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Charmed-quark model for narrow resonances*

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An isospin suppression is used as a possible explanation of the narrow width of the 3.1-GeV resonance in a model with three charmed quarks. This follows from an analogy with ρ-ω mixing and the $\omega \to 2\pi$ decay. The decays and widths of radial excitations of the 3.1-GeV resonance are discussed. The weak couplings of the model predict different decays for charmed particles than other models with charm; in particular, K mesons are not always found in the decays. An experimental test which clearly distinguishes this model from other models is given.

I. INTRODUCTION

A. Quark models and charm

The quark model[1-3] of Gell-Mann and Zweig has been very successful in accounting for the spectroscopy and the approximate masses, couplings, and decay widths for the large number of hadrons found in the last two decades. Further evidence of quarks may be implied from scaling behavior[4] in eN, νN, and perhaps e^+e^- scattering. It was hoped (and still is) that the latter experiment would resolve the question of whether there were one or three colors[5] of quarks or similar extensions[6] of the number of quarks which solved problems of statistics and which more recently have been applied to the problem of quark confinement.[7]

While general sentiment seemed to favor three color triplets (of the $\mathcal{P}$, $\mathcal{N}$, and λ quarks with charges $\frac{2}{3}$, $-\frac{1}{3}$, and $-\frac{1}{3}$), it was argued by some that a fourth and "charmed" quark[8] $\mathcal{P}'$ (with charge $\frac{2}{3}$ and having three colors also) was necessary to suppress strangeness-changing neutral currents to first[9] and higher[10] orders. This effect is reflected in the suppression of decays such as $K_L \to \mu^+\mu^-$. The magnitude of that suppression put strong upper limits on the mass of particles containing charmed quarks. Because the advocates of charm had in mind this result plus the "increasing" value[11] of $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ which was greater than the expected value $R=2$ (from three color triplets), they were not surprised[12-15] at the discovery of a resonance[16,17] in e^+e^- scattering and the e^+e^- decay mode (in pp scattering) at $\sqrt{s}=3.1$ GeV. It was thought to be a meson $\mathcal{P}'\overline{\mathcal{P}}'$ which has been called J and ψ.

The charm hypothesis[18-21] leads to several interesting predictions. The $\mathcal{P}'$ and $\overline{\mathcal{P}}'$ have parallel spins, which gives spin 1, resulting in the name "orthocharmonium." The existence of a "paracharmonium"[14] state (spin zero) follows. One must also find charmed particles (such as $\mathcal{P}'\overline{\mathcal{N}}$), and their masses (as estimated in Ref. 13) should be around 2 GeV. The charmed particles should almost always decay into at least one K meson. The decay mode $K+\pi$ should be observed, among others. There should also be charmed baryons with masses around or above 2.3 GeV. Also possible in this model is the existence of radial excitations[19,22,23] of the 3.1-GeV resonance. The dominant decays, if these resonances are below charm threshold, will include those into the ψ (J) (plus other particles). If a radial excitation lies above charm threshold, it will decay dominantly into charmed mesons and will be as wide as or wider than the ρ meson.

The ρ^0, ω, ϕ, and ψ are predicted to be produced in e^+e^- scattering in a 9 : 1 : 2 : 8 ratio (from charges added coherently and squared), and the leptonic widths ($V \to e^+e^-$ or $\mu^+\mu^-$) are expected to be approximately in that ratio. The quantity R defined above should have an asymptotic value of $3\frac{1}{3}$ in this model compared to 2 in the three-color-triplet model.

One of the remarkable features of the ψ resonances was its long lifetime or narrow decay width. Charm advocates[13] had expected it to be narrower (although no one anticipated 75 keV) than resonances with the strongest decays since the decay into two charmed mesons ($p'\overline{n}+\overline{p}'n$) was assumed to be below threshold. All other decay modes are said to violate the Okubo-Zweig-Iizuka (OZI) rule[2] since the $\mathcal{P}'$ quarks in ψ must annihilate in order for decay into uncharmed mesons to occur. A similar decay is $\phi \to \rho\pi$, which is 660 keV wide [although it is close to the threshold for decay, which $\psi \to \rho\pi$ (etc.) is not].

