Hadronic Production of the New Resonances: Are Gluons Important?

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In analogy with the Drell-Yan model for quark-antiquark annihilation into massive virtual photons, we study the possibility that the (presently) hypothetical pseudoscalar partner (η_c) of the new vector resonance (φ_c) observed at 3095 MeV is produced via gluon-gluon annihilation. This framework allows us to estimate cross sections for η_c production in hadronic reactions and also suggests the interesting possibility of employing η_c production as a probe of the distributions of gluons in hadrons. In addition estimates are made for the production of pairs of charmed hadrons.

One of the most interesting 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.

In this Letter we discuss a novel extension of the Drell-Yan mechanism.[4] In particular we wish to focus attention on the possibility that the states containing a $c\bar{c}$ pair are produced dominantly, not via quark-antiquark interactions as in the usual Drell-Yan picture, but rather through the interaction of gluons. (By the term gluon we are referring to the presumed vector constituent of hadrons which mediates the interaction between the quarks but which is inaccessible to the usual weak and electromagnetic probes.) The motivation for this suggestion follows from (1) the "experimental" result that only about half of the proton's momentum seems to reside in the charged constituents[5] (the remainder is presumably carried by the gluons) and (2) the fact that 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 $\varphi_c(3095)$ 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 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.[6] This is all 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. 1 which is described by the formula

$$E_{\eta_c}\frac{d\sigma}{dp_{L\eta_c}} = (x_+ + x_-)\frac{d\sigma}{dx_L} = \frac{8\pi^2\Gamma_{\eta_c}}{M_{\eta_c}^{\ 3}}[x_+F_g^{\ A}(x_+)][x_-F_g^{\ B}(x_-)], \quad (1)$$

where

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

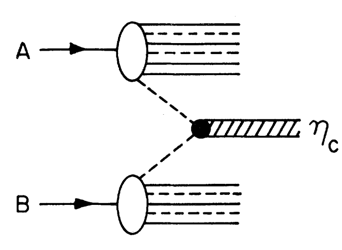

FIG. 1. Production of η_c by two-gluon annihilation. Notation: solid lines for quarks and dashed lines for gluons. The incoming hadrons are labeled A and B.

$x_L = 2p_{L\eta_c}/\sqrt{s}$ (p_A is in the $+L$ direction), and $s = (p_A + p_B)^2$. The function $F_g{}^A(x)$ describes the probability of finding a gluon of momentum fraction x in hadron A, summed over the polarizations and averaged over the SU(3)′octet of gluons. With this definition of $F_g{}^N(x)$ for nucleons, where the gluons carry half the momentum, the appropriate normalization is

$$\int dx\, x F_g{}^N(x) \approx \tfrac{1}{16}. \qquad (2)$$

The total production cross section is given by

$$\sigma_{\eta_c} = \frac{8\pi^2 \Gamma_{\eta_c}}{M_{\eta_c}{}^3} \tau \int_\tau^1 \frac{dx}{x} F_g{}^A(x) F_g{}^B\left(\frac{\tau}{x}\right). \qquad (3)$$

Now focus on the rather striking properties of Eq. (1) (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_+ and x_-.[7] The ratio of the cross sections at two different values of x_+ but at the same x_- must be *independent* of x_-. 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. (1) is that, if this mechanism is dominant, data over a range in s and x_L (i.e., over a range in $x_\pm$) 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. (2), 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.

In the following, we will estimate the magnitude of the cross section for nucleon-nucleon collisions due to this gluon mechanism. To do this, a form must be assumed for the gluon distribution $F(x)$. In the absence of any complete theory, the simple form $F(x) = C_n(1-x)^n/x$ was used, with $C_n = (n+1)/16$ chosen to ensure the normalization of Eq. (2). Four cases of possible interest are $n = 7$, 5, 3, and 0, which integers are motivated elsewhere.[8] Lacking any experimental information, we have used values typical of the simple charmonium picture,[2,6] $M_{\eta_c} = 3.05$ GeV and $\Gamma_{\eta_c} = 5$ MeV. In Fig. 2(a), we display the results of calculations for total η_c production in nucleon-nucleon collisions [Eq. (3)] as a function of energy, using the parameters given above. Note that in the energy range 200–800 GeV^2, cross sections between 100 nb and 1 μb are anticipated and that

