Hadronic production of the new resonances: Probing gluon distributions

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Assuming that the new resonances observed at 3095 and 3684 MeV are bound states of a new, heavy quark and its antiquark, we consider several models for the production of such states in hadronic collisions. The dominant mechanism by which these particles couple to other hadrons (composed of normal quarks) may be via gluons. In analogy with the Drell-Yan model for quark-antiquark annihilation into a massive virtual photon, those new particles with even charge conjugation may be regarded as produced by gluon-gluon annihilation. Thus the (presently) hypothetical 0^{-+} partner (η_c) of the observed particles may serve as a short-distance probe of the gluon distributions within hadrons. We estimate the production cross section of η_c in nucleon-nucleon collisions using various models for gluon distributions. In addition, estimates are made for the production of final states containing pairs of charmed hadrons in the central region.

One of the most interesting (and, for us, most appealing) proposals concerning the identity of the newly discovered resonances[1] is that, within the framework of the quark model, these particles are bound states of a new, heavy quark (c) and its antiquark ($\bar{c}$).[2] The most popular speculation is that these heavy quarks carry the heretofore unobserved quality of charm.[3] However, the specific quantum number content of the new quarks is not really germane to the present discussion. We shall utilize the term charm only as a general label for some new quantum number. The features which are relevant are the conjectures that the quarks are massive and that the new particles, being composed of quarks, are hadrons. Consequently, it is interesting to consider by what mechanisms these particles and their charmed brothers can be produced in purely hadronic reactions. Such studies are useful to determine both how the particles can be efficiently produced and how their properties can be probed in production processes.

First consider briefly some conventional possibilities. One candidate is the multiperipheral cluster model, which adequately describes nondiffractive particle production.[4] In such a model the production of heavy hadrons arising from the production of even heavier clusters is suppressed at presently available energies because of the limitations on momentum transfers present in the model. Hence, any attempt to numerically estimate production cross sections will crucially depend on the assumption as to how the momentum transfers are cut off, a feature about which the usual applications have little to say.[5] Even the size of the asymptotic cross section (where $t_{\min}$ effects are small) is difficult to estimate reliably, although the observed small couplings (narrow width) of the new resonances suggest asymptotic production cross sections smaller than those for a cluster of pions of comparable mass. These considerations plus experience with the production of proton-antiproton pairs,[6] requiring 2-GeV clusters, suggest that the production of the new particles of mass > 3 GeV via multiperipheral cluster production will not be an important effect, at least up to the energies available at the CERN ISR ($s \leq 3600$ GeV^2). However, this conclusion should be tempered by the fact that even the cross sections considered in detail below are not really large, and a more quantitative investigation would be useful.

One can also estimate the production of charmed hadrons within a conventional Regge exchange framework but including charmed Reggeons. Again the results are too small to encourage experiment ($\sigma < 1$ nb).[7]

An alternative approach, which is explored below, is to exploit the assumed quark content of the new resonances and make estimates within the context of an extension of the Drell-Yan model.[8] In the usual application of this model, one studies the production of massive photons via quark-antiquark annihilation (See Fig. 1). Although the Drell-Yan mechanism cannot be derived from the light-cone or short-distance point of view, its motivation

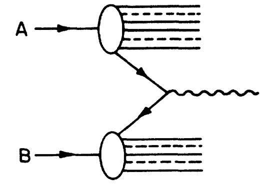

FIG. 1. Quark-antiquark annihilation into a massive, virtual photon. The notation in this and subsequent figures is solid lines for quarks, dashed lines for gluons, and wavy lines for photons. The incident hadrons are labeled by A and B.

within the quark-parton model is straightforward, especially since the leading absorptive corrections can be shown to be absent.[9] A direct application of this mechanism to the present case, assuming that the massive photon converts to the $\psi(J)(3095)$, $J^P = 1^-$, $c\bar{c}$ state (hereafter called ϕ_c), is unsatisfactory in at least two respects. First, one predicts a ϕ_c production cross section which is too small to explain the observations at BNL.[10] Secondly, one is ignoring the possibility of a direct hadronic coupling between the ϕ_c and ordinary (u, d) quarks. The existence of some form of direct hadronic coupling is required to explain the differences in the signal-to-background ratios (with appropriate account taken of the experimental resolution) between the experiments at SPEAR and at BNL (see Ref. 1). In particular, the ratio is considerably larger in the hadron-induced process. This hadronic coupling is also directly indicated in the SPEAR results by the fact that one can deduce the relation

$$\frac{\Gamma_{\phi_c \to \text{“}\gamma\text{”} \to \text{hadrons}}}{\Gamma_{\phi_c \to \text{hadrons}_{\text{total}}}} \approx 10\text{–}30\%.$$

