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CHARMED RESONANCES IN TWO-PHOTON COLLISIONS*

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ABSTRACT

The production of charmed particles in two-photon processes is calculated. The results obtained are relevant for e^+e^- machines at energies accessible at DORIS and PEP. In particular, we predict that two body final states consisting of $D\bar{D}$, $D^*\bar{D}^*$ and $D\bar{D}^*$ will have a signal/background ratio of almost 2/1. The calculational scheme is that of a charmonium model where effects due to the strong coupling of the $c\bar{c}$ resonances to the decay channels are taken into account. As a by-product of this calculation we find a manifest realization of the duality ansatz.

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Studies on e^+e^- annihilation of one-photon exchange[1] have helped greatly in contributing to our understanding of the bound state spectra of heavy quarks. Surely one-photon physics will continue to be a useful tool for studying new flavors of quark; however, its cross section is falling as energy increases. The opposite is true of the creation of hadrons via two-photons[2] (double bremsstrahlung). At energies now available in colliding rings the two-photon cross section is already comparable to the one-photon cross section, and studies of two-photon processes will be a useful tool for studying what might now be called "old" physics, i.e., charm.

In this short note, we report a study of production of charmed mesons and of $C = +$ charmonium resonances in two-photon collisions. This process is useful for further testing the potential that binds the quarks and will provide additional information about the spectrum of heavy quarks. We work in the context of a non-relativistic charmonium model of heavy quark bound states,[3] which was extensively studied by the Cornell group,[4,5,6] and include effects due to coupling of resonances to decay channels. We may remind the reader that this model has been quite successful in explaining the charm production observed in e^+e^- annihilation via one-photon: The simple version of the model predicted the Ψ' as the radial excitation[3] of the J/Ψ and existence of the ^3P_j states[5] between the Ψ' and J/Ψ. Including the effects of the decay channels allowed an accurate prediction of the mass and width of the $^3D_1(3772)$ [6] and gave a reasonable description of the one-photon physics[5] up to $W = \sqrt{s} = 4.5$ GeV.

Let us now proceed with our study of two-photon collisions. The simple model would have $Q\bar{Q}$ states bound by a potential

$$V(r) = -\frac{4\alpha_s}{3r} + \frac{r}{a^2} \tag{1}$$

and neglect coupling to decay channels. The production of a $C=+$ narrow resonance i proceeds as shown in Fig. 1a and the cross section is[2]

$$\sigma(ee\to eei) = \frac{16\alpha_s^2}{M_i^3}(2J_i+1)\,\Gamma(i\to\gamma\gamma)\,\ell n^2\left(\frac{E}{m_e}\right)f(z) \quad . \tag{2}$$

Here E is the beam energy, z is $M_i/2E$ and f is the Low function

$$f(z) = (2+z^2)^2\,\ell n\,\frac{1}{z} - (1-z^2)(3+z^2) \quad . \tag{3}$$

The above equation is true for any $C=+$ state. Given the potential model for quarkonium, one can calculate the widths. For $^1S_0$ states, $i=\eta_c$ and

$$\Gamma(\eta_c\to 2\gamma) = \frac{64}{27}\,\frac{\alpha^2}{M_{\eta_c}^2}\,|R(0)|^2 \tag{4}$$

where R(0) is the radial wave function at the origin, normalized by $\int|R|^2r^2dr = 1$.

Most of the narrow $C=+$ resonances can be studied in radiative decays of $C=-$ states. The opportunity for observing new $C=+$ states lies in two-photon production above charm threshold, where the coupling of the $c\bar{c}$ resonances to the decay channels has large effects on the masses and widths.[7] We consider only the channels $C_1\bar{C}_2$, where $C_i = D, D^*$, F, or F^*; these two body final states dominate close to threshold. Because we have one extended object decaying into two extended objects, the shapes of the resonance curves will not be Lorentzian. The nodes of the resonance's wave functions, for example, will introduce zeros into the decay amplitudes. The production of $C_1\bar{C}_2$ final state proceeds as depicted in Fig. 1b.

