PHYSICAL REVIEW D VOLUME 15, NUMBER 5 1 MARCH 1977

Comment on P-state dominance in the hadronic production of narrow resonances

C. E. Carlson*†
Department of Physics, College of William and Mary, Williamsburg, Virginia 23185

R. Suaya‡
Department of Physics, McGill University, Montreal, Quebec H3C3G1
(Received 5 April 1976)

We show that the process $gg \rightarrow P \rightarrow$psion + a (a = hadron or γ, g = gluon) explains the observed features in the hadronic production of ψ/J and ψ' and the absence of hadronic production of ψ'', ψ''', etc.

Recent experiments[1] have observed the $\psi'(3.7)$ in p-Be collisions at a rate of approximately 1.7% that of the $\psi/J(3.1)$ in the $e\bar{e}$ channel. Previously,[3] we proposed that the mechanism responsible for the production of ψ particles is the one displayed in Fig. 1. That is, the ψ particles are not produced directly, but come from the decays of P-wave intermediate states,[2,3] which in turn are produced from collisions of gluons which are constituents of the initial hadrons.[4] Here we extend the model straightforwardly to calculate production of the ψ' and explain the absence of higher $J^{PC}=1^{--}$ psion states in hadronic collisions.

The total cross section is given simply as

$$\sigma_{\text{total}} = \sum_n \frac{8\pi^2}{{M_{nP}}^3} \sum_J \sum_a \frac{\Gamma(n^3P_J \rightarrow gg)\,\Gamma(n^3P_J \rightarrow \psi + a)}{\Gamma_{\text{total}}(n^3P_J)} \times \tau \int_\tau^1 \frac{dx}{x} f_g(x) f_g\left(\frac{\tau}{x}\right). \quad (1)$$

In this equation, each P state is labeled by its principle quantum number n and M_{nP} is its mass (we neglect the fine and hyperfine splitting), Γ is the particular decay width, $\tau = {M_{nP}}^2/s$, and $f_g(x)$ is the probability distribution function in momentum for the gluons in the hadron, which we take to be[5]

$$f_g(x) = \frac{n+1}{16}\,\frac{1}{x}(1-x)^n. \quad (2)$$

The very small production of the higher vector states follows from the important remark that the sum over P states receives large contributions only from those few states which are below the threshold for decay into charmed particles. The reason is that the total decay width of a P state whose mass is lower than the charm-production threshold is approximately given by its two-gluon decay (a decay mechanism which violates the Okubo-Zweig-Iizuka rule). On the other hand, for the P states which can decay into charmed particles (Okubo-Zweig-Iizuka–allowed) we expect that

$$\Gamma(n^3P_J \rightarrow gg) \ll \Gamma_{\text{total}}(n^3P_J). \quad (3)$$

This fact, aided by the factor ${M_{nP}}^{-3}$ and the diminishing phase space, ensures that contributions from higher P states are negligible.

The observed widths of the psions and the rise in R indicate that the threshold for decay into charmed particles is about 4 GeV. This leads us to predict that the higher vector states observed at SPEAR (at 4.1, 4.45, ... GeV) can be produced in hadronic collisions only at negligible rates. Further, the ratio of ψ' to ψ/J hadronic production will be small because only photon decays of the 3P can feed into the ψ' (the mass difference between the 3P and ψ' is expected to be about 200 MeV so that either quantum-number conservation or phase space prevents any decay $3P \rightarrow \psi'$ + hadron). The explicit calculation shown below confirms that the ratio of ψ' to ψ/J hadronic production given by our model is of the right magnitude. Also, it is clear that if the structure seen at 6 GeV (see Ref. 6) in hadronic collisions is real and is due to a bona fide resonance it cannot, within the context of this model, be a bound state of the standard SU(4) quarks (u, c, s, d). We shall elaborate on this point later.

Let us now consider quantitatively the two lowest states, $\psi/J(3.1)$ and $\psi'(3.7)$. For the ψ/J both the 2P (3.44) and 3P (3.95) can contribute. The decay processes involved are $2P \rightarrow \psi/J + \gamma$, $3P \rightarrow \psi/J + \gamma$, $3P \rightarrow (\psi' \rightarrow \psi/J + \text{anything}) + \gamma$, and $3P \rightarrow \psi/J + \omega$.[7]

As input for this calculation we need the widths of the P waves into two gluons. This calculation

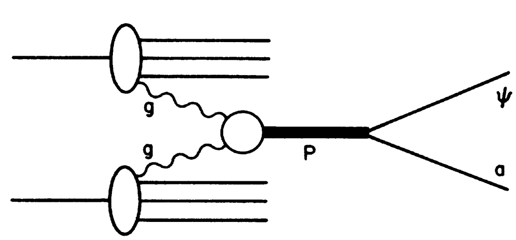

FIG. 1. Process of producing ψ-like particles in hadronic collisions. The state "a" can be γ, ω, 3π, etc.