[This result follows by combining the observations[1] that the ratio for $(\phi_c \to \mu^-\mu^+)/(\phi_c \to \text{hadrons})$ is about 8% and the value of $R = (\text{“}\gamma\text{”} \to \text{hadrons})/(\text{“}\gamma\text{”} \to \mu^-\mu^+)$ *off* resonance is between 2.5 and 3.0.] The question now arises as to the nature of this coupling. In analogy to massive photon production, one could imagine the ϕ_c produced directly by the annihilation of an ordinary quark-antiquark pair in hadronic collisions. An upper limit on the magnitude of this coupling to nonstrange, noncharmed quarks (u, d) can be obtained as follows. Suppose that the total hadronic decay width of the $\phi_c(3095)$ is due to the process $\phi_c \to \text{“}q\bar{q}\text{”}$ (see Fig. 2), that is, we calculate the decay width $\Gamma_{\phi_c \to \text{hadrons}}$ *as if* it were all due to $q\bar{q}$ final states. This hypothesis is analogous to the assumption that the rate for e^+e^- annihilation into hadrons is given by $e^+e^- \to \sum_q q\bar{q}$. In fact, the concept of calculating a process *as if* various intermediate and/or final states are well described by only a few quark degrees of freedom, instead of the much larger number of possible hadronic degrees of freedom and in spite of the fact that quarks are not actually observed, is at the heart of the parton model. The validity of such a calculational scheme can now be at least partially justified within the framework of asymptotically free field theories. We shall not give a detailed summary of the developments and problems contained in the recent efforts in this direction, but we shall happily utilize several of the results.[11] We return to the original argument: The coupling of $\phi_c(3095)$ to pairs of ordinary (u, d) quarks (summed over these quarks and their three colors) is bounded above by $\Gamma_{\phi_c\,\text{tot}} \approx 100$ keV. This, in turn, leads to an upper bound for the total hadronic production cross section per nucleon via this mechanism. For the process $N + N \to \phi_c + X$, the cross section is given by (ignoring the $p_\perp$ distribution of the partons and any sophisticated threshold effects)

$$\sigma_{\phi_c}^{\text{D-Y}} \leq \frac{12\pi^2\Gamma_{\phi_c\,\text{tot}}}{9M_{\phi_c}} \int dx_1\,dx_2\,\delta(x_1x_2s - M_{\phi_c}{}^2) \times [F_q^N(x_1)F_{\bar{q}}^N(x_2) + q \leftrightarrow \bar{q}], \quad (1)$$

where we have assumed that the resonance is narrow compared to the rate of variation of the gluon distributions. To evaluate Eq. (1) we have used the parton distribution functions of Farrar.[12] The explicit factor of $\frac{1}{9}$ arises from the inclusion of color in the present calculation (the sum over color is already included in $\Gamma_{\phi_c\,\text{tot}}$). The upper bounds which result from this calculation for both $\phi_c(3095)$ and $\phi_c'(3684)$, with $\Gamma_{\text{tot}} = 100$ keV in both cases, are illustrated in Fig. 3. Note that, for

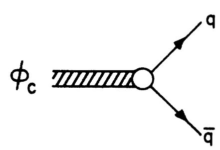

FIG. 2. "Decay" of a ϕ_c into a pair of nonstrange, noncharmed quarks.