Since the ψ is only 75 keV wide an additional explanation of the width is necessary. One approach to this problem is that of Appelquist and Politzer,[14] who have argued that this additional suppression is due to the features of an "asymptotically free"[24,25] quark-gluon model. In the Appelquist-Politzer model, the annihilation of the

$\mathcal{P}'$ quarks takes place via three color gluons. The asymptotic effective coupling to these gluons is expected to be small. Since the ψ is much more massive than the ϕ, the coupling α_s is expected to be smaller, leading to a narrow width for ψ.

B. Three charmed quarks

The model proposed here has much in common with those described above but differs with respect to aspects of several of the main features discussed. Among these are the following: (1) A different explanation for the narrow width is given. (2) Additional particles are predicted. (3) The decays of some types of charmed particles will usually not include a K meson. (4) R has an asymptotic value of 4.

The same mechanism for suppression of strangeness-changing neutral currents is present in this model. Similar masses and decay widths for paracharmonium, radial excitations, and charmed particles are expected.

The basic hypothesis of this model[26] is that there is a second set of quarks $\mathcal{P}'$, $\mathcal{N}'$, and λ' similar to the first set $\mathcal{P}$, $\mathcal{N}$, and λ but much heavier and having the quantum number charm. These are assumed to have the same charges ($\frac{2}{3}$, $-\frac{1}{3}$, and $-\frac{1}{3}$) and relative masses as the $\mathcal{P}$, $\mathcal{N}$, and λ; in particular, $m(\mathcal{P}')\approx m(\mathcal{N}')$ [an estimate from linear mass relations[15,27] gives $m(\mathcal{P}')\approx 4m(\mathcal{P})$, but no use of this is necessary here]. As before, each quark comes in three colors.

The original charmed-quark model with one charmed quark $\mathcal{P}'$ has four new mesons $\mathcal{P}'\overline{\mathcal{P}}'$, $\mathcal{P}'\overline{\mathcal{N}}$, $\mathcal{P}'\overline{\mathcal{P}}$, and $\mathcal{P}'\overline{\lambda}$ (plus antiparticles). The SU(6) spectroscopy obtained here yields, unfortunately, quite a few more particles. The only ones to be considered among the new uncharmed mesons will be $\frac{1}{2}(\mathcal{P}'\overline{\mathcal{P}}'-\mathcal{N}'\overline{\mathcal{N}}')$, $\frac{1}{2}(\mathcal{P}'\overline{\mathcal{P}}'+\mathcal{N}'\overline{\mathcal{N}}')$, and $\lambda'\overline{\lambda}'$, which for the vectors (states of orthocharmonium) are defined as ρ_2, ω_2, and ϕ_2. Similarly the pseudoscalars (states of paracharmonium) are defined as π_2, η_2, and η_2'. Among the charmed mesons, discussion will be limited to $\mathcal{P}'\overline{\mathcal{N}}$, $\mathcal{P}\overline{\mathcal{N}}'$, $\mathcal{P}'\overline{\lambda}$, and $\mathcal{P}\overline{\lambda}'$.

The ρ_2, ω_2, and ϕ_2 are produced in e^+e^- scattering in the same 9 : 1 : 2 ratio as ρ, ω, and ϕ. It is ρ_2, therefore, which can be identified with the resonance[17] at 3.1 GeV in e^+e^- scattering. The ω_2, which will be very close to the ρ_2, will be shown in Sec. III to be very difficult to observe in e^+e^- scattering (in part because of the 9 : 1 ratio). The ϕ_2 is expected to lie at or above 4.1 GeV. The observed[28,29] 3.7- and 4.1-GeV resonances are assumed to be radial excitations of ρ_2.

