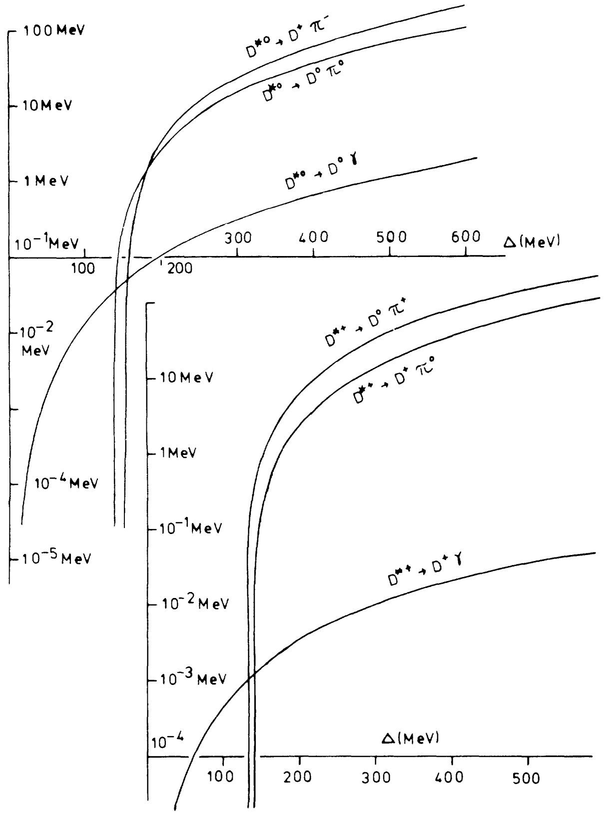

FIG. 1. Decay rates $\Gamma_{D^*\to D\pi}$ and $\Gamma_{D^*\to D\gamma}$ in the charmed quark model: $\Delta \equiv D^{*0} - D^0$.

For $\Delta > 200$ MeV one gets

$$\begin{aligned} &\Gamma_{D^{*0}\to D^+\pi^-} : \Gamma_{D^{*0}\to D^0\pi^0} : \Gamma_{D^{*0}\to D^0\gamma} \\ &\quad \simeq 1{:}0.5{:}10^{-2}, \\ &\Gamma_{D^{*+}\to D^0\pi^+} : \Gamma_{D^{*+}\to D^+\pi^0} : \Gamma_{D^{*+}\to D^+\gamma} \\ &\quad \simeq 1{:}0.5{:}3\times 10^{-3}. \end{aligned} \tag{17}$$

In view of the fact that, experimentally, Δ appears to be about 140 MeV, very nearly a pion mass, and is not measured with high accuracy, one may not be able to calculate the decay rates of $D^* \to D\pi$ very accurately.

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[1] V. Lüth, in Proceedings of the International Neutrino Conference, Aachen, West Germany, 1976 (to be published).

[2] A. De Rújula, in Proceedings of the International Neutrino Conference, Aachen, West Germany, 1976 (to be published).

[3] S. Ono, Nucl. Phys. B107, 522 (1976).

[4] S. Ono, to be published.

[5] D. B. Lichtenberg, Phys. Rev. D 12, 3760 (1975).

[6] A. Le Yaouanc, L. Oliver, O. Pène, and J. C. Raynal, Nucl. Phys. B37, 552 (1972).

[7] S. Ono, Phys. Rev. D 9, 2005, 2670 (1974).

Gauge Theory of *CP* Nonconservation*

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It is proposed that *CP* nonconservation arises purely from the exchange of Higgs bosons.

Ever since the discovery[1] that *CP* conservation is not exact, the mystery has been why it is so feebly violated.[2] In many proposed theories,[3] one must arrange to have *CP* to be approximately conserved, by making the appropriate constants in the Lagrangian to have sufficiently small values. However, one would prefer a more natural explanation.

Renormalizable gauge theories[4] of the weak and electromagnetic interactions provide a mechanism which could violate *CP* conservation with about the right strength: the Higgs boson. The coupling strength of a Higgs boson to a quark or lepton of mass m is of order $mG_F^{1/2}$ (where G_F is the Fermi coupling constant), so that the exchange of a Higgs boson of mass m_H produces an effective Fermi interaction with coupling of order $G_F m^2/m_H^2$. For reasonable mass values,[5] this is "milliweak." However, in order for the Higgs exchange to appear as a natural explanation for a feeble *CP* nonconservation, one must understand why *CP* conservation is strongly violated in the Higgs exchange, *and nowhere else*. In this paper, I wish to present a realistic gauge theory, in which *CP* nonconservation automatically arises in just this way.[6]

We assume an SU(2)⊗U(1) gauge theory,[4] with the usual four quarks[7]: $\mathcal{P}_1$ and $\mathcal{P}_2$ have charge $+\frac{2}{3}$