THE ORTHOCHARMONIUM STATES FROM GENERALIZED VECTOR DOMINANCE

G.J. GOUNARIS and E.K. MANESIS
University of Ioannina, Ioannina, Greece

and

A. VERGANELAKIS
CERN, Geneva, Switzerland

Received 13 February 1975

From GVD, Local Duality, asymptotic U(4) symmetry and the assumption that the 3.1, 3.7 GeV states are bound charmed quarks, we predict their $\Gamma_e\Gamma_h/\Gamma$ ratios. Their small hadronic widths are attributed to the low intercept of the φ_c- trajectory. Equation $\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-) = 4.1 \pm 0.3$, should be established for $\sqrt{s} \gtrsim 7$ GeV.

The discovery of two narrow resonances in recent experiments [1–4] was not entirely unexpected [5,6]. An attractive interpretation [7,8] is that they are vector mesons formed from bound charmed quark pairs. In the Generalized Vector Dominance (GVD) approach we expect a series [6] of such states which are radial excitations of the lowest orthocharmonium state and denoted by φ_{cn}. Their masses are given by [6,9]

$$m^2_{\varphi cn} = m^2_{\varphi c}(1 + a_c n), \tag{1}$$

$(n = 0, 1, 2, ...)$.
The two discovered resonances at 3.1 and 3.7 GeV are probably the first two in the series, and are accordingly called φ_c, φ_{c1}. They are very narrow because the would-be allowed decay modes into a pair of charmed mesons are energetically forbidden [5], due to the large mass of the lowest charmed states (~2 GeV say). Starting from the third resonance, φ_{c2}, we expect their widths to become appreciable and increase linearly with the masses.

The purpose of this note is to present the expected properties of these mesons in a GVD framework [6,9].

Consequences from the current propagator: At energies much above the threshold for charmed particle production, we expect an asymptotic U(4) symmetry for the hadronic contribution to the absorptive part of the current propagator[‡1]. This means [6,9]

$$R^{\alpha\beta}(s) = \frac{(2\pi)^3}{3s} \sum_{\text{hadrons}} \langle 0|j^\alpha_\mu|\text{h}\rangle\langle \text{h}|j^\beta_\mu|0\rangle\, \delta^{(4)}(p_\text{h} - q) \underset{s\to\infty}{\longrightarrow} C\delta_{\alpha\beta}, \tag{2}$$

where $\alpha, \beta = 0, 1, ..., 15$ and C is a constant. From this [6,9]

$$\frac{(2\pi)^3}{3s} \sum_{\text{hadrons}} \delta^{(4)}(p_\text{h} - q)\langle 0|j^\text{c}_\mu|\text{h}\rangle\langle \text{h}|j^\text{c}_\mu|0\rangle \underset{s\to\infty}{\longrightarrow} \frac{2}{a_\rho f^2_\rho}. \tag{3}$$

Here j^c_μ is the charm current and $a_\rho = 2$ defines the spacing of the ρ-like mesons [10,9]. The new Local Duality (LD) demands that the r.h.s of (3) should average the l.h.s. even at low energies where the resonance structure is conspicuous. Assuming that LD is applicable to the extreme case of averaging around just *one* resonance, we find [6,8]

$$\frac{\Gamma(\varphi_c \to e^+e^-)\Gamma(\varphi_c \to \text{h})}{\Gamma_{\varphi_c}} = \frac{8\alpha^2}{27}\left(\frac{a_c}{a_\rho}\right)\left(\frac{4\pi}{f^2_\rho}\right) m_{\varphi_c} = 3.98 \pm 0.42 \text{ keV} \tag{4a}$$

‡1 Actually we may have to include in (2) all intermediate states of the form "hadrons" and "γ + hadrons".

$$\frac{\Gamma(\varphi_{c1} \to e^+e^-)\Gamma(\varphi_{c1} \to h)}{\Gamma_{\varphi_{c1}}} = \frac{8\alpha^2}{27}\left(\frac{a_c}{a_\rho}\right)\left(\frac{4\pi}{f_\rho^2}\right)\frac{m_{\varphi_c}^2}{m_{\varphi_{c1}}} = 3.34 \pm 0.35 \text{ keV}. \tag{4b}$$

Here we used $a_c = 0.42$, which is obtained from (1) and the assumption that the 3.1, 3.7 GeV resonances are just the first two in the series. The results are sensitive to a_c. The experimental results are respectively [11, 12] 5.1 ± 0.4 keV and 2.4 ± 0.2 keV. The agreement with (4) is satisfactory. In fact, it becomes excellent when we compare the *sum* of (4a) plus (4b) with data [11]. This is encouraging since it indicates that LD works better when we average around two resonances at a time. Our success implies also that there is *no* other narrow resonance in between, or below 3.1 GeV. If another resonance at ~3.4 GeV existed then $a_c = 0.21$ and our predictions (4) would have been destroyed.

