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Spectroscopy of the New Mesons*

Thomas Appelquist,† A. De Rújula, and H. David Politzer‡

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

and

S. L. Glashow§

Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 11 December 1974)

The interpretation of the narrow boson resonances at 3.1 and 3.7 GeV as charmed quark-antiquark bound states implies the existence of other states. Some of these should be copiously produced in the radiative decays of the 3.7-GeV resonance. We estimate the masses and decay rates of these states and emphasize the importance of γ -ray spectroscopy.

Two earlier papers^{1,2} present our case that the recently discovered^{3,4} and confirmed⁵ resonance at 3.105 GeV is the ground state of a charmed quark bound to its antiquark, by colored gauge gluons: orthocharmonium I. More recently, a second state at 3.695 GeV has been reported⁶ with an estimated width of 0.5–2.7 MeV and a partial decay rate ~ 2 keV into e^+e^- . We interpret this state as an S-wave radial excitation, orthocharmonium II, with $J^P = 1^-$ and $I^G = 0^-$. Here are three indications of the correctness of our interpretation: (1) Much of the time, orthocharmonium II decays into orthocharmonium I and two pions. This behavior suggests that orthocharmonium II is an excited state of orthocharmonium I.⁷ (2) The leptonic width of orthocharmonium II is about half that of orthocharmonium I, not unexpected for an excited state whose wave function at the origin is smaller. (3) Orthocharmonium II is not seen in the Brookhaven National Laboratory–Massachusetts Institute of Technology experiment.⁸ In a thermodynamic model,⁹ the production cross section of a hadron of 3.7 GeV is suppressed by $\sim 10^{-2}$ relative to that of a hadron of 3.1 GeV. Moreover, the leptonic branching ratio of orthocharmonium II is smaller than that of orthocharmonium I by a factor of 10.

We predict the existence of other states of charmonium with masses less than 3.7 GeV, a

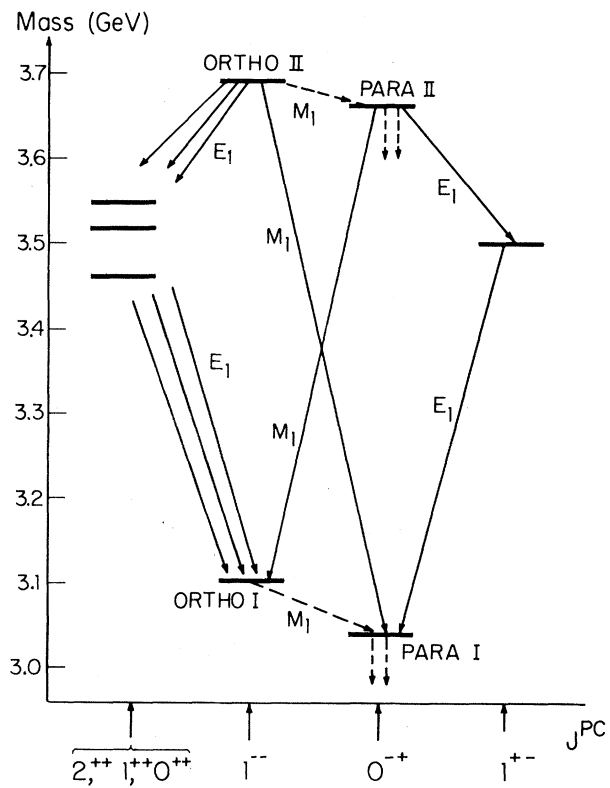


FIG. 1. Masses and radiative transitions of charmonium.

TABLE I. Meson table (charmonia).

