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Drell-Yan annihilation process and the production of the new 3.1- and 3.7-GeV resonances*

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We investigate the implications of the SLAC data on production and decay of the new 3.1-GeV resonance for the cross section observed at Brookhaven assuming dominance of the Drell-Yan quark-antiquark annihilation mechanism. Consistency of the predicted magnitude with experiment may be obtained, given certain assumptions which shed light on the nature of the new resonance. Corresponding expectations for the 3.7-GeV resonance are discussed.

The recent discovery of heavy vector particles at SLAC and Brookhaven[1] has generated considerable excitement. In an attempt to shed additional light on the particles' nature (we call the 3.1-GeV resonance "ψ") we have investigated the possibility of explaining the production cross section observed at Brookhaven for the ψ using the SLAC experimental results and the Drell-Yan[2] quark-antiquark annihilation process of Fig. 1(a). We employ the recently developed parton distribution functions[3-5] for quarks and antiquarks inside a nucleon.

To begin, let us first suppose that the 3.1-GeV resonance, ψ, though possibly composed of a charmed quark-antiquark pair, $\mathcal{P}'$-$\bar{\mathcal{P}}'$, decays into only normal uncharmed hadronic states. This is, for instance, consistent with the ideas of Appelquist and Politzer,[6] in which ψ has a mass below the charmed quark-antiquark pair threshold and hence decays via electromagnetic and gluon-induced mixing to normal quark decay modes. Such a picture is capable of providing a natural explanation of the observed size of the effective hadronic and e^+e^- coupling constants of ψ. This allows us to estimate these two important effective coupling constants, $g_{\psi e^+e^-}$ and $\langle g_{\psi a\bar a}\rangle$, the ψ coupling to e^+e^- pairs and its average effective coupling to $\mathcal{P}$ and $\mathcal{N}$ quarks, respectively. (We ignore strange-quark couplings for the moment.) In so doing we implicitly assume that ψ does not decay any appreciable portion of the time to visible channels which explicitly include nonhadronic particles, as well as hadrons, or to hadronic channels which may not be reasonably thought of as a separated $q\bar q$ pair with intervening vacuum polarization. For instance, decay modes, which include an on-shell photon (which is not a decay product of an unstable final state hadron) as well as several hadrons, would be counted in the SLAC experiment as hadronic channels, but should not be included in estimating $\langle g_{\psi a\bar a}\rangle$. Any contribution from such "pseudohadronic" channels to the hadronic cross section observed at SLAC will thus reduce the magnitude of the Drell-Yan annihilation cross section due to normal quarks.

If we take ψ to have simple γ_μ coupling to quarks and electrons, we obtain [see Fig. 1(b)]

$$\sigma^{\text{Resonant}}_{e^+e^-\to\psi\to i\bar i}(s) = \frac{4\pi}{3}\,\frac{g_{\psi e^+e^-}{}^2}{4\pi}\,\frac{g_{\psi i\bar i}{}^2}{4\pi}\,\frac{m_\psi{}^2}{(s-m_\psi{}^2)^2+m_\psi{}^2\Gamma_\psi{}^2}\,. \quad (1)$$

We now make the parton-model-like replacement

$$\sigma^{\text{Res}}_{e^+e^-\to\psi\to\text{hadrons}} \equiv \sum_a \sigma^{\text{Res}}_{e^+e^-\to\psi\to a\bar a}$$

$$(a=\mathcal{P} \text{ or } \mathcal{N} \text{ quark})\,.$$

In other words, we replace the sum over all purely hadronic channels by the sum over uncharmed, nonstrange, quark-antiquark pairs. Clearly this must be regarded as an order-of-magnitude estimate. In this approximation the total width of ψ is (ignoring quark masses)

$$\Gamma_\psi = \frac{m_\psi}{3}\left(\sum_a \frac{g_{\psi a\bar a}{}^2}{4\pi} + 2\frac{g_{\psi e^+e^-}{}^2}{4\pi}\right) \quad (2)$$

(the factor of 2 assumes μ-e universality), and the integrated total cross section is

$$I \equiv \int \sigma^{\text{Res}}_{e^+e^-\to\psi\to\text{all}}(s)\,ds = 4\pi^2\frac{g_{\psi e^+e^-}{}^2}{4\pi}\,. \quad (3)$$