The ω_2, which is much wider in this model than the ρ_2, is found (Sec. III) to be the particle produced at Brookhaven National Laboratory (BNL),[16] although at higher energies ρ_2 can also be produced in pp scattering.

In Sec. II the narrow decay width of the ψ (ρ_2) observed at the Stanford Linear Accelerator Center (SLAC)[17] is hypothesized to be due to an isospin suppression. An analogy is made with the narrow width of the decay mode $\omega\to 2\pi$ which violates G parity but which occurs [$\Gamma(\omega\to 2\pi)=130$ keV] because of ρ-ω mixing. The basic hypothesis is that ρ_2 must decay through annihilation of the $\mathcal{P}'$ and $\overline{\mathcal{P}}'$ quarks and that the (strong) decay can only occur via three color gluons or some other isospin-zero mode. The ρ_2 which has isospin 1 (isospin of the charmed quarks) is able to decay into hadrons only because of ρ_2-ω_2 mixing. As a result the ρ_2 is much narrower than ω_2.

Several of the implications of different decay and production modes of the ρ_2 and ω_2 are discussed in Sec. III. The leptonic widths and the magnitude of α_s are among the topics discussed. A crucial test of the model is suggested which results from the existence of both a ρ_2 and an ω_2. The test, one hopes, will disprove this model or most other models.

Section IV is devoted to the resonances at 3.7 and 4.1 GeV. Radial excitations and the ϕ_2 are considered along with the problem of charm threshold. The allowed decays of the 3.7-GeV resonance are discussed.

The weak couplings of the model are presented in Sec. V. The suppression of strangeness-changing neutral currents will be evident. The nature of the decays of charmed particles and the problem of "observing" charm are discussed. In this model some charmed mesons decay into $\mu\nu$, $\pi\mu\nu$, $\pi\pi$, $\pi\pi\pi$, etc.

II. THE NARROW WIDTH OF ψ AT SLAC

One of the remarkable features of the 3.1-GeV resonance which must be explained is the narrow 75-keV width observed at SLAC. The mass of charmed particles had been estimated in Ref. 13 to be greater than half of the mass of ψ. Therefore, the ρ_2 and ω_2 are assumed to be below threshold for decay into two charmed particles (e.g., $\mathcal{P}'\overline{\mathcal{P}}'\to\mathcal{P}'\overline{\mathcal{N}}+\mathcal{N}\overline{\mathcal{P}}'$), which, in analogy to $\phi\to K\overline{K}$ ($\lambda\overline{\lambda}\to\lambda\overline{\mathcal{N}}+\mathcal{N}\overline{\lambda}$), is the only decay allowed by the OZI rule.[2] This rule allows only diagrams in which all quark lines begin and end in different particles. The decays of ρ_2 and ω_2 (as in the single-charm model) into noncharmed hadrons violate this rule since the $\mathcal{P}'$ and $\overline{\mathcal{P}}'$ must annihilate, or they would be found in the final-state particles.

Another decay which violates the OZI rule is $\phi \to \rho\pi$ ($\lambda\bar{\lambda} \to \mathcal{P}\bar{\mathcal{N}} + \mathcal{N}\bar{\mathcal{P}}$). $\Gamma(\phi \to \rho\pi)$ is only 660 keV,[30] but one must keep in mind that there is very little phase space available for this decay. If one divides the width by the p-wave kinematical factor p^3/m^2 ($p/2$ = momentum of each decay product in the center-of-mass system), one obtains an effective width of $\Gamma(\phi \to \rho\pi) \approx 15$ MeV.

Since the hadronic decay of ψ (here both the ρ_2 and ω_2) violates the OZI rule, it will also be narrower than ordinary strong decays. The factor obtained above is clearly not enough to explain the 75-keV width observed. Appelquist and Politzer[14] argue that the annihilation decay occurs through three color gluons and that by asymptotic freedom concepts[24,25] the effective couplings of the gluons will decrease in going from the mass of ϕ to the mass of ψ—enough, it is assumed, to account for the 75-keV width of ψ.