Higher φ_c's should have appreciable (hadronic) widths. Proceeding as before we find for $n \geqslant 2$

$$\Gamma(\varphi_{cn} \to e^+e^-) \doteq \frac{8\alpha^2}{27}\left(\frac{a_c}{a_\rho}\right)\frac{4\pi}{f_\rho^2}\frac{m_{\varphi_c}^2}{m_{\varphi_{cn}}}. \tag{4c}$$

The φ_{c2} is expected from (1) at $m_{\varphi_{c2}} \approx 4.2$ GeV. This is in agreement with recent data which indicate a resonance at [12] 4.1 GeV. We predict $\Gamma(\varphi_{c2} \to e^+e^-) = 2.9 \pm 0.3$ keV, which should soon be checked at SPEAR.

For energies *much* above the threshold for charmed particle production we have [6, 8]

$$\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \frac{3\pi}{a_\rho}\frac{4\pi}{f_\rho^2}\left(1 + \tfrac{1}{3} + \tfrac{8}{9}\right) = 4.1 \pm 0.3 \tag{5}$$

while in the whole region $\sqrt{s} \gtrsim 2$ GeV we find [6]

$$\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \frac{4\pi}{a_\rho}\frac{4\pi}{f_\rho^2} + \frac{8}{3}\frac{a_c}{a_\rho}\frac{4\pi}{f_\rho^2} m_{\varphi_c}^2 \sum_{n=0}^{\infty} \frac{\Gamma(\varphi_{cn} \to h)}{(s - m_{\varphi_{cn}}^2)^2 + m_{\varphi_{cn}}^2 \Gamma_{\varphi_{cn}}^2} \frac{s}{m_{\varphi_{cn}}}. \tag{6}$$

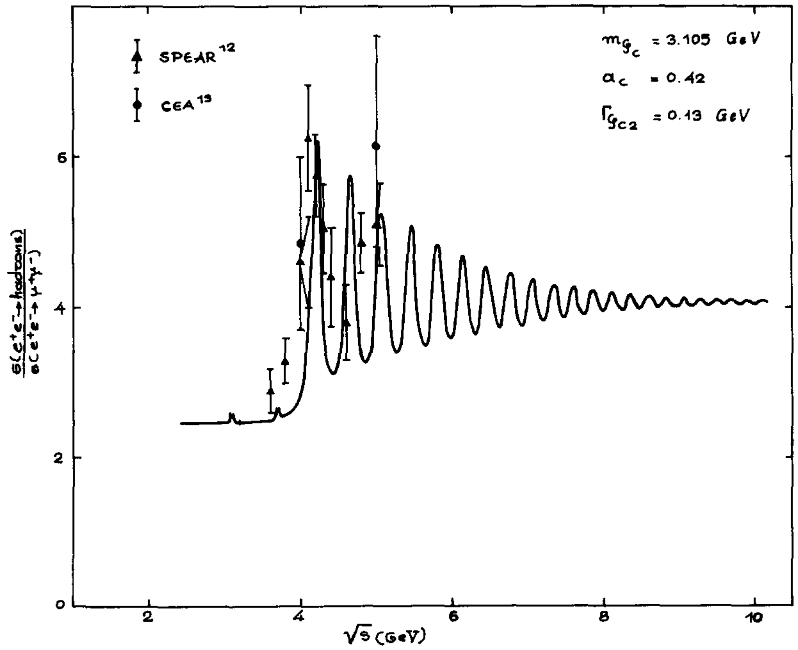

Fig. 1. $\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ as a function of $\sqrt{s}$ from GVD and U(4) asymptotic symmetry.