The SPEAR data are said to yield[7] partial widths of order

$$\Gamma(\psi\to e^+e^-) \approx 2.5 \text{ keV},$$
$$\Gamma(\psi\to \text{hadrons}) \approx 60 \text{ keV}\,, \quad (4)$$

corresponding to

$$\frac{g_{\psi e^+e^-}{}^2}{4\pi} \approx 2.4\times 10^{-6}, \quad \frac{I}{2m_\psi} \approx 6000 \text{ nb MeV}\,. \quad (5)$$

Rough integration of the data yields somewhat larger values (by approximately 30%). For definiteness we take the values (5). For future reference we define the branching ratio

$$R_\psi \equiv \frac{\sum_a g_{\psi a\bar{a}}{}^2/4\pi}{g_{\psi e^+e^-}{}^2/4\pi}\,, \tag{6}$$

which we approximate as being 25.

We can now proceed with our consideration of the Drell-Yan annihilation mechanism. Let us begin by calculating only those contributions due to normal quarks [$q=\mathcal{P}$ or $\mathcal{N}$ in Fig. 1(a)]. Following Ref. 8 (see also Ref. 4) we obtain (Q^2 is the e^+e^- mass squared)

$$\int \sigma^{\rm Res}_{p+p\to\psi+X\to e^+e^-+X}(Q^2)\,dQ^2 = \frac{4\pi^2}{R_\psi+2}\sum_a \frac{g_{\psi a\bar{a}}{}^2}{4\pi}\int [f_a(x_1)f_{\bar{a}}(x_2)+f_{\bar{a}}(x_1)f_a(x_2)]\,\delta(x_1x_2s-m_\psi{}^2)\,dx_1dx_2\,. \tag{7}$$

[We explicitly exhibit the inclusion of antiquarks as well as quarks from each proton in Fig. 1(a). The $f_a(x)$ and $f_{\bar{a}}(x)$ in (7) represent the probabilities of finding a quark or antiquark, respectively, in a proton with a fraction x of the proton's linear momentum, P, as $P\to\infty$.] Note that for our order-of-magnitude calculations we ignore off-shell dependence of $g_{\psi a\bar{a}}{}^2/4\pi$. This is fairly well justified as the distribution functions, and hence the contributions in (7), become small when the quarks are substantially off the shell. In computing the cross section to compare with experiment we use the precise distribution-function forms and normalizations determined in Ref. 3 (see also Ref. 4 and Ref. 5) using a combination of high-transverse-momentum scaling laws[9] (or direct dynamical calculations[3]), sum-rule constraints, and SLAC deep-inelastic data. In particular, the form of a valence-quark distribution function is very different from that of a sea-quark distribution function. ("Sea" quarks are those responsible for Pomeron-type behavior in deep-inelastic scattering.) For instance, the sea-quark distribution function is suppressed as $x\to 1$ by an extra factor of $(1-x)^4$. In comparing to the Be data we average over proton and neutron targets (using isospin symmetry) and make the replacement

$$\frac{g_{\psi a\bar{a}}{}^2}{4\pi} \approx \tfrac{1}{2}R_\psi \frac{g_{\psi e^+e^-}{}^2}{4\pi}\,, \tag{8}$$

corresponding to equal coupling of $\mathcal{P}$ and $\mathcal{N}$ quarks to ψ. The computed cross section (per nucleon) at $p_{\rm lab}=28.5$ GeV/c is [using (5) and ignoring threshold effects for the moment]

$$\int \sigma^{\rm Res}_{p+N\to\psi\to e^+e^-+X}(Q^2)\,dQ^2 = 1.1\times 10^{-8}\ \text{mb}\,. \tag{9}$$

This is to be compared with an experimental cross section of approximately 10^{-7} mb, estimated in Ref. 1 by assuming particular distributions for the observed ψ particle as a function of its longitudinal and transverse momenta outside the region covered by the experimental counters. As pointed out in Ref. 8, it is of great interest to *measure* these dependences as they provide a detailed test of the quark distribution functions, including their associated transverse-momentum dependence (discussed in Ref. 8), proposed in Refs. 3 and 4. It is not presently clear how use of these theoretically expected forms would modify the result quoted above. Thus one should probably not trust the experimental number as more than an order-of-magnitude estimate. We also reiterate that the result (9) may be too low if the values (5) are, in fact, somewhat too small.