For fixed beam energy E and any final state $x = C_1\bar{C}_2$

$$\frac{d\sigma}{dW}\, ee \to eex(E) = 4\left(\frac{\alpha}{\pi}\right)^2 \ell n^2\left(\frac{E}{m_e}\right) f\left(\frac{W}{2E}\right) \frac{\sigma_{\gamma\gamma\to x}(W)}{W} \tag{5}$$

with $W = \sqrt{s}$ being the energy of the hadronic final state in the photon-photon c.m. We describe the OZI-rule allowed decays by the Hamiltonian

$$H_I = \frac{1}{2}\sum_{i=1}^{8}\int :\rho_a(\vec{x})\, V(\vec{x}-\vec{y})\, \rho_a(\vec{y}) : d^3x d^3y \tag{6}$$

where ρ_a is the color charge density

$$\rho_a(\vec{x}) = \Psi^+(\vec{x})\, \frac{\lambda_a}{2}\, \Psi(\vec{x}) \tag{7}$$

The dressed propagator of the $c\bar{c}$ resonances is given diagrammatically in Fig. 2 and is

$$\mathcal{G}(E) = \frac{1}{E - H_0 - \Omega} \tag{8}$$

where H_0 includes the binding potential, Eq. (1), and the effect of the decay Hamiltonian is contained in Ω, whose matrix elements are

$$\Omega_{n,m} = \sum_{i,j}\int d^3p\, \frac{\langle\Psi_n|H_I|C_i\bar{C}_j\rangle\langle C_i\bar{C}_j|H_I|\Psi_m\rangle}{E - E_i(p) - E_j(p) - io} \tag{9}$$

where Ψ_n is a charmonium bound state wave function (eigenstate of H_0), and $E_i = (M_i^2 + p^2)^{1/2}$ where M_i is the mass of a charmed meson. The poles of $\mathcal{G}$ give us the physical (renormalized) masses and widths of the $c\bar{c}$

states.' The wave functions and unrenormalized masses of the $c\bar{c}$ states are got by a computer solution of the Schroedinger equation; for the charmed mesons we use Gaussian wave functions obtained by variational calculation using only the linear potential.

The imaginary part of $\Omega_{n,m}$ is easily calculated, and its real part is then gotten by a dispersion integral. The dressed propagator $\mathcal{G}$ then follows directly. The expressions for the total $\gamma\gamma$ cross section may be obtained in terms of $\mathcal{G}$, and the radial wave functions of the $c\bar{c}$ bound states $R_{n,L}(r)$. For the $^1S_0$ intermediate states,

$$\sigma_{\gamma\gamma\to {}^1S_0} = -\frac{2\pi}{W^2}\,\frac{e_c^4\alpha_s^2}{m_c^2}\sum_{n,m} R_{n,0}(0)\,R_{m,0}(0)\,\langle\Psi_n|\mathcal{G}^{+}\mathrm{Im}\,\Omega\mathcal{G}|\Psi_m\rangle \quad (10)$$

For the $^3P_0$ states we have

$$\sigma_{\gamma\gamma\to {}^3P_0} = -\frac{2\pi}{W^2}\,\frac{9e_c^4\alpha^2}{m_c^4}\sum_{n,m} R'_{n,1}(0)\,R'_{m,1}(0)\,\langle\Psi_n|\mathcal{G}^{+}\mathrm{Im}\,\Omega\mathcal{G}|\Psi_m\rangle \quad (11)$$

and the $^3P_2$ contribution looks the same as the preceeding equation except that $\mathcal{G}$ and $\mathrm{Im}\Omega$ for the $^3P_2$ channels are used and we multiply by $(4/15)(2J+1) = 4/3$. The sum over n and m is carried to the 6 radial quantum numbers, the final states are $D\bar{D}$, $D\bar{D}^* + \bar{D}D^*$, $D^*\bar{D}^*$, and the corresponding channels for F's are also summed over. The $^3P_1$ states give a small contribution; when the photons are both on shell, the coupling of the $^3P_1$ to the two photons is zero.

We use the latest published parameters of the Cornell group[8] and make no further adjustments in these parameters. They were chosen to best describe the spacings of the narrow resonances and the $^3S_1$ experimental data, i.e., $e^+e^-\to$ charm. We then calculate $\mathrm{Im}\,\Omega$ for the $^1S_0$ and

^3P_j channels and the cross sections $\sigma(^1S_0)$, $\sigma(^3P_0)$, and $\sigma(^3P_2)$ and add them together. The resulting cross section for ee $\rightarrow$ ee$C_1\bar{C}_2$ is plotted in Fig. 3 for a beam energy of 15 GeV. Channels that we have omitted can make this curve, Fig. 3, unreliable for values of W above 4.5 GeV.

Also shown is the cross section for ee $\rightarrow$ ee$c\bar{c}$, ignoring final state interactions. The same value of the charm quark mass is used. Duality is satisfied, in the sense that if we average the cross section with resonances over a wide enough range of W we get the same result as for pointlike quarks with no strong interactions.