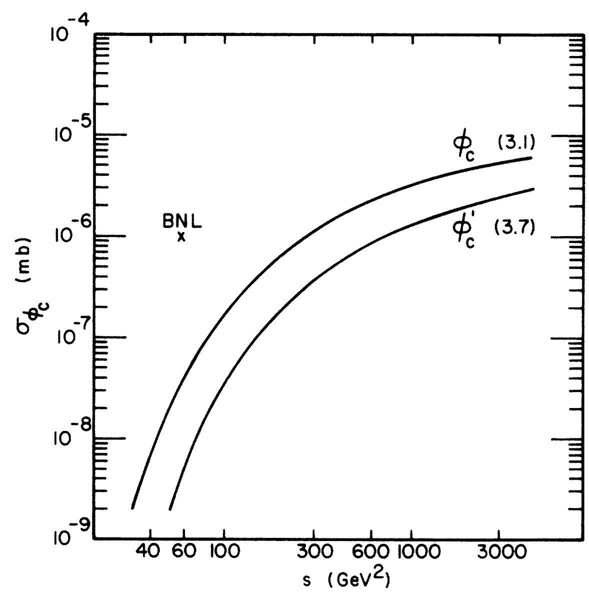

FIG. 3. Upper limit for ϕ_c (3095) and ϕ_c'(3684) production due to nonstrange, noncharmed quark pair annihilation. The values $\Gamma_{\phi_c} = 100$ keV and $M_{\phi_c} = 3.1$ GeV were assumed.

$s \approx 60$ GeV^2, the cross section is bounded by $\approx 5 \times 10^{-35}$ cm^2, to be compared with the reported value of order 10^{-33} cm^2 at BNL.[10] In addition, notice that an upper bound on the contribution of the usual Drell-Yan process, "$q\bar{q}$" $\to \gamma \to \phi_c$, is obtained simply by replacing $\Gamma_{\phi\ \mathrm{tot}}$ by $\Gamma_{\phi_c \to \gamma \to \mathrm{hadrons}}$ in Eq. (1). As remarked earlier, the coupling to hadrons via a photon is 10–30% of the total rate to hadrons, so this is an even less tenable explanation of the observed signal. [See also "note added."]

It is also possible to consider a component of $c\bar{c}$ pairs to be present in the "wee sea" of ordinary (uncharmed) hadrons and then to produce the ϕ_c directly (presumably with large coupling) from the collision of these constituents. However, the magnitude of such a contribution is limited by the success of the usual valence quark model in describing the structure functions of deep-inelastic electron and neutrino scattering. Again, we expect a production rate too small to explain the observed signal.[13]

We turn now to the central results of this paper, which arise from a novel extension of the above mechanism. In particular there exists the possibility that the states containing a $c\bar{c}$ pair are produced, predominantly, not via quark-antiquark annihilation, but rather through the interaction of the vector gluons which are also presumed to be present as constituents of hadrons. The motivation for this suggestion follows because (1) the "experimental" result is that only about half of the proton's momentum seems to reside in the charged constituents[14] (the remainder is presumably carried by the gluons) and (2) within the framework of the asymptotically free picture of $c\bar{c}$ bound states the dominant hadronic decays are calculated *as if* $c\bar{c}$ annihilated into a small number of gluons. In particular, the $\phi_c(3095)$ decays via three gluons whereas its pseudoscalar (η_c) partner (which is nearly degenerate in mass) decays into two gluons. From this picture, the width of the η_c decay into two gluons is estimated to be ≈ 75 times that of the ϕ_c into three gluons, i.e., $\Gamma_{\eta_c} \approx 5$ MeV.[15] This is made plausible by arguing that, in a region well above the masses of the ordinary quarks and not too near the threshold for the production of charmed particles, one can use perturbation theory in the (small) effective strong coupling α_s, which turns out to be ≈ 0.25 here.[2] All this suggests that there may be a fairly sizable η_c production in hadronic reactions via the direct coupling of two gluons. Hence, we imagine the reaction $A + B \to \eta_c + X$ to proceed as shown in Fig. 4, which is described by the formula

$$\frac{d\sigma_{\eta_c}}{dx_L} = \frac{8\pi^2 \Gamma_{\eta_c \to 2g}}{M_{\eta_c}} \left[\int \int dx_1 dx_2 \delta(x_1 x_2 s - M_{\eta_c}{}^2) \delta(x_1 - x_2 - x_L) F_g^A(x_1) F_g^B(x_2) \right], \tag{2}$$

where $s = (p_A + p_B)^2$ and $x_L = 2p_{L\eta_c}/\sqrt{s}$ (p_A is in the $+L$ direction). The function $F_g^A(x_1)$ describes the probability of finding a gluon of momentum fraction x_1 in hadron A (summed over the polarizations of the gluon, where only two are assumed to be relevant here with massless gluons). Note that Γ_{η_c} implicitly contains a sum over gluon species, i.e., over the octet of states in the SU(3)$'$ of color, so that F_g corresponds to the gluon distribution averaged over the various types of gluons. In fact, since normal hadrons are color singlets, all the individual gluon distributions are equal, which is why we need define only a single gluon distribution (with no color index) and express the color combinatorics as a separate factor. For similar reasons, when the amplitude for this process (Fig. 4) is squared, only terms diagonal in the gluon color contribute, which is also necessary for the validity of the simple, factorized form of Eq. (2). With this definition of $F_g^N(x)$ for nucleons, where the gluons carry half the momentum, the appropriate normalization is