However, it will be assumed here that this factor from asymptotic freedom is only adequate for the width of ω_2 (whereas, as discussed in Sec. I B and Sec. III, it is the ρ_2 that is the narrow resonance observed at SLAC).

The relative widths of ρ_2 and ω_2 are found in analogy with the 2π decays of ρ and ω. Since ω and π mesons have negative G parity, and G parity is conserved by the strong interactions, the decay $\omega \to \pi + \pi$ is forbidden although $\rho \to \pi + \pi$ is allowed because of the ρ's positive G parity. However, isospin [one component of G parity: $G = C(-1)^I$] is not conserved by the electromagnetic interactions. As a result, the ρ and ω, which are very close in mass ($m_\rho = 770$ MeV and $m_\omega = 783$ MeV) and have the same spin, parity, and C, are mixed electromagnetically so that[31-35]

$$\rho = \rho_0 + \epsilon_1 \omega_0\,, \quad \omega = \omega_0 - \epsilon_1 \rho_0\,, \tag{2.1}$$

where ϵ_1 is small. Therefore, ω is able to decay into $\pi + \pi$ to order ϵ_1^2. One finds experimentally[36] that $\Gamma(\omega \to 2\pi) = 130$ keV and $\Gamma(\rho \to 2\pi) = 150$ MeV, a "suppression" factor of 10^3.

For ρ_2 and ω_2, the roles are reversed. The ω_2, it will be argued, can decay into hadrons, but the hadronic decay of ρ_2 is forbidden except through mixing with ω_2. As discussed above and in Sec. I A, the hadronic decay of the 3.1-GeV resonance (which must be by annihilation of the $\mathcal{P}'$ and $\bar{\mathcal{P}}'$ quarks) has been assumed by some authors to occur via a color-singlet state of three color gluons (this is analogous to the decay of ϕ or ψ into $\mu^+\mu^-$, which occurs via a photon). The color group commutes with the isospin group, hence the gluons have isospin zero. The ρ_2 meson has isospin one (the isospin referred to here is an isospin associated with the charmed quarks $\mathcal{P}'$, $\mathcal{N}'$), and therefore cannot decay into isospin-zero gluons. The assumption that three gluons mediate the decay is not necessary here, only that an isospin-zero mode mediates the decay and prevents ρ_2 decay into hadrons.

However, the ω_2 has isospin zero and hence can decay into gluons; it is completely analogous to the $\mathcal{P}'\bar{\mathcal{P}}'$ meson of the single charm models. Following the discussion above, the ρ_2 can decay via the isospin-zero mode because of electromagnetic mixing with the ω_2, which is expected to be very close in mass to ρ_2. The electromagnetic current

$$J_\mu = \tfrac{2}{3}\bar{\mathcal{P}}\gamma_\mu \mathcal{P} - \tfrac{1}{3}\bar{\mathcal{N}}\gamma_\mu \mathcal{N} - \tfrac{1}{3}\bar{\lambda}\gamma_\mu \lambda + \tfrac{2}{3}\bar{\mathcal{P}}'\gamma_\mu \mathcal{P}' - \tfrac{1}{3}\bar{\mathcal{N}}'\gamma_\mu \mathcal{N}' - \tfrac{1}{3}\bar{\lambda}'\gamma_\mu \lambda' \tag{2.2}$$

indicates that isospin SU(2) and charmed isospin SU(2)′ invariance can be broken by the electromagnetic interactions. In analogy with Eq. (2.1), one has

$$\rho_2 = \rho_{20} + \epsilon_2 \omega_{20}\,, \quad \omega_2 = \omega_{20} - \epsilon_2 \rho_{20}\,, \tag{2.3}$$