| Name | $I^G(J^P)$ | Mass (GeV) | Full Width (MeV) | Partial Decay Mode | | | | | | |
|--|--|----------------------|--------------------|---|---|------------|-------|-----------------------------|----------------------|------------------|
| | | | | Mode | Partial width Γ or Fraction % | | | | | |
| Para I | $0^+(0^-)$ | 3.05 | 6.5 | Hadrons ^a | ~100% | | | | | |
| | | | | 2γ | .2% | | | | | |
| Ortho I (J(3104)) (ψ (3104)) | $0^-(1^-)$ | 3.104 | .075 | Hadrons ^a | 87% | | | | | |
| | | | | e^+e^- | 5% | | | | | |
| | | | | $\mu^+\mu^-$ | 5% | | | | | |
| | | | | Hadrons ^a + γ ^b | 2.7% | | | | | |
| | | | | Para I + γ | .2% | | | | | |
| | $\nu\bar{\nu}$ | < 10 ⁻⁴ % | | | | | | | | |
| P ₀ P ₁ P ₂ P ₁ ' | $0^+(0^+)$ $0^+(1^+)$ $0^+(2^+)$ $0^-(1^+)$ | ~3.5 | ~3. | Ortho I + γ Para I + 2π Hadrons ^a | dominant small or zero (P ₀ , P ₁ ') < 2% | | | | | |
| | | | | | Para II | $0^+(0^-)$ | ~3.67 | > 5. | Hadrons ^a | $\Gamma = 4$ MeV |
| | | | | | | | | Para I + 2π | substantial | |
| | | | | | | | | P ₁ ' + γ | $\Gamma = .15$ MeV | |
| | | | Ortho I + γ | $\Gamma \lesssim .9$ MeV | | | | | | |
| | | | 2γ | $\Gamma = 5$ keV | | | | | | |
| Ortho II (ψ '(3695)) | $0^-(1^-)$ | 3.695 | ~1. | Ortho I + 2π | dominant | | | | | |
| | | | | Para I + γ | $\Gamma < .25$ MeV ^c | | | | | |
| | | | | P ₀ + γ | $\Gamma \lesssim .16$ MeV | | | | | |
| | | | | P ₁ + γ | $\Gamma \lesssim .16$ MeV | | | | | |
| | | | | P ₂ + γ | $\Gamma \lesssim .16$ MeV | | | | | |
| | | | | Hadrons ^a | $\Gamma \sim 46$ keV | | | | | |
| | | | | e^+e^- | $\Gamma \sim 2$ keV | | | | | |
| | | | | $\mu^+\mu^-$ | $\Gamma \sim 2$ keV | | | | | |
| | | | | Para II + γ | $\Gamma \lesssim 24$ eV | | | | | |
| | | | | $\nu\bar{\nu}$ | $\Gamma < 4$ eV | | | | | |
| | Charmed pairs | ? | | | | | | | | |

^aHadrons: states not containing charmonia.

^bRef. 14.

^cRef. 15.

fortiori lying below charm threshold. These states should be narrow (less than 7 MeV), and should enjoy a perplexing variety of experimentally accessible decay modes. (See Fig. 1 and Table I.)

Corresponding to each $J^{PC} = 1^{--}$ state of orthocharmonium, we predict a 0^{-+} state of paracharmonium,^{1,2} split in mass from the former by the strong-interaction analog of hyperfine splitting. A Coulombic description of the ground states may be a trustworthy order-of-magnitude ap-

proximation. Using it, we find

$$\Delta M = \frac{1}{8} [(9/\alpha^2)\Gamma/M]^{1/2} M,$$

where M is the mass of orthocharmonium I and Γ is its partial width into e^+e^- . If this width is 4 keV, $\Delta M \approx 65$ MeV. It is intriguing to note that a narrow $\bar{p}p$ resonance at 3.05 GeV was reported¹⁰ years ago. We also predict a paracharmonium II state lying a few dozen MeV below orthocharmonium II. Neither state of paracharmonium is produced by nor decays into lepton pairs.

Other states of charmonium should lie between the I and II levels just as many conventional mesons lie between the $\rho(770)$ and $\rho'(1600)$. Such states should be exceptionally narrow—unlike their conventional counterparts—because they are kinematically forbidden to decay into charmed pairs. Moreover, their direct hadronic decays require the annihilation of the charmed quarks into gluons and are damped by the asymptotic-freedom mechanism.^{1,2} Their radiative decays are dominant and are estimated below.

We estimate that the lowest P -wave states of charmonium with $J^{PC}=0^{++}, 1^{++}, 2^{++}$, and 1^{+-} and $I=0$ should lie near 3.5 GeV. Two arguments for this are as follows: (1) The $\rho\rho'$ splitting is 800 MeV while the orthocharmonium-I-orthocharmonium-II splitting is 600 MeV. This suggests that the splitting between orthocharmonium I and the P -wave states is 0.75 times the splitting of the corresponding $\lambda\bar{\lambda}$ states, $\varphi(1019)$ and $f'(1516)$. (2) In a Coulomb potential, the first P state is degenerate with the second S state, while in a harmonic-oscillator potential it lies halfway between the first two S states. For charmonium, we expect an intermediate result.