Before proceeding further we must discuss the effect upon the estimate (9) of properly including threshold effects. At $p_{\rm lab}=28.5$ GeV/c, the maximum allowed lepton pair or resonance mass is

$$\sqrt{s} - 2m_{\rm proton} \approx 5.64\ \text{GeV}$$

since two protons must appear in the final state. (In parton-model terms, the "cores" left behind by the annihilating quark and antiquark can be thought of as having masses at least as large as that of a proton.) Because the ψ mass is not so very much smaller than this maximum possible

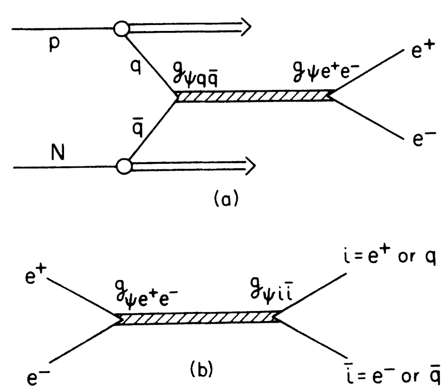

FIG. 1. (a) Drell-Yan quark-antiquark annihilation diagram for producing the new particle ψ. (b) ψ production and decay into e^+e^- or quark-antiquark pair in e^+e^- collisions.

value, inclusion of these effects will result in a non-negligible reduction in the estimate (9). A technique for incorporating thresholds in the parton annihilation diagram was developed in Ref. 8. It consists of exposing the transverse-dependence of the distribution functions, f, and of replacing the δ function of Eq. (7) by a more precise form, which includes all corrections of order $m_{\text{core}}/\sqrt{s}$ relative to 1, involving these transverse momenta and the core masses. As threshold is approached, satisfaction of the δ-function condition is possible for a diminishing range of the transverse-momenta integrations. The range of integration becomes zero when Q^2 or $m_\psi{}^2 = s - 4m_{\text{core}}\sqrt{s} \approx (\sqrt{s} - 2m_{\text{core}})^2$. Thus given core masses and given the transverse-momentum dependence of the various wave function components (the natural power-law forms, derived in Ref. 8, are scaled by the core masses), we can calculate the effect upon (9) of the threshold. We find that, for core masses equal to the proton mass, (9) is reduced by about 50%, yielding for the integrated ψ cross section at $p_{\text{lab}} = 28.5$ GeV/c

$$\int \sigma^{\text{Res}}_{\cdots} \approx 0.45 \times 10^{-8} \text{ mb}. \tag{10}$$

As p_{lab} increases, larger values are, of course, obtained. For instance, at $p_{\text{lab}} = 33.0$ GeV/c (the maximum Brookhaven energy) the cross section is predicted to be twice its value at $p_{\text{lab}} = 28.5$ GeV/c.

We can now proceed to discuss other contributions. First, as a point of reference, we give the value corresponding to Eq. (10) which one would obtain if ψ coupled only to λ and $\bar{\lambda}$ quarks (at both SPEAR and Brookhaven) rather than to nonstrange quarks. Because of the necessity, in this case, of annihilating a q and $\bar{q}$, both of which are "sea"-quark nucleon-wave-function components (because of the nucleon quantum numbers λ's and $\bar{\lambda}$'s can be present only as $q\bar{q}$ sea pairs, in addition to the usual $\mathcal{P}$, $\mathfrak{N}$ valence quarks), with consequent extra damping as $x \to 1$, one obtains (keeping the core mass equal to a proton mass) a result lower than that of Eq. (10) by a factor of approximately *200*. Thus λ and $\bar{\lambda}$ annihilation cannot be a major factor in ψ production at Brookhaven.