A few further comments are in order. The cross section is measurable although not large. With a luminosity of $10^{32}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$, we expect about 100 events/day in a W range of 1 GeV. One, of course, needs to use calorimetry to measure the final state energies. The requirement of low hadronic energy deposition should eliminate the 1γ events. The main background comes from ee $\rightarrow$ ee$u\bar{u}$, which at $W=4$ GeV is roughly twice as large as the ee $\rightarrow$ ee$c\bar{c}$ cross section shown in Fig. 3. However, this background can be considerably reduced by identifying strange particles in the final state. The sharp peaks observed are mainly due to the P-states, as the S-state contributions are smaller and broader. The information that can obtained on the size and locations of these peaks should be quite useful in further delineating the effective potential that binds heavy quarks.

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REFERENCES

(a) Present Address: San Jose State University, San Jose, CA 95192.

1. See, for example, the review by G. J. Feldman and M. L. Perl, Phys. Rep. 33C, 285 (1977).
2. S. J. Brodsky, T. Kinoshita and H. Terezawa, Phys. Rev. D4, 1532 (1971).
3. T. Appelquist and H. D. Politzer, Phys. Rev. Lett. 34, 43 (1975).
4. E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane and T. M. Yan, Phys. Rev. D17, 3090 (1978), ibid. D21, 203 (1980).
5. E. Eichten *et al.*, Phys. Rev. Lett. 34, 369 (1975) and 36, 500 (1976).
6. K. D. Lane and E. Eichten, Phys. Rev. Lett. 37, 477 (1976).
7. R. G. Thomas, Phys. Rev. 80, 136 (1950); J. D. Ehrman, Phys. Rev. 81, 412 (1951).
8. These are $(4/3)\alpha_s = 0.52$, $a = 2.12$ GeV^{-1}, $m_c = 1.84$ GeV, $m_u = m_d = 0.335$ GeV, $m_s = 0.45$ GeV.
9. It has been shown for the case of e^+e^- annihilation that duality in this sense follows from non-relativistic potential models; we have verified that the proof can be extended to two-photon processes. See, for example, J. S. Bell and J. Pasupathy, Phys. Lett. 83B, 389 (1979); C. Quigg and J. Rosner, Phys. Rev. D17, 2364 (1978); M. Krammer and P. Leal-Ferreira, Rev. Bras. Fis. 6, 7 (1976).

FIGURE CAPTIONS

Fig. 1. (a) Production of narrow $c\bar{c}$ bound states via two photons.

(b) Production of exclusive charmed meson channels via two photons.

Fig. 2. The dressed propagator for $c\bar{c}$ bound states.

Fig. 3. The cross section $d\sigma/dW$ for charmed meson production, summed over the channels $D\bar{D}$, $D\bar{D}^* + D^*\bar{D}$, $D^*\bar{D}^*$ and the corresponding channels for F's. The dashed line is $d\sigma/dW$ for $c\bar{c}$ pairs with no binding in the final state.