$$\int dx\, x F_g^N(x) \approx \tfrac{1}{16}\,. \tag{3}$$

Evaluating the two integrals and specializing to the case of nucleon-nucleon scattering ($F_g^A = F_g^B \equiv F$), we can write Eq. (2) in the simple form

$$E_{\eta_c} \frac{d\sigma}{dp_{L\eta_c}} = (x_1 + x_2) \frac{d\sigma}{dx_L} = \frac{8\pi^2 \Gamma_{\eta_c}}{M_{\eta_c}{}^3} [x_1 F(x_1)][x_2 F(x_2)], \tag{4}$$

where

$$x_{1,2} = (\tau + \tfrac{1}{4} x_L{}^2)^{1/2} \pm \tfrac{1}{2} x_L = \frac{1}{\sqrt{s}} (E_{\eta_c} \pm P_{L\eta_c})$$

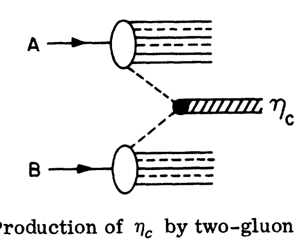

FIG. 4. Production of η_c by two-gluon annihilation.

with $\tau = M_{\eta_c}{}^2/s$. Note that the expression $xF(x)$ is just the gluon *momentum* distribution. The total production cross section assumes the form

$$\sigma_{\eta_c} = \frac{8\pi^2\Gamma_{\eta_c}}{M_{\eta_c}{}^3}\,\tau \int_\tau^1 \frac{dx}{x}\,F(x)F(\tau/x). \qquad (5)$$

Now focus on the rather striking properties of Eq. (4) (which is just the invariant cross section integrated over $p_\perp$, which we have ignored here). The first important feature is the factorization in the variables x_1, x_2.[16] The ratio of the cross section at two different values of x_1 but at the same x_2 must be *independent* of x_2. An experimental test of this property should be very useful in establishing the validity of the picture discussed here. The most exciting prospect suggested by Eq. (4) is that, if this mechanism is dominant, data over a range in s and x_L (i.e., over a range in $x_{1,2}$) will enable one *to determine the gluon distribution* (including the normalization, if M_{η_c} and Γ_{η_c} are known). Thus one can actually hope to test the momentum sum rule, Eq. (3), and check the entire underlying quark-gluon picture. Finally, having determined the gluon distributions in nucleons, one may obtain the gluon distributions for mesons by observing η_c production with meson beams.

Since gluons carry no isospin, the gluon probability distributions must be identical for all members of a given multiplet, e.g., for a proton and a neutron or for a π^+ and π^-. [To the extent that SU(3) or SU(4) is a good symmetry, the same statement would apply to all members in a given SU(3) or SU(4) multiplet.] Similarly, the gluon distributions for particle and antiparticle must be equal. (Of course, the cross sections for $\pi^\pm p \to \eta_c X$ would be equal in a more conventional multiperipheral scheme as well.)

In order to estimate the magnitude of the cross section due to this gluon mechanism, a form must be assumed for the gluon distribution $F(x)$. In the absence of any complete theory, the simple form