is similar to the one for the decay of the corresponding positronium state into two photons.[8] The result is

$$\Gamma(^3P_0\to gg) = (\tfrac{2}{3})\, 9\, \frac{\alpha_g^2}{m^4}\left|\frac{d\phi}{dr}\right|^2_{r=0} = \tfrac{15}{4}\Gamma(^3P_2\to gg)\,, \qquad (4)$$

where $\alpha_g \approx 0.2$, m is the mass of the quark, ϕ is the radial wave function, and the factor of $\frac{2}{3}$ is due to color. The results of our calculation[9] are $\Gamma(2\,^3P_0\to 2g) = 1.29$ MeV and $\Gamma(3\,^3P_0\to 2g) = 1.98$ MeV. We also need the electric-dipole matrix elements, which are $|\langle 1S|\vec{r}|2P\rangle| = 1.24\ (\mathrm{GeV})^{-1}$, $|\langle 2S|\vec{r}|3P\rangle| = 1.79\ (\mathrm{GeV})^{-1}$, and $|\langle 1S|\vec{r}|3P\rangle| = 0.14\ (\mathrm{GeV})^{-1}$; the corresponding $E1$ transition widths are $\Gamma(2P\to\psi/J+\gamma) = 270$ keV, $\Gamma(3P\to\psi/J+\gamma) = 54$ keV, and $\Gamma(3P\to\psi'+\gamma) = 269$ keV. Neglecting for the time being the width $\Gamma(3P\to\psi/J+\omega)$, we can calculate the cross sections.

What is relevant for the comparison to the experimental data[1] is $d\sigma/dx_{\mathrm{c.m.}}|_{x=0}$, which we calculate along with the total cross section. At $x = 0$, we obtain for $s = 750\ (\mathrm{GeV})^2$

$$\left.\frac{d\sigma(\psi')}{dx}\right|_{x=0} \times B(\psi'\to e\bar{e}) = 0.46 \text{ nb} \quad [\text{Ref. 1: } (0.44\pm 0.24) \text{ nb}]\,,$$

$$\sigma_{\mathrm{total}}(\psi')\times B(\psi'\to e\bar{e}) = 0.26 \text{ nb}\,,$$

where B is the branching ratio. The corresponding values for ψ/J including the three processes that involve photons are

$$\left.\frac{d\sigma(\psi/J)}{dx}\right|_{x=0} \times B[(\psi/J\to e\bar{e})] = 8.97 \text{ nb} \quad [\text{Ref. 1: } (29\pm 8) \text{ nb}]\,,$$

$$\sigma_{\mathrm{total}}(\psi/J)\times B[(\psi/J\to e\bar{e})] = 5.2 \text{ nb} \quad [\text{Ref. 1: } (11\pm 3) \text{ nb}]\,.$$

Therefore the simple processes $P\to\psi\gamma$ could account for 30 to 50% of the ψ/J cross section depending on what we choose to compare to. We could stop here with no further ado, but it is interesting to speculate on the possible hadronic decay channels $\Gamma(3P\to\psi/J+\omega)$. Calculation of the $\Gamma(3P\to\psi/J+\omega)$ is unreliable. It requires a detailed knowledge of the fraction of light quarks in the $3P$ wave function.[10] Rather than attempt an *ab initio* calculation, we will use the experimental data[1] on the ratio of the ψ' to ψ/J cross section to estimate $\Gamma(3P\to\psi/J+\omega)$. The value we need to fit the ratio is $\Gamma(3P\to\psi/J+\omega) = 1.1$ MeV or 1.35 MeV, using the differential or total cross sections, respectively. (Our spectrum[5] in x is somewhat different from the one assumed in Ref. 1.) The presence of the $\Gamma(3P\to\psi/J+\omega)$ modifies our previous calculations. We now obtain $\sigma_{\mathrm{total}}(\psi/J)\times B = 8.5$ nb. We can then calculate the ψ/J and ψ' cross sections for all energies. The predicted total cross sections are plotted in Fig. 2. We agree with the available experimental data[11] within a factor of 2 (using our calculation to complete an x spectrum whenever full data were not available). This is compatible with the experimental error limits, but we are always on the low side.

Our success with the psions encourages us to consider the enhancement reported at 6 GeV. The experiment at Fermilab reports[6]

$$\left.\frac{d\sigma(\Upsilon)}{dx_{\mathrm{c.m.}}}\right|_{x=0} \times B(\Upsilon\to l\bar{l}) = 14.6 \text{ pb} = 14.6\times 10^{-36} \text{ cm}^2 \text{ at } s = 750\ (\mathrm{GeV})^2.$$

However, this "resonance" has not yet been seen at SPEAR,[12] and we make our comments with some trepidation.