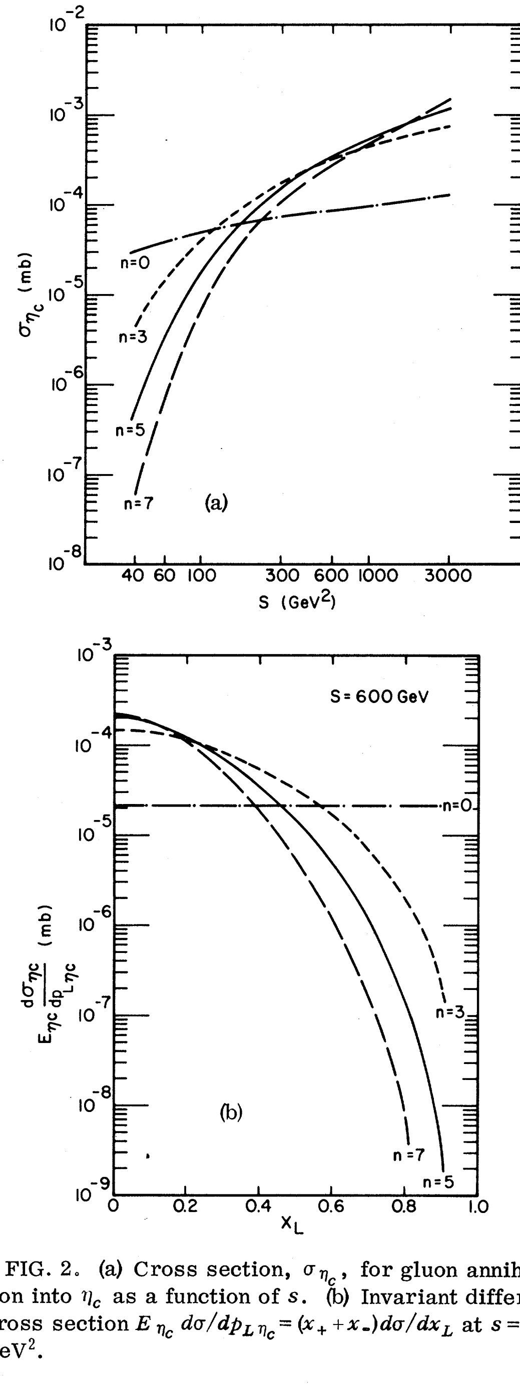

FIG. 2. (a) Cross section, σ_{η_c}, for gluon annihilation into η_c as a function of s. (b) Invariant differential cross section $E_{\eta_c}\, d\sigma/dp_{L\eta_c} = (x_+ + x_-) d\sigma/dx_L$ at $s = 600$ GeV^2.

this value is essentially independent of the value of n. Even larger cross sections are expected at the CERN intersecting storage rings. 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. (1)] is illustrated in Fig. 2(b) for an energy of $s = 600$ GeV^2. Note that for pp collisions the differential cross section is symmetric about $x_L = 0$. Although the detailed forms of the curves depend on the particular gluon distributions, there is a general peaking at $x_L = 0$ (except for $n = 0$) which becomes more pronounced as s increases.

A slightly more speculative exercise concerns estimating the production of hadrons of nonzero charm. In the present context we shall assume 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 $\to c\bar{c}$, where the $c\bar{c}$ pair is treated as free. In the spirit of asymptotic freedom, one assumes that, at least well above threshold, the cross section predicted for this simple process (with no final-state interactions) is a good description of the actual production rate for final states containing two charmed *hadrons*. This process is described by

$$\frac{d\sigma_{c\bar{c}}}{dM^2} = \frac{\tilde{\sigma}(M^2)}{s}\int_\tau^1 \frac{dx}{x} F(x)F\left(\frac{\tau}{x}\right), \qquad (4)$$

where M is the mass of the $c\bar{c}$ pair and as before $\tau = M^2/s$. The quantity $\tilde{\sigma}(M^2)$ is the cross section for two gluons to produce a $c\bar{c}$ pair of mass M. This is proportional to the corresponding two-photon cross section,[9]

$$\tilde{\sigma}(M^2) = C_{\text{color}}(2\pi\alpha_s^{\,2}/M_c^{\,2}) \times \frac{(\gamma^2 + 4\gamma + 1)\ln(\gamma + \beta\gamma) - \beta\gamma(\gamma + 3)}{(\gamma + 1)^3}. \qquad (5)$$

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 was actually used for numerical studies.