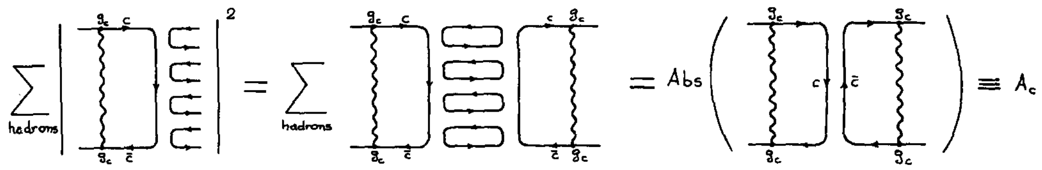

Fig. 2. Quark diagram contributing to process $\varphi_c \to$ (only hadrons).

Using the experimental results for the first two resonances [1–4] and assuming a linear dependence of the width on the mass for the higher vector mesons [6], we obtain the curve shown in fig. 1. It corresponds to $\Gamma_{\varphi_{c2}} = 0.13$ GeV. Also shown are the experimental data [12,13]. We see again that the experimental peak at 4.1 GeV is somewhat shifted in our calculations. Notice also that the asymptotic value of the ratio (6) will be achieved for $\sqrt{s} \gtrsim 7$ GeV.

Why the new resonances are so narrow? We argue that the small values of $\Gamma(\varphi_c \to$ only hadrons), $\Gamma(\varphi_{c1} \to$ only hadrons) can be explained on the basis of Zweig's rule and analogy to $\Gamma(\varphi \to 3\pi)$. Since the masses of these mesons are probably lower than the two charmed particle threshold [5,7], the diagram shown in fig. 2 should be a reasonable approximation to process $\varphi_c \to$ (only hadrons). The wavy lines appearing as initial and final-state interactions in fig. 2, describe the initial binding of the quarks in the φ_c-state. They subsequently annihilate to produce hadrons. We find

$$\Gamma(\varphi_c \to \text{only hadrons}) = \frac{A_c}{m_{\varphi_c}} \approx \frac{g_c^4}{m_{\varphi_c}} \,\mathrm{Im}\, F_{\varphi_c}^{J=1}(c\bar{c} \to c\bar{c})_{s=m^2_{\varphi_c}} . \tag{7}$$

$F_{\varphi_c}^{J=1}(c\bar{c} \to c\bar{c})_{s=m^2_{\varphi_c}}$ gives the contribution of the φ_c-trajectory to process $c\bar{c} \to c\bar{c}$, at $s = m^2_{\varphi_c}$ and s-channel angular momentum $J = 1$. From ordinaly duality we have on the average[‡2]

$$\mathrm{Im}\, F_{\varphi_c}^{J=1}(c\bar{c} \to c\bar{c})_{s=m^2_{\varphi_c}} \sim (m^2_{\varphi_c})^{\alpha_{\varphi_c}(0)-1} . \tag{8}$$

Here $\alpha_{\varphi_c}(0)$ is the intercept of the φ_c-trajectory. From (1) and the Veneziano-like assumption that all $c\bar{c}$ trajectories are parallel to each other we deduce

$$\alpha_{\varphi_c}(0) = 1 - 1/a_c = -1.4. \tag{9}$$

Then (7)–(9) give

$$\Gamma(\varphi_c \to \text{only hadrons}) \sim g_c^4 (m^2_{\varphi_c})^{\alpha_{\varphi_c}(0)-3/2} . \tag{10}$$

Treating in analogy $\varphi \to 3\pi$, we find

$$\Gamma(\varphi \to 3\pi) \sim g_\lambda^4 (m^2_\varphi)^{\alpha_\varphi(0)-3/2} \tag{11}$$

where the intercept of the φ-trajectory is given by [6]

$$\alpha_\varphi(0) = 0.375. \tag{12}$$

Using (9)–(12) we obtain[‡3]

$$\Gamma(\varphi_c \to \text{only hadrons}) \sim \frac{(m^2_{\varphi_c})^{\alpha_{\varphi_c}(0)-3/2}}{(m^2_\varphi)^{\alpha_\varphi(0)-3/2}} \Gamma(\varphi \to 3\pi) \left(\frac{g_c}{g_\lambda}\right)^4 \sim 1 \cdot \left(\frac{g_c}{g_\lambda}\right)^4 \text{ keV}. \tag{13}$$

Eq. (13) depends crucially on (9). Similar results hold also for φ_{c1}. We conclude that the small widths Γ_{φ_c}, $\Gamma_{\varphi_{c1}}$ may be understood on the basis of a low φ_c-trajectory and the assumption that the effective binding of the $c\bar{c}$ sys-

‡2 The −1 in the exponent comes from the s-channel partial wave expansion of the Regge representation of the amplitude.

