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Fraction of K^- in the e^+e^- annihilation at 4.15 GeV—The charm and color scheme*

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A model based on the SU(4) × SU(3)′ group is proposed. The 4.15-GeV bump in the e^+e^- reaction is associated with a sum of the closely spaced color-excited resonances, in order to explain the recently observed K fraction.

Since the discovery of the new resonances,[1] various models based on the charm[2] or color[3] scheme have been proposed. However, all models so far meet with difficulty in explaining the recently observed fraction of K^-'s with momentum less than 0.7 GeV/c per event in e^+e^- annihilation at 4.15 GeV.[4] The experimental value is 0.22 ± 0.03, which is consistent with the nonresonant background value, while an estimated value[5] in the charm scheme is 0.35 and the color schemes give either too large or too small a value depending on the identification of the 4.15-GeV peak as the color excited φ or ω. In this paper we present a model which resolves this question and is consistent with all the existing experimental data.

The model is based on the SU(4)×SU(3)′ group, i.e., the three-quartet quark model. This is the most natural group of hadron symmetry which contains the charm quantum number[6] as well as the color quantum numbers.[7,8] We believe that it is most likely that both quantum numbers will be observed in nature.

The essential part of the model is the following:

(1) The broad bump around 4.15 GeV (with total width ≃200 MeV) is a series of the color excited states of ρ, ω, and φ and possibly their radial or angular momentum excitations. We reject the usual charm interpretation that the broad resonance is a second radial excitation of φ_c which is broad because it lies above the threshold for associated production of charm carrying mesons. Such an interpretation indicates an enhancement of the fraction of K^- per event above the background value, due to the Iizuka-Okubo-Zweig (IOZ) rule,[9] which is not seen. Similarly, if the 4.15-GeV peak is a color excitation of the φ, decay modes involving kaons should dominate, which would also indicate an enhancement above the background value. If the 4.15-GeV peak is a color excited ω, however, decays into strange particles are comparable to those into nonstrange particles, and thus the fraction of K^- per event should be of the order of the background value.

(2) The narrow resonance at 3.1 GeV is the $c\bar{c}$ bound system, usually denoted by φ_c, where c and $\bar{c}$ stand for the charm quark and anticharm quark, respectively.

(3) As to the identification of the 3.7-GeV resonance, we consider as examples two possible schemes: The resonance at 3.7 GeV is either (a) a radially excited state of φ_c or the spin triplet state with orbital angular momentum $L=2$, or (b) it is the color excited state of φ_c.

Below, we discuss the characteristics of these schemes. Let us denote the vector-meson states in the SU(4)×SU(3)′ group by $\varphi_i^j \equiv (\varphi_i, \varphi_j')$, $i=0,1,2,\ldots,15$ and $j=0,1,2,\ldots,8$ or, using particle symbols in each space, by (ω,φ'), (φ,ρ'), etc. We assume, in addition to the usual 16-plet assignment for vector mesons in SU(4), also nonet symmetry in the color space. The states associated with the 4.15-GeV bump in (1) are expressed as (ρ,ρ'), (ω,ρ'), (φ,ρ'), (ρ,ω'), (ω,ω'), (φ,ω'), and their excited states $(\rho,\rho')'$, etc., while the low-lying particles are $(\rho,\varphi')\equiv\rho$, $(\omega,\varphi')\equiv\omega$, $(\pi,\varphi')\equiv\pi$, etc.

Each of the color-excited states can decay into the low-lying states, e.g.

$$\begin{aligned}(\rho,\rho') &\to 2(\pi,\varphi')\,,\\ (\varphi,\rho') &\to (K,\varphi') + (\bar{K},\varphi')\\ &\to (K,\varphi') + (\bar{K}^*,\varphi')\,, \quad \text{etc.,}\end{aligned}$$

since the color φ' is a mixture of the color singlet and the color octet. These rates, however, are suppressed by the IOZ rule in the color space. Assuming that the natural width for strong interaction decays is proportional to the mass of the decaying particle and using the suppression factor by the IOZ rule,

$$r_s = \frac{\Gamma(\varphi \to 3\pi)}{\Gamma(\omega \to 3\pi)} \approx \frac{1}{15}\,,$$

we estimate the width of each of the color excited states in the 4.15-GeV bump to be

$$\Gamma = \Gamma_{\rho\to 2\pi} \frac{M_{4.15}}{M_\rho} r_s = 800 \times (\tfrac{1}{15}) \approx 50\ \text{MeV}\,.$$