None of the P states are coupled to e^+e^- , but they are produced by the radiative (one-photon) decays of orthocharmonium II. Figure 1 displays the anticipated states of charmonium and the allowed monochromatic radiative decay modes.

There are three kinds of radiative transitions: (1) One state of charmonium may decay into another, and a monochromatic photon.² Only transitions between states of opposite C are allowed. Those changing parity are favored electric-dipole transitions, with rates $\lesssim \frac{84}{27}\alpha k^3 R^2$; transitions between states of the same parity are magnetic-dipole transitions, with rates $\lesssim \frac{84}{27}\alpha k^3 M^{-2}$, where R and M are the size and mass of charmonium, and k is the photon momentum.¹¹ This is just a rough estimate, possibly an upper limit. (2) A state of charmonium may decay directly in-

to two photons,^{1,2} like π^0 . This transition is forbidden to orthocharmonium, and probably negligible for the P states. (3) A state of charmonium may decay directly into one photon plus conventional hadrons. These transitions require the annihilation of the charmed quarks, and are negligible.¹²

The magnetic-dipole transition from orthocharmonium II at rest to parachocharmonium I should yield a monochromatic 585-MeV photon. Its partial width is estimated to be $\lesssim 250$ keV.¹¹ The linewidth is ~ 7 MeV, this being mainly the width of the daughter, parachocharmonium I. Its discovery would confirm the existence of parachocharmonium,^{1,2} possibly already seen in $\bar{p}b$,¹⁰ and our estimate of the hfs.

Orthocharmonium II also decays into the three C -even P -wave levels, yielding three closely spaced monochromatic photons with energies ~ 200 MeV. Although these decay modes have less available energy, they have larger (electric-dipole) matrix elements. We expect decay widths of order ~ 160 keV. These radiative widths are comparable with the observed 2π de-excitation of orthocharmonium II to orthocharmonium I, and the C -even P -wave states may be copiously produced. We must stress the crudity of these estimates, because they depend crucially on the unknown mass differences, and involve unknown overlap integrals that we may only bound.

The 2π de-excitations of C -even P -wave charmonium are negligible.¹³ These P -wave states will decay mainly into orthocharmonium I plus a photon with partial widths of order 3 MeV.

The direct decays of charmonium states (into hadrons not containing other charmonium states) provide a good test of the explicit suppression mechanism discussed in Refs. 1 and 2. In the standard $SU(3)'$ twelve-quark gauge model of the strong interactions the direct decay of orthocharmonium II into hadrons proceeds via three gluons and satisfies¹

$$\frac{\Gamma(\text{orthocharmonium II} \rightarrow \text{hadrons})}{\Gamma(\text{orthocharmonium II} \rightarrow e^+e^-)} = \frac{5}{18\pi} \frac{\pi^2 - 9}{\alpha^2} \alpha_s^3(3.7),$$

where $\alpha_s(3.7)$ is the gluon coupling constant at 3.7 GeV.¹⁴ We obtain $\Gamma(\text{orthocharmonium II} \rightarrow \text{hadrons}) \sim 40$ keV, using $\Gamma(e^+e^-) \sim 2$ keV. (This result depends on our assumption that orthocharmonium II, like orthocharmonium I, is a bound state of charge $\pm \frac{2}{3}$ quarks.) Another competitive mechanism, involving a one-photon intermediate state, yields an additional contribution to $\Gamma(\text{orthocharmonium II} \rightarrow \text{hadrons})$ of order $R\Gamma(e^+e^-) \sim 6$ keV, where $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ near orthocharmonium II.

Parachocharmonium I can decay into hadrons only directly, and proceeds via two gluons, satisfying

$$\Gamma(\text{parachocharmonium I} \rightarrow \text{hadrons}) = \frac{2}{3} [\alpha_s(3.1)/\alpha]^2 \Gamma(\text{orthocharmonium I} \rightarrow e^+e^-) \sim 6.5 \text{ MeV}.$$

We have used the experimental result $\Gamma(\text{orthocharmonium I} \rightarrow e^+e^-) \sim 4 \text{ keV}$. The 2γ decay mode of paracharmonium I is similar to its direct hadronic decay, and should have a branching ratio $\Gamma(\text{paracharmonium I} \rightarrow 2\gamma)/\Gamma(\text{paracharmonium I} \rightarrow \text{all}) = 2\alpha^2/\alpha_s^2 = 10^{-3}$. The direct decay of paracharmonium II into hadrons and its 2γ mode are similarly estimated. Because the paracharmonium states have much larger matrix elements for decay into hadrons, they are produced more copiously in hadron collisions than the corresponding orthocharmonium states.