However, it is not impossible for charmed quark-antiquark annihilation to play a substantial role. The reason is that the coupling of ψ to $\mathcal{P}'$-$\bar{\mathcal{P}}'$ is not expected to be small (no electromagnetic or off-shell gluon diagrams are required to introduce mixing, as they were for normal quarks; the ψ is already primarily $\mathcal{P}'$-$\bar{\mathcal{P}}'$). For instance, the analog of (2) for the ρ width (for which the direct decay mode should dominate) yields

$$\frac{g_{\rho\mathcal{P}\bar{\mathcal{P}}}{}^2}{4\pi} + \frac{g_{\rho\mathfrak{N}\bar{\mathfrak{N}}}{}^2}{4\pi} \approx \tfrac{3}{7}\,. \tag{11}$$

[Similar estimates in the case of the ϕ are more difficult owing to the nearness of the K^+K^- (i.e., $\lambda\bar{\lambda}$) threshold.] We adopt this value for $g_{\psi\mathcal{P}'\bar{\mathcal{P}}'}{}^2/4\pi$.

This large coupling could not be utilized were it not that $\mathcal{P}'$-$\bar{\mathcal{P}}'$ annihilation to produce a resonance below $\mathcal{P}'$-$\bar{\mathcal{P}}'$ threshold is possible in the Drell-Yan mechanism since the quarks $q, \bar{q}$ in Fig. 1(a) are off-shell. Any suppression associated with this off-shell requirement is incorporated, by definition, in the probability distribution functions for $\mathcal{P}'$-$\bar{\mathcal{P}}'$ pairs in nucleons. As for λ-$\bar{\lambda}$ pairs $\mathcal{P}'$ and $\bar{\mathcal{P}}'$ quarks occur only in the nucleon "sea" wave-function component. Thus the appropriate $\mathcal{P}'$-$\bar{\mathcal{P}}'$ distribution-function forms are the same as for the λ-$\bar{\lambda}$ case, but their absolute magnitude could be smaller; after all, a larger mass sets the scale for charmed quarks as compared to their uncharmed counterparts. The most important effect, however, is the possibility that the charmed "cores" left behind by the charmed quarks in Fig. 1(a) are heavier than their uncharmed counterparts and, thus, push the entire process nearer threshold.

However, let us momentarily ignore both effects and make the sea SU(4) symmetric[10] [instead of SU(3) symmetric]. Because the *total* sea contribution to deep-inelastic scattering is fairly determined by the deep-inelastic data (see Ref. 3), one must in general decrease the magnitude of each quark type's sea component from that appropriate to the SU(3)-symmetric case by a factor of

$$\sum_{q=\mathcal{P}\mathfrak{N}\lambda} e_q{}^2 \Big/ \sum_{q=\mathcal{P}\mathfrak{N}\lambda\mathcal{P}'} e_q{}^2 = \tfrac{12}{20}$$

in going to the SU(4)-symmetric situation. Adopting this approach and using

$$g_{\psi\mathcal{P}'\bar{\mathcal{P}}'}{}^2/4\pi \approx \tfrac{3}{7}\,,$$

we would then obtain a $\mathcal{P}'$-$\bar{\mathcal{P}}'$ annihilation contribution to the ψ Brookhaven cross section a factor of

$$\frac{g_{\psi\mathcal{P}'\bar{\mathcal{P}}'}{}^2/4\pi}{R_\psi g_{\psi e^+e^-}{}^2/4\pi} \frac{1}{200} \left(\tfrac{12}{20}\right)^2 \approx 13 \tag{12}$$

times the result of Eq. (10). Thus both the normal-quark and charmed-quark contributions to ψ production could be comparable and their combined contribution could explain the Brookhaven data.

However, as mentioned, it is possible that the core masses that one should associate with charmed-quark annihilation should be larger than the proton mass. This is sensitive to the communication between the two cores of Fig. 1(a). For instance, the undesirable charm quantum numbers of the two cores could be neutralized by a vacuum-polarization-type communication between their "wee," or slow-moving, members. (Such communication must occur in any case—regardless of charm—in order that objects with quark quantum numbers not appear in the final state.) In this instance, use of core masses the size of the proton mass could be justified. To demonstrate the importance of this assumption we give results appropriate to core masses twice the proton mass. At $p_{\rm lab}=28.5$ GeV/c the factor (12) is multiplied by 10^{-4} and the charmed-quark contribution becomes negligible. With such large core masses associated with charmed quarks, increasing the energy has a dramatic effect. For instance, increasing $p_{\rm lab}$ to 33 GeV/c causes the charmed-quark contribution to rise by a factor of 200.