The quantity most likely to be of general experimental interest is the total cross section $\sigma(s, M_{\text{th}}^{\,2})$ obtained from Eq. (4) by integrating from some threshold mass $M_{\text{th}}^{\,2}$ up to 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 $\alpha_s = \frac{1}{4}$. As would be expected, the differential cross section [Eq. (4)] falls rapidly with increasing M^2, so that the total cross section $\sigma(s, M_{\text{th}}^{\,2})$ is dominated by the threshold region. We find a total cross section of the order of 1 μb at $s \approx 600$ GeV^2 independent of the value of n (within a factor of 2). As with η_c production, the energy dependence from $s = 60$ to $s = 600$ GeV^2 is quite sensitive to the value chosen for n. In any case, our results suggest rates for charmed-hadron production which should be detectable experimentally.[10] More detailed numerical results are presented in Ref. 8.

Let us turn now to the question of φ_c production. 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. The calculation of the cross section requires knowledge of the probability distribution for finding 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. However, barring some unforeseen enhancement,[11] 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. 2 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 $pN \to \varphi_c X$ at $s = 60$ GeV^2 of order 2×10^{-33} cm^2 (assuming a 5% branching ratio to leptons). However, if the cross section is peaked at $x_L = 0$, as suggested in Fig. 2(b), this is an overestimate by a factor 1.5–4. Preliminary results[12] 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 and so this preliminary result suggests a φ_c cross section comparable to the η_c-production estimates in Fig. 2. As discussed above this is 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. Elsewhere,[8] we elaborate further the model discussed above and review several more conventional possibilities for φ_c production.

In any case it seems likely that further surprises are in store for us. In the meantime, the estimates discussed in this paper might serve as a guide for experimentalists.[13] 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.

We are pleased to acknowledge many stimulating discussions with our colleagues both at the Fermilab and elsewhere. In particular, we thank W. Bardeen, J. Carazzone, B. W. Lee, and C. Quigg for several helpful discussions.

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[1]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974); J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974); C. Bacci *et al.*, Phys. Rev. Lett. 33, 1408 (1974); G. S. Abrams *et al.*, Phys. Rev. Lett. 33, 1453 (1974).

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

[3]For a recent review see M. K. Gaillard, B. W. Lee, and J. L. Rosner, Fermilab Report No. Pub-74/86-THY, 1974 (Rev. Mod. Phys., to be published).

[4]S. D. Drell and T.-M. Yan, Phys. Rev. Lett. 25, 316 (1970).

[5]See, for example, D. H. Perkins, in *Proceedings of the Fifth Hawaii Topical Conference in Particle Physics, Honolulu, Hawaii, 1973,* edited by P. N. Dobson, Jr., V. Z. Peterson and S. F. Tuan (Univ. of Hawaii Press, Honolulu, Hawaii, 1974).

[6]These results appeared originally in the first paper of Ref. 2. See also B. W. Lee and C. Quigg, Fermilab Report No. 74/110-THY, 1974 (unpublished).

[7]A similar factorization does not occur in the ordinary Drell-Yan model because quarks and antiquarks are distinguishable particles with different distributions.

[8]M. B. Einhorn and S. D. Ellis, Fermilab Report No. 75/17-THY, 1975 (unpublished).

[9]J. M. Jauch and F. Rohrlich, *The Theory of Photons and Electrons* (Addison-Wesley, Reading, Mass., 1955), p. 269.

[10]R. D. Field and C. Quigg [Fermilab Report No. 75/17-THY, 1975 (unpublished)] have shown that charmed-particle production based on the exchange of Reggeons is also expected to be quite small ($\lesssim$nb).

[11]Some effect is not impossible if, for example, the presumably large multiplicity of wee gluons plays some role.

[12]B. Knapp *et al.*, Phys. Rev. Lett. 34, 1044 (1975).

[13]We have not discussed how the η_c is actually to be detected. Two reasonable candidates are $p\bar{p}$ and $\gamma\gamma$ final states but it is difficult to ascertain what the branching ratio should be (see, e.g., Refs. 2 and 6). If we take the φ_c as an example, the $p\bar{p}$ branching ratio is $\sim 0.1\%$, whereas if we replace α_s by α in our calculation of Γ_{η_c} to get the $\gamma\gamma$ yield we again find a branching ratio (to $\gamma\gamma$) less than 1%. Thus the situation for two-body modes is not overly encouraging, but we would prefer to wait for the experimental dust to settle before drawing any conclusions.