An exciting but unlikely possibility is that orthocharmonium II may lie just slightly above charm threshold. (It cannot be very much higher, lest it become too broad.) We estimate, from a comparison with ϕ decay,

$$\Gamma(\text{orthocharmonium II} \rightarrow \text{charmed pair}) = \left(\frac{M^2 - 4\mu^2}{M_\phi^2 - 4M_K^2} \right)^{3/2} \frac{M_\phi^2}{M^2} \Gamma(\phi \rightarrow \bar{K}K),$$

where μ is the mass of the lightest charmed 0^- meson, and M is the mass of orthocharmonium II. So long as orthocharmonium II is not more than 20 MeV above charm threshold, this partial decay width is $< 1 \text{ MeV}$. This would be a wonderful source of charmed particles. If orthocharmonium II is not just above threshold, it is still possible that a higher excitation of charmonium may be.

If such a copious source of charmed 0^- mesons is available, then e^+e^- annihilation becomes the method of choice for the discovery of charm. Not only can the new particles be found, but we anticipate a charmed analog to the miraculous $K_0\bar{K}_0$ system. Let D_0 and \bar{D}_0 denote the $(\mathcal{P}\bar{\mathcal{P}}')$ and $(\mathcal{P}'\bar{\mathcal{P}})$ charmed pseudoscalars. Both states will have similar decay rates Γ into states of $S=+1$ and $S=-1$, respectively, because of the predominant $\cos\theta$ weak couplings. However, a mixing between them is expected to take place by virtue of the $\sin\theta$ weak couplings, yielding a mass splitting between the CP -even and CP -odd states of order $\Gamma \tan^2\theta$. When an oppositely charmed pair is produced, a few percent of the time ($\sim \tan^2\theta$), one of the particles decays "wrongly," yielding a final state with $S=\pm 2$ (or, with two equally charged leptons as well as $S=\pm 2$, in the case of semileptonic decays).

We are grateful to our colleagues at Massachusetts Institute of Technology and Harvard University, particularly Howard Georgi and R. Shankar, for many conversations. We also thank A. Pais for discussions and encouragement.

Note added.—After this manuscript was completed, we received two preprints on the same topic, one by E. Eichten, K. Gottfried, T. Kinoshita, J. Kogut, K. D. Lane, and T.-M. Yan¹⁵ and another by C. G. Callan, R. L. Kingsley, S. B. Treiman, F. Wilczek, and A. Zee. Quantitative estimates of the orbitally excited levels of charmonium have recently been made by B. Harrington, S. Y. Park, and A. Yildiz, "Orbital Ex-

citations in Charmonium" (to be published).

*Work supported in part by the National Science Foundation under Grant No. MSP73-05038 A01.

†Alfred P. Sloan Foundation Fellow.

‡Junior Fellow, Harvard Society of Fellows.

§Permanent address: Department of Physics, Harvard University, Cambridge, Mass. 02138.

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⁷As reported by W. Sullivan, New York Times, 16 December 1974, p. 66; R. Schwitters, private communication.

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⁹See, for instance, R. Hagedorn, CERN Report No. 71-12 (unpublished).

¹⁰H. Braum *et al.*, "Search for Heavy Boson Resonances in $\bar{p}n$ Interactions at 5.55 GeV/c," paper submitted to the International Conference on Elementary Particles, Amsterdam, The Netherlands, 30 June–6 July 1971 (unpublished). We thank E. Berger for informing us of this reference.

¹¹We use 0.75 as an upper bound on the overlap integral for orthocharmonium II \rightarrow paracharmonium I + γ [see R. Shankar and J. Borenstein, "Can γ -ray Spectroscopy Throw Light on the Charmonium Picture?" (to be published)], and 0.5 fm for the charmonium size R .

¹²The branching ratio (orthocharmonium I \rightarrow hadrons + γ)/(orthocharmonium I \rightarrow hadrons) can be explicitly calculated in the quark-gluon model to be $16\alpha/15\alpha_s$.

¹³The 0^{++} state is forbidden to decay into paracharmonium I and two pions. The 1^+ and 2^+ decays encounter severe centrifugal barriers. Moreover, the available energy for the decay is much smaller than for the

2π de-excitation of paracharmonium II.