$$F(x) = \frac{C_n}{x}(1-x)^n \qquad (6)$$

was used, with $C_n = \frac{1}{16}(n+1)$ chosen to ensure the normalization of Eq. (3). Four cases of possible interest are (1) $n=7$, for which the gluon distribution resembles that of the $q\bar{q}$ sea,[12] (2) $n=5$, which is obtained from a naive extention of the Brodsky-Farrar rules,[17] (3) $n=3$, as if gluons are like valence quarks, and (4) $n=0$, the extreme case of equipartition of momentum. (For pions the analogous choices would be $n=5$, 3, 1, and 0.) To obtain the absolute normalization of the cross section, one must choose values for M_{η_c} and Γ_{η_c}. Lacking any experimental information, we have used values typical of the simple charmonium picture,[2,15] $M_{\eta_c} = 3.05$ GeV and $\Gamma_{\eta_c} = 5$ MeV. In Fig. 5, we display the results of calculations for total η_c production in nucleon-nucleon collisions [Eq. (5)] as a function of energy, using the parameters given above. Note that for $100 < s < 1000$ GeV^2 cross sections between 100 nb and 1 μb are anticipated and that this value is essentially independent of the value of n. Even larger cross sections are expected at the CERN ISR. Depending on the value of n, a dramatic increase with energy, by as much as three orders of magnitude, may be observed from $s = 60$ GeV^2 through $s = 3000$ GeV^2. The behavior of the differential cross section [Eq. (4)] is illustrated in Fig. 6 for energies of $s = 60$, 600, and 3000 GeV^2. (Note that for pp collisions the cross section is symmetric about $X_L = 0$.) Although the detailed form of the curves depends on the particular gluon distribution, the qualitative connection between the increase with s in Fig. 5 and the peaking at $x_L = 0$ in Fig. 6 should be a general result.

A slightly more speculative exercise concerns estimating the production of hadrons of nonzero charm. In the present context we shall assume

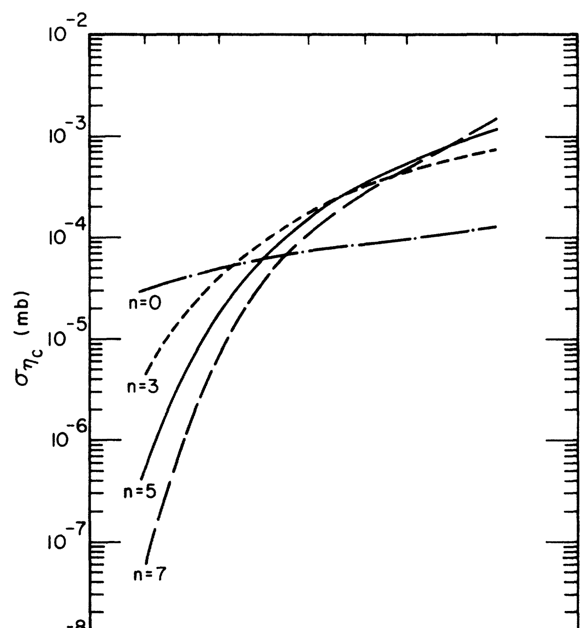

FIG. 5. Cross section, σ_{η_c}, for gluon annihilation into η_c as a function of s, the center-of-mass energy squared. The values of n correspond to the four different gluon distributions discussed in the text [see Eq. (6)]. The values $M_{\eta_c} = 3.05$ and $\Gamma_{\eta_c} = 5$ MeV were assumed.