At this point certain alternative possible pictures can be explored. First of all, any substantial contribution to the "hadronic" SLAC cross sections from "pseudohadronic" decay modes will result in an experimentally unacceptable prediction for the Brookhaven production cross section as a result of normal-quark annihilation. However, such decay modes, if uncharmed, would not affect our calculation of the $\mathcal{P}'$-$\bar{\mathcal{P}}'$ annihilation contribution. Secondly, it is clearly not possible to suppose that ψ decays using charmed hadron modes. This would necessarily (unless ψ was *just* above charmed threshold) imply a small value of $g_{\psi\mathcal{P}'\bar{\mathcal{P}}'}$ (and, of course, still smaller values for $g_{\psi a\bar{a}}$). The charmed-quark annihilation mode would then be greatly suppressed, and the uncharmed-quark annihilation mode would contribute substantially less than the amount in Eq. (10), in contradiction to experiment.

The identification of ψ as the weak-interaction neutral vector boson, Z, may be in difficulty. If we insist that the normal-quark-mode contribution is too small on its own to explain the data, and that some $\mathcal{P}'$-$\bar{\mathcal{P}}'$ annihilation is necessary for consistency, then $g_{\psi\mathcal{P}'\bar{\mathcal{P}}'}$ must be large and Z must be below charmed-quark threshold. This combination would seem fortuitous in view of the presumed weak or electromagnetic-like coupling of Z to all particles and the absence of any immediate connection between the neutral vector boson and charmed-quark masses.

We now turn to the question of background. The background in the e^+e^- channel at Brookhaven is presumably precisely that due to the original off-shell photon, Drell-Yan annihilation mechanism. This has been precisely calculated in Ref. 8, for example. At $Q^2=(3.1\text{ GeV})^2$ ($p_{\rm lab}=28.5$ GeV/c) including protonlike core masses

$$\left(\frac{d\sigma}{dQ^2}\right)_{p+N\to``\gamma"+X\to e^+e^-+X}(Q^2=m_\psi{}^2) = 5.4\times10^{-10}\ \text{mb/GeV}^2\,. \tag{13}$$

In comparison $d\sigma/dQ^2$ due to the resonance is, very approximately (we use 25 MeV as the experimental mass resolution),

$$\left(\frac{d\sigma}{dQ^2}\right)^{\rm Res}_{p+N\to\psi+X\to e^+e^-+X} \approx \frac{10^{-7}\text{ mb}}{2m_\psi\times 25\text{ MeV}} \approx 6.7\times10^{-7}\ \text{mb/GeV}^2\,, \tag{14}$$

implying a background-to-resonance ratio of about 1 : 1000. The prediction using Eq. (10) for the resonance cross section (i.e., keeping only normal-quark modes) is 1 : 70.

At this point it is important to stress, once again, that the predictions given depend critically upon the quark distribution functions we have employed. Those used (from Ref. 3) can be altered slightly without violating either theoretical prejudices or deep-inelastic data. In Ref. 8 a particularly extreme example of such an alteration was investigated (the sea distribution is given an anomalous hump at moderate x values; as opposed to other possible variations, sea alterations of this type obviously result in the largest effects), with the result that the theoretical cross sections we have quoted could be increased by as much as a factor of 10. This extreme case, however, does have undesirable effects upon the valence-quark distribution functions extracted using the sea forms, sum rules, and deep-inelastic data according to the methods of Ref. 3. [For instance, for the form we are considering, Eq. (3.7) of Ref. 8, there are no longer exactly 2 valence $\mathcal{P}$ quarks for every 1 valence $\mathfrak{N}$ quark, and the sea begins to carry a bit too much of the total momentum of the proton for consistency with neutrino data.] Thus, practically speaking, one could relatively easily increase the calculated cross section values quoted here by up to a factor of 3–5. Thus such resonance production cross sections may, eventually, end up putting additional precision constraints upon quark distribution functions.