‡3 This remains unchanged when we use $\alpha_\varphi(0) = 0$.

tem is somewhat bigger than the binding of the $\lambda\bar{\lambda}$ one; i.e., $g_c \gtrsim g_\lambda$. The later assumption seems intuitive. Indeed if c is heavier [5] than λ and the binding potential is similar in both cases and singular at the origin, we expect that c–$\bar{c}$ are closer to each other than λ–$\bar{\lambda}$. Consequently c–$\bar{c}$ should feel stronger forces [7] ‡4.

Photoproduction of φ_c. The existing data on photoabsorption and deep inelastic electroproduction indicate that the Pomeron-φ_c coupling is negligible. In more physical terms this means that we are still below the continuum for charmed particle production. Indeed for $\sqrt{s} \lesssim 7$ GeV the diffractive cross sections obey [6, eqs. (28), (54)]

$$\sigma_D(\varphi p)/\sigma_D(\rho p) = m_\rho^2/m_\varphi^2, \qquad \sigma_D(\varphi_c p)/\sigma_D(\rho p) \ll m_\rho^2/m_{\varphi_c}^2. \tag{14a, b}$$

From (14b) and for $E_\gamma \lesssim 25$ GeV (i.e. $\sqrt{s} \lesssim 7$ GeV) we obtain [6, 14]

$$\left.\frac{d\sigma(\gamma p \to \varphi_c p)}{dt}\right|_{t=0} = \frac{\alpha}{18\pi}\left(\frac{4\pi}{f_\rho^2}\right)\frac{a_c}{a_\rho}\,\sigma_D^2(\varphi_c p) \ll (0.06 \pm 0.02)\ \mu\text{b GeV}^{-2} \tag{15}$$

$$\sigma(\gamma p \to \varphi_c p) = \frac{1}{B}\left.\frac{d\sigma(\gamma p \to \varphi_c p)}{dt}\right|_{t=0} \ll (0.005 - 0.025)\ \mu\text{b} \tag{16}$$

where a slope $B = (3 - 8)\ \text{GeV}^{-2}$ is used.

On the contrary for $E_\gamma \gg 25$ GeV we expect the Pomeron –φ_c coupling to become important. As a first guess let us assume here the twisted loop model [15] which demands (14a) and ‡5

$$\sigma_D(\varphi_c p)/\sigma_D(\rho p) = m_\rho^2/m_{\varphi_c}^2. \tag{14c}$$

The prediction (14a) of this model is correct [15, 6]. So (14c) might also be reasonable. Using (14c) we find that *the inequalities* (15), (16) *become equalities for* $E_\gamma \gg 25$ *GeV*.

We conclude therefore that the cross section for diffractive photoproduction of φ_c's is probably very small, even at very high energies. Consequently the φ_c-contribution to the total photoabsorption cross section remains always negligible [6, 14].

Deep inelastic electroproduction: In our GVD approach we can only calculate the Pomeron and f-A_2-exchange contributions to the deep inelastic structure functions [6]. The predictions obtained are only valid in the small x-region; ($x \lesssim 0.2$ say).

Below the charmed particle threshold, scaling should be apparent for $q^2 \gg m_\rho^2 = 0.6\ \text{GeV}^2$. We have [6]

$$F_{2p}(x) = (1-x)(0.237) + \sqrt{x(1-x)}\,(0.284), \qquad F_{2p}(x) - F_{2n}(x) = \sqrt{x(1-x)}\,(0.095). \tag{17a, b}$$

Above the charmed particle threshold we will have scaling violations. Scaling will be established again for [6]

$$q^2 \gg m_{\varphi_c}^2 = 9.6\ \text{GeV}^2. \tag{18}$$

The predictions at very high energies (say $\nu \gg 30$ GeV; $\sqrt{s} \equiv W \gg 7$ GeV) and in the new scaling region (18) are [6]

$$F_{2p}(x) = (1-x)(0.237)(1 + \tfrac{8}{12}) + \sqrt{x(1-x)}(0.284), \qquad F_{2p}(x) - F_{2n}(x) = \sqrt{x(1-x)}(0.095). \tag{19a, b}$$

In deriving (19) we assumed again (14c). We see from (19), (17) that the φ_c's will cause an increase of the Pomeron contribution to $F_{2p}(x)$ by 67%. Because of exchange degeneracy, the φ_c's will not affect the difference of the structure functions for protons and neutrons in the small x-region.