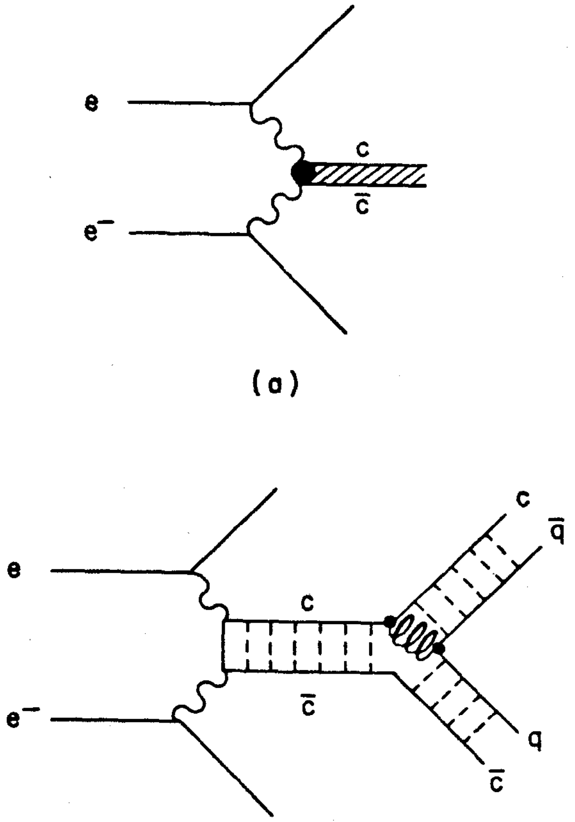

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Fig. 1

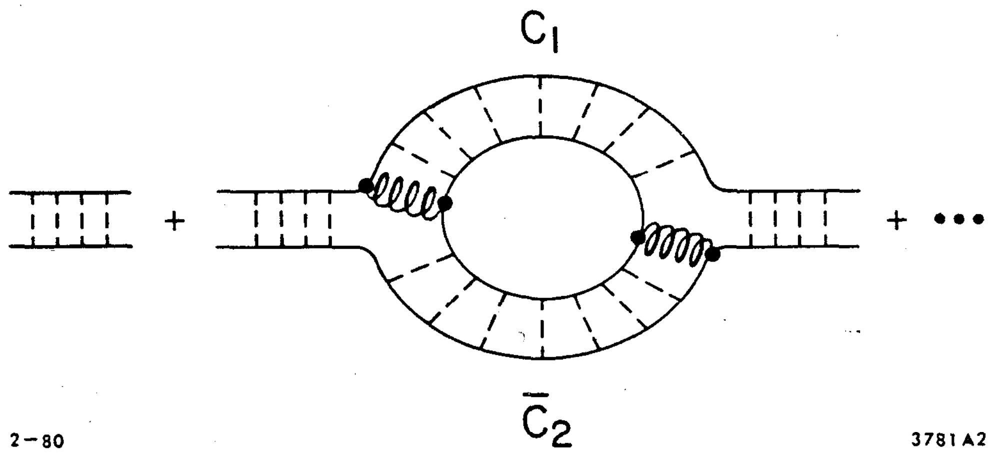

Fig. 2

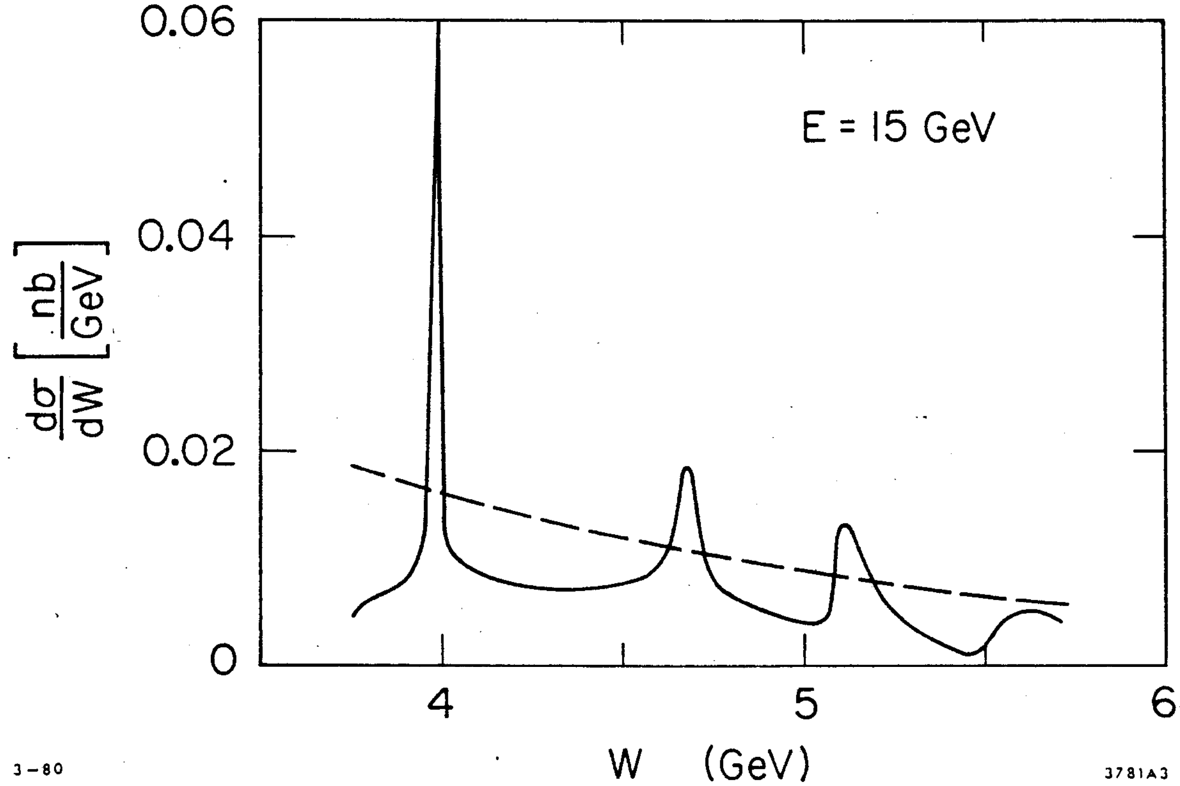

Fig. 3