Now let us turn to the 3.7-GeV resonance. For lack of more precise information we assume that its branching ratios and widths are the same as those of the 3.1-GeV ψ resonance. The only alteration to the Brookhaven production cross section is thus due to the increased mass of the reso-

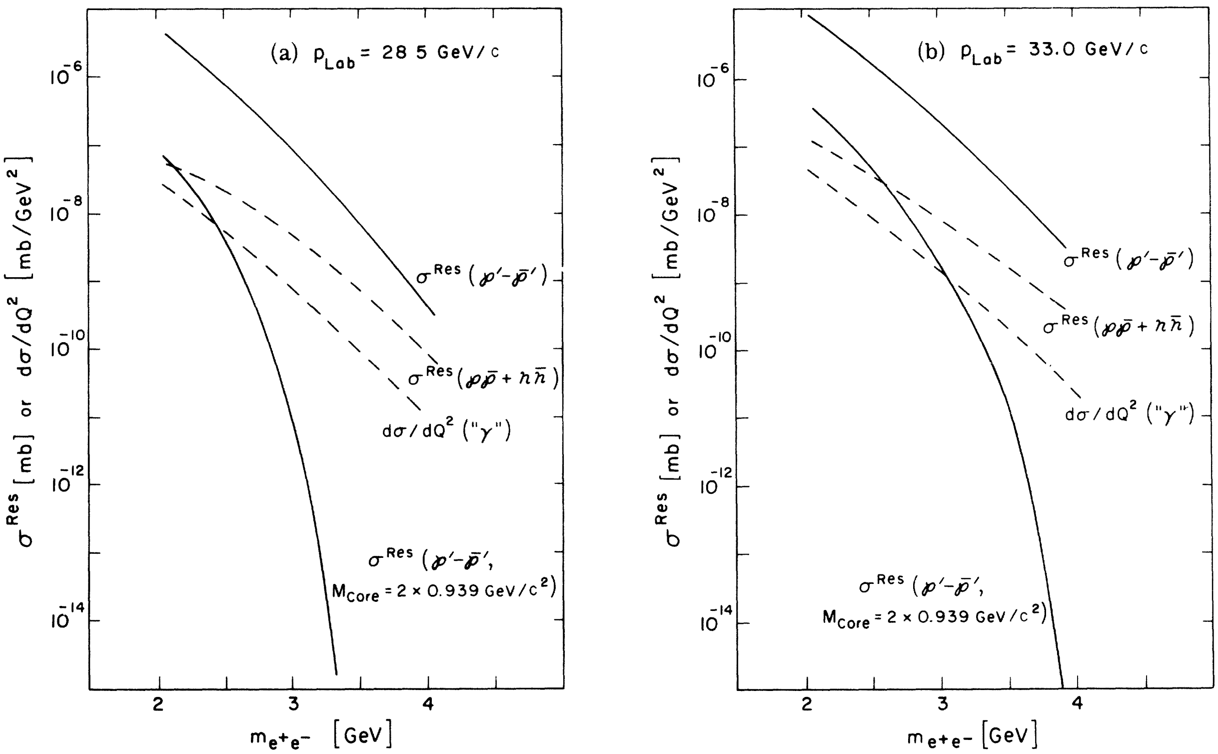

FIG. 2. (a) p_{lab} = 28.5-GeV/c results for σ^{Res} $(a\bar{a})$, σ^{Res} $(\mathcal{P}'\bar{\mathcal{P}}')$, and $d\sigma/dQ^2$ (background), in mb, mb, and mb/GeV^2, respectively. See text for details. (b) As for (a), with p_{lab} = 33.0 GeV/c.

nance. At fixed energy, increasing the mass depresses the cross section.