Hence, if the 6 states or 12 states in the 4.15-GeV bump are closely spaced within 100–200 MeV, it is possible to understand the bump at 4.15 GeV. Since it is the mixture of the color excited states of ρ, ω, and φ, each of them having a relatively broad width, we would find the fraction of $K^-/$ events at this energy to be similar to the background value. Incidentally, we should notice that the shape of the bump does not seem to be a simple Breit-Wigner resonance formula (the higher-mass region has a lower tail, contrary to the Breit-Wigner formula) which would support such an interpretation. The radiative decays of the color excited states also contribute to the width, but only a few MeV.

The identification of the narrow resonances at 3.1 and 3.7 GeV made in items (2) and (3a), respectively, are the same as in the charm schemes, and we rely on the IOZ rule for the explanation of the narrowness of these resonances. The analysis[10] of the experimental data of photoproduction of the 3.1- and 3.7-GeV resonances favors this scheme over the pure color schemes. In view of a negative result[11] in the search for monochromatic γ rays predicted by the charmonium schemes, and also of the ambiguity in the form of the potentials which were used in the calculations, we do not consider the quantitative predictions of the charmonium calculations reliable.

The scheme (3b) implies the identification of the 3.1-GeV resonance as (φ_c, φ') and the 3.7-GeV resonance as (φ_c, ω') and (φ_c, ρ'). By color nonet symmetry the latter two states are degenerate. In this scheme, the transition

$$(\varphi_c, \omega' \text{ or } \rho')_{3.7} \rightarrow (\varphi_c, \varphi')_{3.1} + 2\pi$$

is suppressed by the IOZ rule in color space. However, the scheme may have difficulty in that the radiative decay

$$(\varphi_c, \omega' \text{ or } \rho')_{3.7} \rightarrow (\eta' \text{ or } \eta_c', \varphi') + \gamma$$

may lead to a larger width for this resonance.

In order to show that the close spacing required in the schemes proposed in this article is possible, we derive the masses of the vector mesons in the SU(4)×SU(3)′ group. Since little is known about the dynamics of color symmetry, we assume that the mass term in the Hamiltonian has the form

$$\begin{aligned} H = {} & M_0^2(1, 1') + a(\lambda_8, 1') + b(1, \lambda_8') + c(\lambda_{15}, 1') \\ & + d(\lambda_8, \lambda_8') + e(\lambda_{15}, \lambda_8'), \end{aligned}$$

where λ_i is the 4×4 matrix representation of the ith generator of SU(4), λ_j' is the 3×3 matrix representation of the jth generator of color SU(3)′, and (λ_i, λ_j') denotes the direct product of these matrices. We find that the usual SU(4) mass relations hold for each color component, i.e., for (φ_i, φ_j'), $i = 0, 1, \ldots, 15$, φ_j' fixed; and, similarly, the usual SU(3)′ nonet mass relations hold for each SU(4) component.[2,12] For definiteness we assign $(\rho, \omega' \text{ or } \rho') = 4.1$ GeV and $(\varphi, \omega' \text{ or } \rho') = 4.2$ GeV.

TABLE I. Mass spectrum of vector mesons in SU(4)×SU(3)′ color nonet model.

Particle	Mass (GeV) Scheme (3a)	Mass (GeV) Scheme (3b)	Particle	Mass (GeV) Scheme (3a)	Mass (GeV) Scheme (3b)
(ρ, φ')	0.770 [a]	0.770 [a]	$(\rho, K^{*\prime})$	2.950	2.950
(ω, φ')	0.770	0.770	$(\omega, K^{*\prime})$	2.950	2.950
(φ, φ')	1.019 [a]	1.019 [a]	$(\varphi, K^{*\prime})$	3.056	3.056
(φ_c, φ')	3.095 [a]	3.095 [a]	$(\varphi_c, K^{*\prime})$	4.213 [b]	3.403
(K^*, φ')	0.903	0.903	$(K^*, K^{*\prime})$	3.003	3.003
(D^*, φ')	2.255	2.255	$(D^*, K^{*\prime})$	3.637 [b]	3.184
(F^*, φ')	2.304	2.304	$(F^*, K^{*\prime})$	3.680 [b]	3.234
$(\rho, \rho' \text{ or } \omega')$	4.100 [a]	4.100 [a]			
$(\omega, \rho' \text{ or } \omega')$	4.100	4.100			
$(\varphi, \rho' \text{ or } \omega')$	4.200 [a]	4.200 [a]			
$(\varphi_c, \rho' \text{ or } \omega')$	5.092 [b]	3.685 [a]			
$(K^*, \rho' \text{ or } \omega')$	4.150	4.150			
$(D^*, \rho' \text{ or } \omega')$	4.622 [b]	3.898			
$(F^*, \rho' \text{ or } \omega')$	4.667 [b]	3.951			

[a] Input.