We conclude that contrary to the photoabsorption situation, the contribution of φ_c's to deep inelastic scattering at very high energies will probably be very important.

The basic ingredients in the above derivations were GVD, LD, asymptotic U(4) symmetry for the current propagator, and the assumption that the two narrow resonances are the first of a series of φ_c's. The conclusions are:

‡4 This is the case for the positronium and muonium bound states.

‡5 In the notation of ref. [6] this means $\beta p = \beta p_\varphi = \beta p_{\varphi_c}$.

1) The ratios $\Gamma_e \Gamma_h / \Gamma$ are correctly predicted for these resonances. This result depends crucially on the assumption that there is no other narrow resonance in between.

2) The asymptotic value $\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-) = 4.1 \pm 0.3$ should be practically established for $\sqrt{s} \gtrsim 7$ GeV.

3) The hadronic widths of φ_c and φ_{c1} are suppressed because they lie below the charmed particle threshold and the φ_c- trajectory is very low.

4) The third φ_c is expected at 4.2 GeV in consistence with experiment. Its decay rate to e^+e^- is predicted.

5) For $\sqrt{s} \lesssim 7$ GeV, the Pomeron - φ_c coupling is negligible. Consequently the φ_c's do *not* give any contribution to the photoabsorption and small x deep inelastic electroproduction cross sections.

6) For $\sqrt{s} \equiv W \gg 7$ GeV we expect that the φ_c's will cause ~67% increase to the Pomeron part of the deep inelastic structure functions. $F_{2p}(x) - F_{2n}(x)$ will remain unchanged. The cross section for φ_c diffractive photoproduction will still be very small.

One of us (G.J.G) would like to thank L. Resvanis for informative discussions.

References

[1] J.J. Aubert et al., Phys. Rev. Lett. 33 (1974) 1404.
[2] J.E. Augustin et al., Phys. Rev. Lett. 33 (1974) 1406.
[3] C. Bacci et al., Phys. Rev. Lett. 33 (1974) 1408.
[4] G.S. Abrams et al., Phys. Rev. Lett. 33 (1974) 1453.
[5] M.K. Gaillard, B.W. Lee and J.L. Rosner, FERMILAB-Pub-74/34-THY;
J. Iliopoulos, rapporteurs's talk, XVII Intern. Conf. on High energy physics, London (1974).
[6] G.J. Gounaris, New results on deep inelastic processes from generalized vector dominance, Nuclear Phys. B (in press).
[7] T. Appelquist and H.D. Politzer, Phys. Rev. Lett. 34 (1975) 43;
A. De Rújula and S.L. Glashow, Phys. Rev. Lett. 34 (1975) 46;
H.J. Schnitzer, Quark dynamics and bound charm, to be published.
[8] C.A. Dominguez and M. Greco, Charm, EVDM and narrow resonances in e^+e^- annihilation;
D. Schildknecht and F. Steiner, DESY 74/55.
[9] G.J. Gounaris, Nucl. Phys. B68 (1974) 574.
[10] V. Alles Borelli et al., Phys. Lett. 40B (1972) 433;
M. Conversi et al., Phys. Lett. 52B (1974) 493.
[11] J.D. Jackson, Physics Notes (unpublished).
[12] J.E. Augustin et al., Total cross section for hadron production by electron positron annihilation between 2.4 GeV and 5.0 GeV center of mass energy, submitted to Phys. Rev. Lett.
[13] B. Richter, rapporteur's talk, XVII Intern. Conf. on High energy physics, London (1974);
G. Tarnopolsky et al., Phys. Rev. Lett. 32 (1974) 432.
[14] G. Wolf, Proc. 1971 Int. Symp. on Electron and photon interactions (Cornell University).
[15] C.E. Carlson and P.G.O. Freund, Phys. Lett. 39B (1974) 349.