where ω_{20} may include a very small part of $\bar{\lambda}'\lambda'$ and where ϵ_2 need not be equal to ϵ_1. The mixing parameter ϵ_2 is sensitive to the mass splitting between ρ_2 and ω_2 and to the width of ω_2 (and thereby to the results of asymptotic freedom calculations). The mass splitting has two (nonelectromagnetic) sources, as do ρ and ω: (1) an SU(2)′ tadpole which is equivalent to letting $m(\mathcal{P}') \neq m(\mathcal{N}')$; without knowing mass splittings of charmed particles (such as $\mathcal{P}'\mathcal{P}\mathcal{N}$ and $\mathcal{N}'\mathcal{P}\mathcal{N}$), this required mass splitting of the $\mathcal{P}'$ and $\mathcal{N}'$ quarks is not known, and (2) a small admixture of $\bar{\lambda}'\lambda'$ in ω_2 although because of the large splitting between ω_2 and ϕ_2 this mixture will be smaller here.

The ρ and ω are separated by 13 MeV, and the ratio $\Gamma(\rho \to 2\pi)/\Gamma(\omega \to 2\pi)$ is about 1200. Without further experimental input to limit the assumptions, it is not unreasonable to assume that ρ_2 and ω_2 have a smaller mass difference than ρ and ω, and that the mixing is somewhat greater.

The model is most reasonable if

$$\Gamma(\omega_2 \to \text{hadrons})/\Gamma(\rho_2 \to \text{hadrons}) \approx 15\text{–}70 \tag{2.4}$$

(an experiment described in the next section can determine this number). Given $\Gamma(\rho_2 \to \text{hadrons}) = 75$ keV, Eq. (2.4) gives $\Gamma(\omega_2 \to \text{hadrons}) \approx 1\text{–}5$ MeV. From the BNL experiment,[16] an upper limit of 20 MeV can be placed on the width of ω_2.

III. IMPLICATIONS OF TWO PARTICLES AT 3.1 GeV

The estimated ω_2 width of 1–5 MeV is the width to be compared with the width for $\phi \to \rho\pi$, which, it was argued in Sec. II, is effectively around 15 MeV. If this model should prove to be correct, then the question of asymptotic freedom should be separated from the effects of isospin; to the extent that the ψ decay is analogous to $\phi\to\rho\pi$, the analogy should be made to ω_2, not ρ_2. An implication of this work is that α_s is not particularly small (not $\alpha_s\approx 0.26$).

While it was argued in Sec. I B that ρ_2 and ω_2 are produced at SLAC in a 9 : 1 ratio, the ρ_2 cannot be produced in the BNL experiment[16] for the same reasons that (before isospin mixing) it could not decay into hadrons. At higher energies the dominant mechanism for producing ψ in pp scattering will not be via three gluons but via the exchange of charmed mesons.[37] At these energies, (above $E_{\rm lab}=100$ or 200 GeV), both ρ_2 and ω_2 will be produced with large cross sections. They will, of course, always be produced together with two charmed particles with this mechainsm.

An important question is why the ω_2 has not been observed at SLAC. The first point is, of course, that it is produced $\frac{1}{9}$ as much as ρ_2. The experimental[17] full width (at half maximum) of ψ (here the ρ_2) is 1.9 MeV; however, at $\frac{1}{10}$ of maximum the half width on the right is about 4 MeV. The ω_2 is hidden under the tail of the ρ_2. If the experimental width of ω_2 is larger than that of ρ_2, then the ω_2 peak will be even lower relative to the ρ_2 peak. And finally, ρ_2-ω_2 mixing will further wash out any structure.

Since the ρ_2 decays hadronically only via ρ_2-ω_2 mixing, its hadronic decay products are identical to those of ω_2 (and the $\mathcal{P}'\bar{\mathcal{P}}'$ meson of single-charm models). In particular the ρ_2 decays into odd numbers of pions (which it would do even if it could decay directly, since its uncharmed isospin is zero).