For the normal-quark annihilation mode this suppression should be a factor of about 9 at p_{lab} = 28.5 GeV/c, whereas the $\mathcal{P}'$-$\bar{\mathcal{P}}'$ mode is suppressed by a factor of 20 in going from $Q^2 = (3.1\ \text{GeV})^2$ to $Q^2 = (3.7\ \text{GeV})^2$. (Both factors assume protonlike core masses; if the charmed core has twice the proton mass, the $\mathcal{P}'$-$\bar{\mathcal{P}}'$ contribution is 0 for this and higher values of Q^2.) The failure[11] to observe the higher-mass resonance at Brookhaven, at the same cross section level as the 3.1-GeV resonance, is thus not entirely unexpected. Once again, holding Q^2 fixed, one may also predict the cross section changes expected as s, the total energy, varies. At $Q^2 = (3.7\ \text{GeV})^2$ the normal-quark annihilation contribution rises by a factor of 3 as p_{lab} changes from 28.5 to 33.0 GeV/c (the maximum possible Brookhaven energy), while the charmed-quark annihilation contribution should rise by a factor of 4. (For the larger core masses, the $\mathcal{P}'$-$\bar{\mathcal{P}}'$ contribution is still negligible at this higher energy.) This distinction, in principle, should allow an experimental separation of the two possible production modes, the charmed mode being more rapidly varying in Q^2 and s.

In summary, we present in Figs. 2(a) and 2(b) the cross sections predicted at p_{lab} = 28.5 and 33.0 GeV/c as a function of resonance mass for normal-quark annihilation, $\mathcal{P}'$-$\bar{\mathcal{P}}'$ annihilation, and for the single-photon background. Core masses equal to that of the proton are employed. All coupling constants and widths are held fixed at the values discussed previously for the 3.1-GeV ψ resonance. Also given in Figs. 2(a) and 2(b) is the $\mathcal{P}'$-$\bar{\mathcal{P}}'$ annihilation contribution calculated with core masses twice that of the proton.

Thus mechanisms of the Drell-Yan type seem capable of yielding the observed Brookhaven cross section; further, more detailed measurements of the p_{lab} dependence of the cross section, coupled with more precise numbers at each experimental point, could, however, rule out this explanation. Meanwhile, we may optimistically view the Brookhaven experiment as finally providing some indication of the presence of this long-sought-for parton-model process.

I would like to thank R. Blankenbecler, L. Wolfenstein, L.-F. Li, and R. Willey for helpful discussions. After the present work was completed I was made aware that a similar effort is in progress at SLAC, and that G. Chu is working on a closely related approach.

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[1]J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974); J. J. Aubert *et al.*, *ibid.* 33, 1404 (1974). The vector nature of this particle cannot at the time of writing be regarded as established. However, we shall assume that this new particle is indeed 1^-.

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[3]J. F. Gunion, Phys. Rev. D 10, 242 (1974).

[4]G. Farrar, Nucl. Phys. B77, 429 (1974).

[5]S. J. Brodsky and R. Blankenbecler [Phys. Rev. D 10, 2973 (1974)] also discuss the basic theoretical considerations.

[6]T. Appelquist and H. D. Politzer, Phys. Rev. Lett. 34, 43 (1975).

[7]These numbers come from various private communications.

[8]G. Chu and J. F. Gunion, Phys. Rev. D 10, 3672 (1974). Note that we ignore the colored degrees of freedom, which if included could lead to serious trouble, suppressing all calculated contributions by a factor of 9 (3 in estimating a typical colored-quark coupling constant from total decay data, and 3 from the requirement that only quarks of the same color be allowed to annihilate).

[9]G. Farrar and S. J. Brodsky, Phys. Lett. 31, 1153 (1973); V. Muradyn and A. Tavkhelidze, Nuovo Cimento Lett. 7, 719 (1973).

[10]Note that the very weak mixing allowed by the model of Ref. 6, applicable in describing ψ decay to normal quarks, is not, generally, applicable in considering the charmed quark-antiquark pair contamination in normal hadrons. This is because the necessity (due to the presumed color-singlet nature of ψ) of using three off-shell colored gluons to accomplish hadronic decay of ψ does not hold in the latter situation. Introduction of a single off-shell colored gluon to create a $\mathcal{P}'-\bar{\mathcal{P}}'$ pair, starting from the valence state of a normal hadron, does not cause the hadron to become colored. Thus the same diagram clearly applies to all sea-quark pair creation ($\mathcal{P}, \mathcal{N}, \lambda, \mathcal{P}'$), and SU(4) symmetry is not, *a priori*, impossible.

[11]Private communication from the Ting group.