Following our previous discussion, we will try to understand this structure as a bound state, $b\bar{b}$, of new quarks b of charge $-\frac{1}{3}$. An increase of the number of quark flavors from 4 to 6 has been suggested by the large value of $R = \sigma(e^+e^-\to\text{hadrons})/\sigma(e^+e^-\to\mu^+\mu^-)$ and the possible heavy leptons observed at SPEAR.[13] Several kinds of six-quark models have been studied,[14] but we do not need to discriminate among them.

The parameters needed for the cross-section calculation can be gotten by a series of standard exercises. There are no free parameters, except possibly m_b which we take to be 3 GeV. The

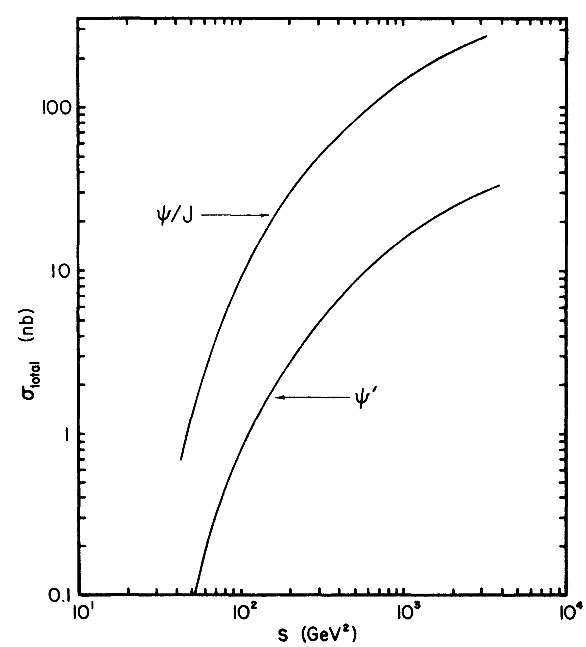

FIG. 2. Total cross sections for $pp\to\psi/J$ + anything and $p+p\to\psi'$ + anything.

strong coupling constant α_g (6 GeV) = 0.17 is obtained from asymptotic freedom[15] with parameters valid for $SU(6) \times SU(3)_c$. We use wave functions for the $2P$ and $1S$ states obtained by a variational calculation with Gaussian trial wave functions (r $\times$Gaussian for the $2P$ state) and a linear potential $V = r/a^2 - V_0$. The parameter a is chosen to be the same as for the psions,[3] $a = 1.94$ (GeV)$^{-1}$, on the grounds that it is a parameter of the "string" that binds the quarks and not of the quarks themselves.[16] The $2P$ mass becomes 6.29 GeV and the necessary widths are $\Gamma(3P_0 \to 2g) = 298$ keV and $\Gamma(3P \to \Upsilon\gamma) = 30$ keV. The branching ratio of Υ into leptons is 0.032, which follows from $\Gamma(\Upsilon \to 3g)/\Gamma(\Upsilon \to e\bar{e}) = (10/9\pi)(\pi^2 - 9)(\alpha_g{}^3/\alpha^2)$. The cross section we calculate (assuming that only the $2P$ contributes) is then

$$\left.\frac{d\sigma(\Upsilon)}{dx_{\mathrm{c.m.}}}\right|_{x=0} \times B = 16 \text{ pb},$$

and the total cross section is $\sigma_{\mathrm{total}}(\Upsilon) \times B = 10.6$ pb, agreeing well with experiment.[6]

The leptonic width of Υ for the linear potential is unfortunately 0.5 keV. However, it is interesting to note that using a Coulomb potential would not change our predicted cross section greatly: With the same values of α_g and m_b, the $\Upsilon\gamma$ width increases by about a factor of 4, while the $2g$ width decreases by about a factor of 5, and the cross section is nearly the same. The leptonic width of the Υ in this case is 0.1 keV.

In this comment we have shown that the hadronic production of narrow vector resonances can be accounted for by the production of P waves by two gluons and the subsequent decay of the P into vector states. We should not need to emphasize the importance of this mechanism which for the first time provides experimental confirmation of processes in which the gluons are more than mere spectators. It gives support to strong-interaction dynamics based on an underlying non-Abelian quark-gluon field theory.

Psion production by means not violating the Okubo-Zweig-Iizuka rule has been suggested.[17] However, this should lead to production of charmed particles in association with the psions, and experiments rule this out by the low observed ratio of 3μ to 2μ production, about 2/3000.[18] Also, production of psions directly from $3g$ must be small as it would lead to a ψ' to ψ/J ratio near $(M_{\psi'}/M_{\psi/J})^3$.