The leptonic widths ($V\to e^+e^-$ or $\mu^+\mu^-$) of ρ_2, ω_2, and ϕ_2 are found by the same calculation that gave their production ratios in e^+e^- scattering. The ratio of leptonic widths of $\rho:\omega:\phi:\rho_2:\omega_2:\phi_2$ is predicted to be approximately 9 : 1 : 2 : 9 : 1 : 2. The first four are found experimentally[38,39] to be 6.4 : 0.75 : 1.35 : 5.2 keV. The single-charm model predicts 9 : 1 : 2 : 8 and is not distinguishable in this manner.

There is a clear test that distinguished this model from most others. It is based on the fact that this model proposes two particles at $\sqrt{s}=3.1$ GeV and that in this model the SLAC[17] and BNL[16] are not looking at the same particle. At BNL, the actual cross section for J (ψ) production is

$$\sigma(\psi)=\frac{\Gamma(\psi\to\text{all})}{\Gamma(\psi\to e^+e^-)}\sigma(\psi\to e^+e^-)\,, \tag{3.1}$$

where $\sigma(\psi\to e^+e^-)$ is measured at BNL. In any model with only one particle at 3.1 GeV, the Γ's are those measured at SLAC (their ratio is approximately 16). In this model $\Gamma(\omega_2)$ are not measured, and [since it is assumed above that $\Gamma(\omega_2\to\text{all})=1\text{–}5$ MeV and $\Gamma(\omega_2\to e^+e^-)=5.2/9$ keV] their ratio is between 1700 and 8500. As a result there is a much larger actual cross section at BNL predicted by this model than by others.

The equality (where p is proton)

$$\frac{\Gamma(\rho_2\to p\bar{p})}{\Gamma(\rho_2\to\text{hadrons})}=\frac{\Gamma(\omega_2\to p\bar{p})}{\Gamma(\omega_2\to\text{hadrons})} \tag{3.2}$$

should hold for the $p\bar{p}$ channel since the hadronic decays of ρ_2 are just those of ω_2. As a result the $p\bar{p}$ channel is a good measure of the actual cross section at BNL (for the reasons given earlier in this section, this experiment must be done at BNL energies). A provisional value[40] for the ratio in Eq. (3.2) is approximately 2×10^{-3}. Then

$$\sigma(\psi\to p\bar{p})=\left[2\times10^{-3}\frac{\Gamma(\psi\to\text{all})}{\Gamma(\psi\to e^+e^-)}\right]\sigma(\psi\to e^+e^-)$$

$$\equiv C_1\sigma(\psi\to e^+e^-) \tag{3.3}$$

where all quantities refer to ψ at BNL. Using the ratios of Γ's given below Eq. (3.1), C_1 is found to be about 0.032 in other models and around 3.4 to 17 in this model. An experiment to measure the $p\bar{p}$ decay mode is currently being done at BNL.[41]

The paracharmonium (pseudoscalar) states should be evident in the $p\bar{p}$ channel. The single-charm model[14] predicts the cross section at BNL for paracharmonium to be approximately 80 times as large as that for orthocharmonium [assuming that the ratio (3.2) is the same for para as for ortho]. That result is not completely applicable in this approach, but if a reasonable estimate for $\sigma(\eta_2)/\sigma(\omega_2)$ is about 20 and

$$\sigma(\text{para}\to p\bar{p})=C_2\sigma(\psi\to e^+e^-) \tag{3.4}$$

then [multiplying the values for C_1 in Eq. (3.3) by 80 or by 20] $C_2\approx2.6$ for other models and C_2 equals 70 to 350 for this model (these are much weaker results than those obtained for orthocharmonium).

Another test which distinguishes some models is, of course, the value of $R\equiv\sigma(e^+e^-\to\text{hadrons})/\sigma(e^+e^-\to\mu^+\mu^-)$, which is predicted to have an asymptotic value of 4.