¹⁴The value of $\alpha_s = 0.26$ at 3.1 GeV was obtained in Ref. 1 from the leptonic branching ratio of orthocharmonium I. Asymptotic freedom reduces this value to 0.22 at 3.7 GeV.

¹⁵E. Eichten *et al.*, Phys. Rev. Lett. **34**, 369 (1975) (this issue). As pointed out by these authors in the transition orthocharmonium II \rightarrow paracharmonium I $+\gamma$, the orthogonality of the wave functions may make our upper limit a gross overestimate.

Spectrum of Charmed Quark-Antiquark Bound States*

E. Eichten, K. Gottfried, T. Kinoshita, J. Kogut, K. D. Lane, and T.-M. Yan†

Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853

(Received 17 December 1974)

The discovery of narrow resonances at 3.1 and 3.7 GeV and their interpretation as charmed quark-antiquark bound states suggest additional narrow states between 3.0 and 4.3 GeV. A model which incorporates quark confinement is used to determine the quantum numbers and estimate masses and decay widths of these states. Their existence should be revealed by γ -ray transitions among them.

Recently two astonishingly narrow resonances have been discovered^{1,2} at 3.105 and 3.695 GeV. In our view the most plausible explanation of this phenomenon is that of Appelquist and Politzer,³ to wit, that they are $c\bar{c}$ -bound states of charmed quarks c which lie below⁴ the threshold M_c for the production of a pair of charmed hadrons.⁵ Because of its similarity to positronium this system has been called charmonium.³ This note is devoted to the spectrum of charmonium.⁶ Many of the phenomena that we shall discuss are accessible to existing experimental techniques.

If the strong interactions are described by an asymptotically free theory, one may hope³ that the short-distance structure of charmonium (in particular, its decay into leptons, and probably also hadrons) is adequately described by perturbation theory in terms of a small "running" coupling constant. In this regime the $c\bar{c}$ interaction would be Coulombic, with a small strong "fine-structure" constant α_s . At larger $c\bar{c}$ separation, on the other hand, there are rather compelling arguments that gauge theories provide for quark confinement.⁷

If α_s is small and the observed levels do not lie far below the threshold M_c , nonrelativistic quantum mechanics should provide a sound zeroth-order guide. Given⁸ the sizable electronic widths Γ_e of $\psi(3695)$ and $\psi(3105)$, it is natural⁹ to assign them to the states 2^3S_1 and 1^3S_1 , respectively. This being said, it is at once clear that there should be other levels below M_c , for any confining potential will raise¹⁰ the $2S$ Coulomb level above its previously degenerate partner $2P$. One

must therefore expect a multiplet of narrow P states below $\psi(3695)$, fed from the latter by $E1$ γ transitions, and decaying in turn into $\psi(3105)$. If 3.7 GeV is not too close to M_c , bound D states could also exist.

It goes without saying that many qualitative features of the spectrum can be surmized without resorting to a detailed model. Nevertheless, we have found it informative to simulate the intricate $c\bar{c}$ interaction by a simple potential that incorporates both the Coulomb and confinement forces:

$$V(r) = -(\alpha_s/r)[1 - (r/a)^2]. \quad (1)$$

That the interaction is far from Coulombic follows from the large $2S$ - $1S$ mass difference, and the fact that⁸

$$\eta \equiv \left| \frac{\psi(1^3S; r=0)}{\psi(2^3S; r=0)} \right|^2 \approx \left(\frac{3.1}{3.7} \right)^2 \frac{\Gamma_e(3105)}{\Gamma_e(3695)} \approx 1.4, \quad (2)$$

in contrast to Ref. 8 for a Coulomb field.¹¹ In analogy with electrodynamics there must also be spin-spin, spin-orbit, and tensor forces, but hopefully they play a secondary role. Near M_c a treatment that accounts for coupling to decay channels is necessary.

We have determined α_s , a , and the charmed-quark mass m_c by solving the wave equation numerically,¹² and by imposing the constraints (a) $M(2^3S) - M(1^3S) = 0.59$ GeV; (b) $\Gamma_e(1^3S) = 5.5$ keV; (c) 1.5 GeV $\approx m_c \approx 2.0$ GeV; and (d) $0.1 \leq \alpha_s \leq 0.4$. Constraint (c) is the requirement that the system be nonrelativistic, and that $\psi(3695)$ lie below M_c ; naive quark phenomenology would set