Let us briefly review the main conclusions of our model:

(a) The $\psi'(3.7)$ production occurs only via $gg \to 3P \to \psi'\gamma$.

(b) The $\psi'(3.1)$ is produced via the decay of the $3P$ and $2P$ intermediate states and 40% of the final states associated with the ψ should contain photons.

(c) The energy dependence of the ψ/J cross section is well reproduced.

(d) We predict that the additional enhancements at 4.1 and 4.4 GeV seen at SPEAR will have negligibly small hadronic cross sections.

Notes added in proof.

(1) Hom *et al.*[19] have recently published results on $\mu^-\mu^+$ in the region of the Υ which did not confirm the existence of a resonance.

(2) In addition to Ref. 18, another group has also reported an upper limit on trimuons.[20]

(3) Ellis, Einhorn, and Quigg[21] have discussed a proposal similar to the one advanced here.

We would like to thank Carlos Hojvat for helpful conversations and R. S. would like to thank the Physics Department of the College of William and Mary for its hospitality.

---

*Research supported in part by the National Science Foundation.

†Work supported in part by the Alfred P. Sloan Foundation.

‡Research supported in part by the National Research Council of Canada and the Quebec Department of Education.

[1]H. D. Snyder *et al.*, Phys. Rev. Lett. 36, 1415 (1976).

[2]Addendum to M. Gaillard, B. Lee, and J. Rosner, Rev. Mod. Phys. 47, 277 (1975); F. Gilman (private communication).

[3]C. E. Carlson and R. Suaya, Phys. Rev. D 14, 3115 (1976).

[4]M. B. Einhorn and S. Ellis, Phys. Rev. D 12, 2007 (1975).

[5]Our results will be quoted using $n = 3$, which seems to give the best results for the ψ/J spectrum; see Ref. 3.

[6]D. C. Hom *et al.*, Phys. Rev. Lett. 36, 1236 (1976).

[7]The $3P \to \psi/J + \omega$ is intended to include all the 3π contributions; presumably the 5π channel is small.

[8]A. I. Alekseev, Zh. Eksp. Teor. Fiz. 34, 1195 (1958) [Sov. Phys.—JETP 7, 826 (1958)]. We (Ref. 3) and R. Barbieri, R. Gatto, and R. Kögerler, Phys. Lett. 60B, 183 (1976), also did this calculation; we were unaware of the earlier positronium results.

[9]The parameters needed are $m = 1.84$ GeV, $V(r) = r/a^2 - V_0$ with $a = 1.94$ (GeV)$^{-1}$ and $\alpha_g(3.1) = 0.2$.

[10]E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, and T.-M. Yan, Phys. Rev. Lett. 36, 500 (1976).

[11]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974); B. Knapp *et al.*, *ibid.* 34, 1044 (1975); F. W. Büsser *et al.*, Phys. Lett. 56B, 482 (1975); K. J. Anderson

et al., Phys. Rev. Lett. 36, 237 (1976).

[12]A search has been made for narrow resonances between 5.7 and 6.4 GeV, and an upper limit has been set which corresponds to $\Gamma(\Upsilon \to e\bar{e}) \lesssim 0.1$ keV if the Υ is a narrow resonance or $B(\Upsilon \to e\bar{e}) < 10^{-5}$ if the Υ is broader than the experimental resolution. M. Breidenbach *et al.* (private communication).

[13]M. Perl *et al.*, Phys. Rev. Lett. 35, 1489 (1975).

[14]Cf. R. M. Barnett, Phys. Rev. Lett. 34, 41 (1975); F. Gürsey, P. Ramond, and P. Sikivie, Phys. Rev. D 12, 2166 (1975); H. Fritzsch, M. Gell-Mann, and P. Minkowski, Phys. Lett. 59B, 256 (1975).

[15]H. D. Politzer, Phys. Rev. Lett. 30, 1346 (1973); D. J. Gross and F. Wilczek, *ibid.* 30, 1343 (1973).

[16]E. P. Tryon, Phys. Rev. Lett. 28, 1605 (1972).

[17]D. Sivers, Nucl. Phys. B106, 95 (1976); J. Gunion, Phys. Rev. D 12, 1345 (1975); M. B. Green, M. Jacob, and P. Landshoff, Nuovo Cimento 29A, 123 (1975).

[18]M. Binkley *et al.*, Phys. Rev. Lett. 37, 578 (1976).

[19]D. C. Hom *et al.*, Phys. Rev. Lett. 37, 1374 (1976).

[20]K. J. Anderson *et al.*, report presented at the XVII International Conference on High Energy Physics, Tbilisi, USSR, 1976 (unpublished).

[21]S. Ellis, M. Einhorn, and C. Quigg, Phys. Rev. Lett. 36, 1263 (1976).