IV. THE RESONANCES AT 3.7 AND 4.1 GeV

Resonancelike structure has been observed[28,29] at $\sqrt{s}=3.7$ and 4.1 GeV in e^+e^- scattering at SLAC. Calculations based on linear potential concepts[19,22,23] are consistent with these being radial excitations of ψ (or ρ_2 here). The resonance[42] at 4.1 GeV is quite wide[29] ($\Gamma=250\text{–}300$ MeV), and therefore is assumed to be above threshold for decay into charmed particles (which may have masses around 1.85 GeV).

Use of a linear mass relation[15,27] and the assumption for quark masses that $m_{\lambda'}/m_{\mathcal{P}'} = m_{\lambda}/m_{\mathcal{P}}$ gives a mass for ϕ_2 around 4.1 GeV. If in fact the ϕ_2 (with a $\phi_2 : \rho_2$ production ratio of 2:9) is at 4.1 GeV, it might not be above threshold for decay into charmed particles ($\lambda'\bar{\lambda}' \to \lambda'\bar{\mathcal{P}} + \bar{\lambda}'\mathcal{P}$, etc.), in which case one might expect a narrow peak (a little wider than ω_2) except for mixing with ρ_2''. ϕ_2 might instead have a higher mass and then decay into charmed particles. The possibility that ϕ_2 is the 3.7-GeV resonance is remote. Another possibility is that the ϕ_2 has a mass of about 2.7 GeV and is above threshold for decay into charmed mesons; ϕ_2 production would be $\frac{2}{9}$ that of ρ_2 and in that region one would expect $R \approx 2\frac{1}{3}$ (if a narrow resonance also exists, it might have a mass of about 2.1 GeV).

The decay of ρ_2' into $\rho_2 + 2\pi$ is equivalent to that decay in the single-charm model. It is also a three-gluon decay, but the energy carried by the gluons in this case is small so that the coupling is expected to be large. Similarly the decay $\rho_2' \to \rho_2 + \eta$ is not suppressed much by the couplings although it is by the kinematical factor for p-wave decay p^3/m^2, which is very small in this case. The $\rho_2' \to \rho_2 + 2\pi$ decay is a mixture of the three-particle ($\rho_2\pi\pi$) decay mode (three-particle decays are greatly suppressed relative to two-particle decays) and the two-particle ($\rho_2\epsilon$) decay mode (which is close to threshold but is an s-wave decay). A decay mode for ρ_2' which may be significant is the decay to p-wave states of ρ_2 by emission of a photon. Such decays have been estimated by Eichten *et al.*[19] to have a total width of about 200 keV. The p-wave states can then photon-decay to ρ_2; this latter decay is significant, because the hadronic decays are suppressed since the wave function at the origin of a p-wave state is zero. In this model this double-photon decay can also end at the ω_2 instead of at ρ_2. Since the ω_2's branching ratio to $\mu^+\mu^-$ is very small, this decay mode would not appear experimentally to be in the category of $\psi' \to \psi +$anything. The decay $\rho_2' \to \pi_2 + \gamma$ is equivalent to that in the single-charm model, which has been estimated[19,43] to be only 1 or 2 keV.

V. WEAK COUPLINGS AND THE DECAY OF CHARMED PARTICLES

The traditional Cabibbo theory[44] of the effective charged weak couplings of quarks is

$$J_{1\mu} = \bar{\mathcal{P}}\gamma_\mu(1+\gamma_5)(\mathcal{N}\cos\theta_C + \lambda\sin\theta_C)\,, \qquad (5.1)$$

which (along with other factors) explains the suppression of the decay $K \to \mu\nu$ with respect to $\pi \to \mu\nu$.