[b] These numbers are obtained under the assumption $e \approx 0$.

TABLE II. Mass parameters (in GeV^2) for SU(4) × SU(3)′ color nonet model of vector mesons.

Mass parameter [a]	Scheme (3a) [b]	Scheme (3b)
$\tilde{a}$	−0.479	−0.479
$\tilde{b}$	9.363	9.363
$\tilde{c}$	−5.412	2.148
d	−0.128	−0.128
e	≈0	4.364

[a] $\tilde{a} = a + d/\sqrt{3} + e/\sqrt{6}$, $\tilde{b} = b + d/\sqrt{3} + e/\sqrt{6}$, $\tilde{c} = c + e/\sqrt{3}$.

[b] In scheme (3a) the value $e \approx 0$ is assumed.

This assignment within the 4.15-GeV bump is, however, arbitrary. For example, if radial excitations spaced two units in mass-squared are considered it would be more appropriate to assign $(\rho, \omega'$ or $\rho') = 4.05$ GeV and $(\varphi, \omega'$ or $\rho') = 4.1$ GeV such that $(\rho, \omega'$ or $\rho')' \approx 4.28$ GeV and $(\varphi, \omega'$ or $\rho')' \approx 4.33$ GeV would lie within the bump. The masses obtained for schemes (3a) and (3b) are given in Table I with the appropriate values for the parameters in Table II. The parameter e cannot be determined from the particle assignments in scheme (3a). For simplicity we choose this to be zero. Thus, although the data suggest a small bump at 5.1 GeV which might be associated with $(\varphi_c, \rho'$ or $\omega')$, the location of this state within scheme (3a) is not well determined. All mass parameters in scheme (3b) are determined from the particle assignments in that scheme.

In this paper we have demonstrated that it is possible to explain the observed fraction K^-/event at 4.15 GeV by interpreting the 4.15-GeV peak as a bunching of several color excited states and possibly their radial or angular momentum excitations. Since this is possible within the more restrictive color nonet symmetry scheme presented here, it is also clearly possible, by appropriate choice of mass parameters, in a scheme in which color nonet symmetry is not assumed. In this case the qualitative features of the model, i.e., bunching of states at 4.15 GeV, would be retained, but the details of the spectrum of masses given in Table I would be changed.

ADDED NOTES

(1) After the completion of the work, we came across articles which handled related schemes: J. C. Pati and A. Salam, ICTP report, 1975 (unpublished); S. Hori *et al.*, Kanazawa University Report No. DPKU-47, 1974 (unpublished). Our scheme, however, is different in that the 4.15-GeV bump is identified with a sum of the closely spaced color excited resonances.

(2) Another alternative scheme identifies $(\varphi_c, \rho'$ or $\omega')_{3.1}$, $(\varphi_c, \omega'$ or $\rho')_{3.7}$, and $(\varphi_c, \varphi')_{4.15}$. This scheme has the advantage that the state $(\varphi_c, \rho'$ or $\omega')_{3.1}$ has the narrowest width because of IOZ rule suppression in both SU(4) and color spaces. The kaon fraction at 4.15 GeV may be consistent with experiment, since the decay modes $(\varphi_c, \varphi') \to 2(\pi, \varphi')$ or $2(\rho, \varphi')$ or $(K, \varphi') + (\bar{K}, \varphi')$, etc., are equally suppressed, and hence we expect no special enhancement of the kaon fraction at 4.15 GeV. The color excited states of the ρ, ω, and φ could either be overlapped in the 4.15-GeV bump region or lie in a higher-mass region.

Finally, it should be pointed out that although we assigned the degenerate color excited states (φ_c, ρ') and (φ_c, ω') to the 3.7-GeV resonance in scheme (3b), it is possible to have one of the states decoupled from the photon as in the Han-Nambu color model.[3]

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