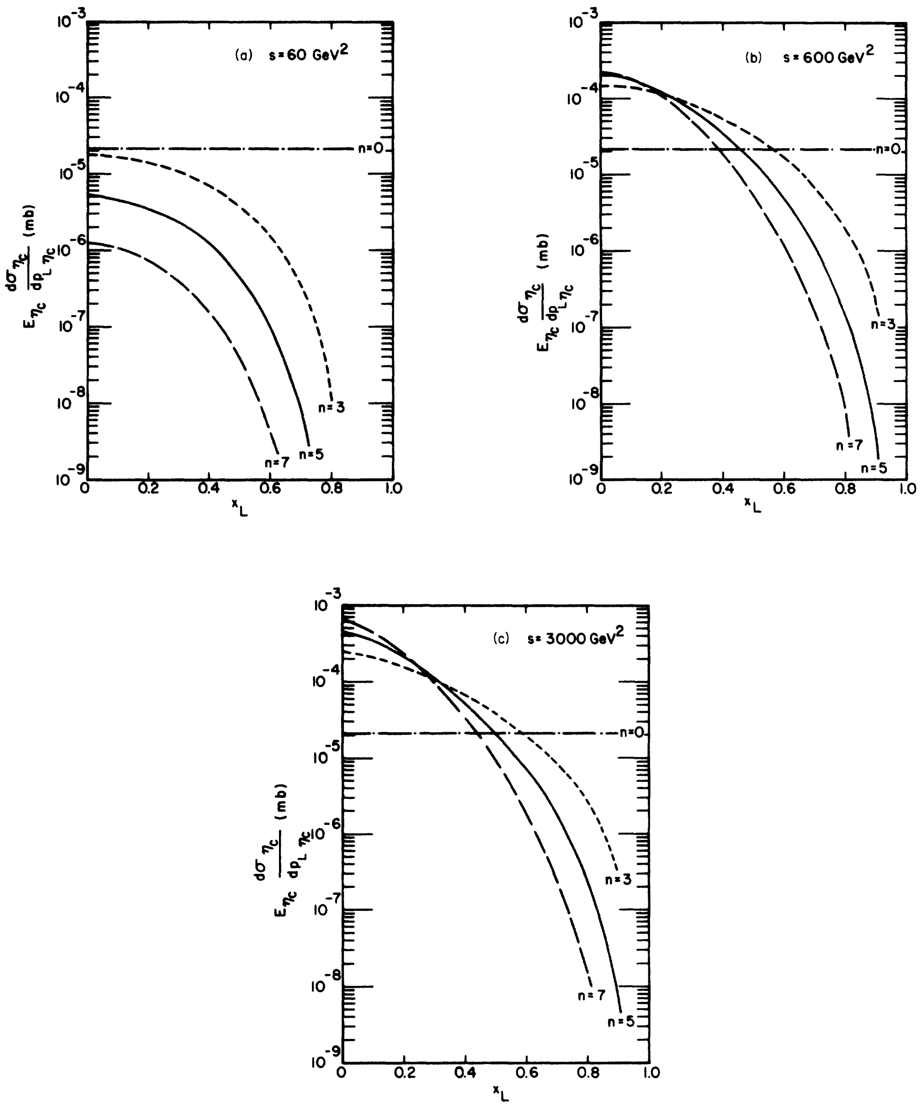

FIG. 6. The invariant differential cross section $E_{\eta_c} d\sigma/dp_L = (x_1 + x_2)d\sigma/dx_L$ as a function of the longitudinal momentum fraction (c.m. system) carried by the η_c. Three energy values are indicated: (a) $s = 60$ GeV^2, (b) $s = 600$ GeV^2, (c) $s = 3000$ GeV^2.

that such hadrons appear when we produce a $c\bar{c}$ pair, not in a bound state. We may estimate this production via the process (two gluons)$\rightarrow c\bar{c}$ as illustrated in Fig. 7. In the spirit of asymptotic freedom, one assumes that, at least well above threshold, the cross section predicted from this diagram (with no final-state interactions) is a good description of the production rate for final states containing two charmed *hadrons*. The process in Fig. 7 is described by

$$\frac{d\sigma_{c\bar{c}}}{dM^2} = \frac{\bar{\sigma}(M^2)}{s} \int_\tau^1 \frac{dx}{x} F(x) F(\tau/x), \tag{7}$$

where M is the mass of the $c\bar{c}$ pair and as before $\tau = M^2/s$. The quantity $\bar{\sigma}(M^2)$ is the cross section for two gluons to produce a $c\bar{c}$ pair of mass M. This is proportional to the corresponding two-pho-

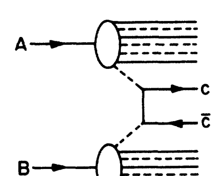

FIG. 7. Pictorial representation of the production of a charmed quark-antiquark pair by two gluons.

ton cross section,[18]

$$\tilde{\sigma}(M^2) = C_{\text{color}} \frac{2\pi\alpha_s^2}{M_c^2}\left[\frac{(\gamma^2+4\gamma+1)\ln(\gamma+\beta\gamma)-\beta\gamma(\gamma+3)}{(\gamma+1)^3}\right]. \tag{8}$$

Here we have defined $y=M^2/4M_c^2$, $\gamma=2y-1$, and $\beta=(2/\gamma)[y(y-1)]^{1/2}$, where M_c is the c quark mass and α_s is the effective coupling. The coefficient C_{color} assumes the value $\frac{16}{3}$ if we sum over all possible color states of the $c\bar{c}$ pair or $\frac{2}{3}$ if we require the pair to be a color singlet. Since it remains unclear how the quarks evolve into hadrons, e.g., whether the process conserves color locally in momentum, the former (more optimistic) example is displayed in subsequent figures.