In 1970 Glashow, Iliopoulos, and Maiani[9] used a charmed-quark model which Bjorken and Glashow[8] had suggested in 1964 to explain the suppression of strangeness-changing neutral currents. In Weinberg-Salam models[10] this type of suppression is found to occur to all orders. The need for the suppression was evident in the small widths for decays such as $K_L \to \mu\bar{\mu}$. The suppression is accomplished by adding a term to Eq. (5.1) which leads to a cancellation:

$$J_{2\mu} = \bar{\mathcal{P}}'\gamma_\mu(1+\gamma_5)(\lambda\cos\theta_C - \mathcal{N}\sin\theta_C)\,. \qquad (5.2)$$

In the model presented here, these two terms are kept (along with the features described above). However, two new terms[26,45] are added which give the weak couplings of the $\mathcal{N}'$ and λ' quarks. These two terms have the opposite handedness as Eqs. (5.1) and (5.2). The four terms are

$$\begin{aligned} J_\mu = {} & \bar{\mathcal{P}}\gamma_\mu(1+\gamma_5)(\mathcal{N}\cos\theta_C + \lambda\sin\theta_C) \\ & + \bar{\mathcal{P}}'\gamma_\mu(1+\gamma_5)(\lambda\cos\theta_C - \mathcal{N}\sin\theta_C) \\ & + \bar{\mathcal{P}}\gamma_\mu(1-\gamma_5)(\mathcal{N}'\cos\theta_a + \lambda'\sin\theta_a) \\ & + \bar{\mathcal{P}}'\gamma_\mu(1-\gamma_5)(\lambda'\cos\theta_a - \mathcal{N}'\sin\theta_a)\,, \end{aligned} \qquad (5.3)$$

where $\theta_C = \theta_a$ is not necessary.

As discussed in Ref. 26, the weak couplings of this model are consistent with experimental results[46] on the ratio of ν and $\bar{\nu}$ cross sections for muonless scattering of ν and $\bar{\nu}$ on nucleons and with experimental results[47] on charge symmetry invariance for ν and $\bar{\nu} + N \to \mu +$ (anything) above and below $E_{\text{lab}} = 30$ GeV.

In the single-charm model there are three charmed mesons: $\mathcal{P}'\bar{\mathcal{P}}$, $\mathcal{P}'\bar{\mathcal{N}}$, and $\mathcal{P}'\bar{\lambda}$. In this model there are several additional mesons; for example, along with the $\mathcal{P}'\bar{\mathcal{N}}$, there is now a $\mathcal{P}\bar{\mathcal{N}}'$. The old charmed particles have a $\mathcal{P}'$ quark which couples (weakly) to λ quarks, and as a result one expects to find a K meson in almost every decay of those charmed mesons. The decays into $K\pi, K\pi\pi, \ldots$ and $K\mu\nu$ are allowed. However, the new charmed mesons such as $\mathcal{P}\bar{\mathcal{N}}'$ (or $\mathcal{P}\bar{\lambda}'$) have an $\mathcal{N}'$ (or λ') quark which couples to a $\mathcal{P}$ quark, and no K mesons need be found. The decays into $\pi\pi, \pi\pi\pi, \ldots, \pi\mu\nu$, and $\mu\nu$ are allowed. The charged multiplicity[29] at (and above) the 4.1-GeV resonance is about 4, and one can assume that the total multiplicity is about 6, or 3 for each charmed decay. As a result one expects K mesons to remain a relatively small fraction of the number of π mesons.

In Ref. 27 it was argued that the K^-p decay mode of the baryon $\mathcal{P}'\mathcal{N}\mathcal{N}$ would be negligible since the strong decay $\mathcal{P}'\mathcal{N}\mathcal{N} \to \mathcal{P}'\mathcal{P}\mathcal{N} + \pi^-$ should be allowed.

This result is maintained here, of course; however, the $\pi^- p$ decay mode of $\mathfrak{N}'\mathcal{P}\mathfrak{N}$ is allowed, and $\mathfrak{N}'\mathcal{P}\mathfrak{N}$ should have no strong decay.

If this model should prove correct, the detection of charmed particles will be difficult, although with adequate statistics, peaks in the $K\pi$ and $\pi^- p$ invariant masses at about 1.9 and 2.3 GeV might be visible.

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