The quantity most likely to be of general experimental interest is the total cross section integrated from some threshold mass M_{th}^2 up to s, given by

$$\sigma_{c\bar{c}}(s,\tau_0)=\int_{\tau_0}^{1}dx_1\int_{\tau_0/x_1}^{1}dx_2F(x_1)F(x_2)\tilde{\sigma}(x_1x_2s), \tag{9}$$

where $\tau_0=M_{\text{th}}^2/s$. The threshold mass M_{th} is given by twice the mass of the lightest charmed hadron, which we take from theoretical estimates[3] to be about 2.25 GeV, giving $M_{\text{th}}^2\cong 20$ GeV^2. Motivated by the charmonium picture[2] we take $M_c=1.5$ GeV and $\alpha_s=\frac{1}{4}$. In Fig. 8 the form of $d\sigma_{c\bar{c}}/dM^2$ [Eq. (7)] is illustrated for the case $s=600$ GeV^2 with the various gluon distributions discussed above. Note that the total cross section will be determined by the low mass range. The total cross section itself, $\sigma(s,\tau_0)$ [Eq. (9)], is plotted in Fig. 9 as a function of s. It is again amusing that, at typical Fermilab energies, $s\approx 600$ GeV^2, the predicted cross section is ≈ 1 μb, independent of the value of n to within a factor of 2. However, the energy dependence from $s=60$ to $s=600$ GeV^2 is quite sensitive to the parameter n. But for $300<s<1000$ GeV^2 the change should be only an order of magnitude, again almost independent of the details of the gluon distribution. In any case these results are suggestive of rates for charmed hadron production which should be detectable experimentally.

Let us digress for a moment and return to the question of ϕ_c production, for which we found only very small cross sections earlier. By charge-conjugation invariance and color conservation, the ϕ_c couples to a minimum of three gluons.[2] In the spirit of the preceding discussion, the dominant mechanism of ϕ_c production might be the annihilation of two gluons from one hadron with one gluon from another as illustrated in Fig. 10. The calculation of this cross section requires knowledge of the probability distribution to find two gluons in a hadron. We have even less reliable intuition about this quantity than about the single-gluon distribution and we will not present any calculation.

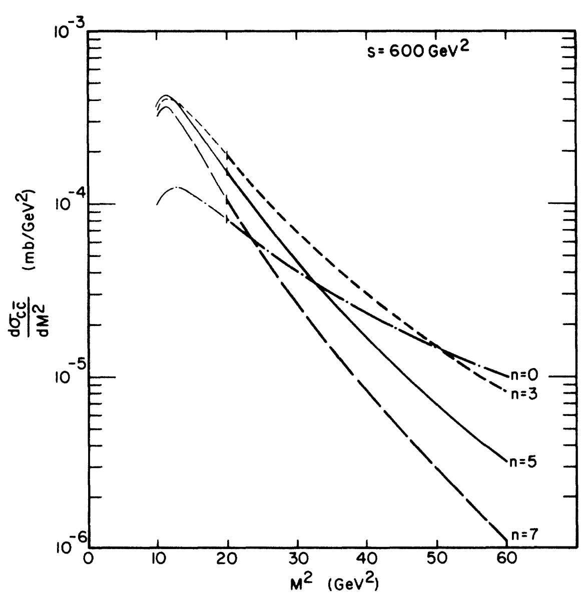

FIG. 8. The $c\bar{c}$ pair cross section $d\sigma_{cc}/dM^2$ as a function of M^2 for $s=600$ GeV^2.

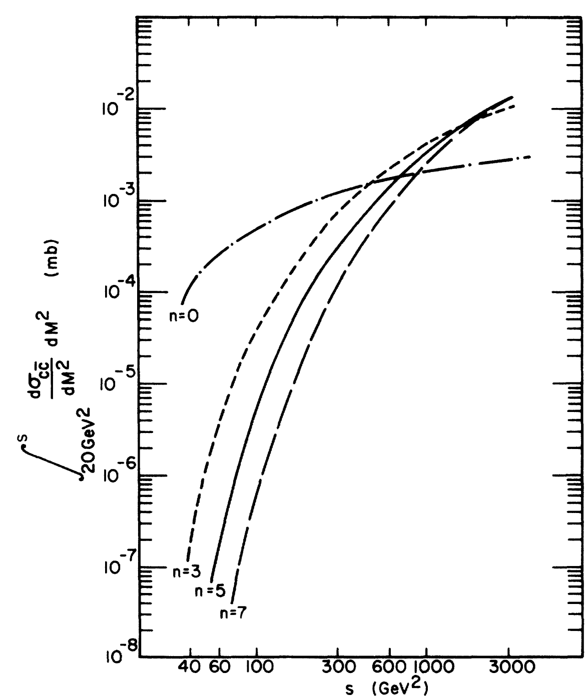

FIG. 9. The estimated total charmed hadron pair cross section, $\sigma(\tau_0, s)$, as a function of s. The value $M_{\text{th}}^2=20$ GeV^2 is used.

However, barring some unforeseen enhancement,[19] this ϕ_c cross section should be smaller than the η_c cross section by at least a factor α_s (α_s/π?). Hence we regard the curves in Fig. 5 for η_c production as likely upper limits for ϕ_c production via similar processes.

It is difficult to compare our estimates with the presently available, somewhat limited, data. Assuming an x_L-independent cross section, Aubert *et al.*[1] estimate a cross section for $pN \to \phi_c X \to e^+e^- X$ at $s = 60$ GeV^2 of order 10^{-34} cm^2 based on their data near $x_L = 0$. If the branching ratio to e^+e^- is $\approx 5\%$, the total production cross section should be of order $\sigma_{\phi_c} \sim 2\times 10^{-33}$ cm$^2 \sim 2$ nb. However, if the cross section is peaked at $x_L = 0$, as suggested in Fig. 6, this is an overestimate by a factor 1.5–4. Preliminary results[20] on ϕ_c production with a neutron beam at Fermilab suggest a cross section per nucleon of about 10^{-31} cm^2 ($x_L > 0.24$). The neutron beam flux peaks around 250 GeV/c, so this preliminary result suggests a ϕ_c cross section comparable to the η_c production estimates in Fig. 5. As discussed above, this is again somewhat larger than one might expect from the mechanisms discussed here. While there are undoubtedly other dynamical sources of production for these particles, as yet we know of none which competes quantitatively with the one discussed here. Perhaps further surprises are in store for us. In the meantime, the estimates discussed in this paper might serve as a guide for experimentalists.[21] We emphasize again the intriguing possibility that if the gluon annihilation mechanism does indeed dominate the production process, the production of the new heavy particles may serve to probe the gluons in a manner quite analogous to the role played by massive photons for the charged constituents of matter.

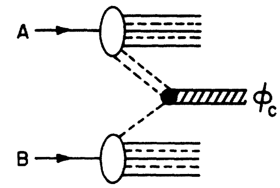

FIG. 10. Pictorial representation of the production of ϕ_c by three gluons.

Note added. Since the original manuscript was written, further data on $\psi(3095)$ production have become available: From Fermilab, see B. Knapp *et al.*, Phys. Rev. Lett. 34, 1044(1975). From the CERN ISR, see F. W. Büsser *et al.*, Phys. Lett. 56B, 482(1975). Using the x distributions given in Fig. 6, we can estimate the total cross section for ψ production: The observed cross section times dimuon branching ratio at Fermilab is 3.6 nb for $|x| \geq 0.24$. The ratio of the total area to the area for $x \geq 0.24$ varies between 1.3 and 3 for the cases shown. Taking the dimuon branching ratio to be 7%, we obtain a total cross section of between 65 and 155 nb. In the ISR experiment, the cross section is measured only in a small neighborhood of $x = 0$ ($|x| \leq 0.025$). $E_\eta d\sigma/dp_\parallel = d\sigma/dy$ in this region is quoted as 7.5 nb. The total cross section depends, of course, on the x distribution assumed. If we take the distributions shown in Fig. 6(c), then we find that σ_T lies between 60 nb ($n = 7$) and 215 nb ($n = 0$), which overlaps the values given from the Fermilab experiment. (With only nine events from the ISR, it is impossible to make any statement about the energy dependence.)

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[2] T. W. Appelquist and H. D. Politzer, Phys. Rev. Lett. 34, 43 (1975); A. De Rújula and S. L. Glashow, *ibid.* 34, 46 (1975).

[3] For a recent review see M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. 47, 277 (1975).

[4] For recent developments in such models, see, for example, E. L. Berger and G. C. Fox, Phys. Lett. 47B, 162 (1973); E. L. Berger, *ibid.* 49B, 369 (1974); G. Ranft and J. Ranft, Nucl. Phys. B83, 285 (1974).

[5] We thank J. Rosner for sharing with us the results of his studies of $t_{\min}$ effects in such processes.

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