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Production of $J\,(\psi)$ in pp scattering*

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The hypothesis of a heavy-quark-antiquark meson (orthocharmonium) for the 3.1-GeV resonance leads, in the context of a general peripheral model, to predictions for the cross sections (and their energy dependence) for $J\,(\psi)$ production. The $p_\perp$ dependence is predicted to be quite different from that of the pion. At higher energies, charmed particles are expected to be produced in conjuction with each $J\,(\psi)$. Related problems are discussed.

I. INTRODUCTION

In a previous paper,[1] we have discussed the cross sections and $p_\perp$ dependence for $J\,(\psi)$ production in pp scattering. It was indicated that the energy and $p_\perp$ dependence of these cross sections might be quite different from π or ρ production. In this paper, an elaboration of the model and calculations is given along with more detailed predictions.

The recent discovery[2-4] of narrow resonances $[J\,(\psi)]$ at 3.1 and 3.7 GeV at the Brookhaven National Laboratory (BNL) and the Stanford Linear Accelerator Center (SLAC) has prompted much speculation about the production of $J\,(\psi)$ in hadronic scattering processes.[5] Among the problems to be investigated are the following: (1) the absolute magnitude and the energy dependence of the total cross section for $J\,(\psi)$ production, (2) the associated production of charmed particles with $J\,(\psi)$, (3) the variation of the $p_\perp$ dependence of the inclusive spectrum with energy, (4) the energy dependence of the inclusive spectrum for $J\,(\psi)$ production at $x=0$ and small $p_\perp$, and (5) the nonobservation[6] of the 3.7 GeV resonance at $E_{\rm lab}=30$ GeV.

The results obtained here and in Ref. 1 are based on two assumptions: first, the assumption of the nature of the particle, that it is a meson of heavy quarks $(\mathcal{P}'\overline{\mathcal{P}}')$[7-9]; the assumption that the new quantum number is charm is not necessary, and the particular symmetry scheme assumed does not affect the dynamical results. The second assumption is of the mode of production of the particle, that it can be described by a general peripheral model (which is closely related to parton models[10]).

Perhaps the most dramatic prediction obtained here is the rise of the cross section for $J\,(\psi)$ production from $E_{\rm lab}=30$ GeV to 1500 GeV by about two orders of magnitude (although it should be emphasized that at very small $p_\perp (p_\perp \lesssim 0.1$ GeV/c) the rise is smaller). At the highest energies, the associated production of two charmed particles with each $J\,(\psi)$ is predicted.

In order to calculate cross sections, use is made of a general peripheral model[10] which accurately describes the inclusive production of π, K, and ρ mesons in the central plateau region. The model has a simple internal-exchange parameterization which (with quark-model symmetry assumptions on coupling constants only) yields the relative magnitudes of π, K, and ρ production and their $p_\perp$ dependence for both large and small $p_\perp$. At large transverse momentum the model has been shown[10] to be equivalent to parton models for processes such as $pp\to\pi+$anything, and yields the fixed $x_\perp$ scaling observed at CERN ISR.[11] However, where most quark-parton models are not accurate at small $p_\perp$, this approach is accurate because of its exact treatment of the energy- and mass-dependent phase space. The mass dependence is very important because of the very large mass of the $J\,(\psi)$. Because of the associated production of charmed particles with the $J\,(\psi)$ at high energies, another factor in the calculations is the threshold behavior of the missing mass; this effect, which is accounted for by the model, drastically suppresses the cross sections at lower energies. Although the model uses SU(3) and SU(4) couplings, the radical differences in mass are considered in the internal exchanges, the produced particle's mass, and the associated production thresholds.

Some of the data for $J\,(\psi)$ production cross sections have been obtained at $x\equiv 2p_\parallel/\sqrt{s}\approx 0$ (or other limited x regions). Since the x dependence for the production of particles of different masses (which were not in the incoming beam or target) seems to be somewhat similar, the experimentalists are able to estimate $J\,(\psi)$ cross sections integrated over x. By making the same assumption, we are able to extrapolate our central plateau results to obtain integrated x results.

II. THE GENERAL PERIPHERAL MODEL

The peripheral production model for particles produced in the central region ($x \approx 0$) is shown in Fig. 1(a). Although we will concentrate on smaller transverse momentum, the production of particles at large $p_\perp$ can also be viewed as a meson-quark scattering[10,12] as shown in Fig. 1(b) where the meson is observed. Since the quark in Fig. 1(b) is unobserved, it can be included in the right-hand blob as in Fig. 1(a). The meson is considered to have a form factor which leads to $p_\perp^{-8}$ behavior instead of the canonical $p_\perp^{-4}$ behavior.[13] In Ref. 14 the possibility of $p_\perp^{-12}$, $p_\perp^{-8}$, and $p_\perp^{-4}$ (or s^{-6}, s^{-4}, and s^{-2}) behavior in different regions of $p_\perp$ and s was examined [corresponding to meson-meson, meson-quark, and quark-quark scattering in Fig. 1(b)]; however, the power of $p_\perp$ will not affect the results here.

From Fig. 1(a), the single-particle spectrum (from which the cross sections will later be calculated) can be expressed as

$$E\frac{d\sigma}{d^3p}=\frac{1}{s}\int d^4p'\int d^4k'\delta^4(p'+k'+p)\beta_L{}^2(t_L)\beta_R{}^2(t_R)\times A_L(s_L',t_L)A_R(s_R',t_R)\,, \quad (2.1)$$

where β_L and β_R are the propagators and $t_L=p'^2$ and $t_R=k'^2$. The above form is summed over the allowed (pseudoscalar and vector) exchanges with the appropriate SU(3) or SU(4) couplings (in analogy with φ production). The form-factor dependence is for convenience included in A_L and A_R, the off-shell absorptive parts from the inclusively summed particles. The propagator for pion exchange is $(m_\pi{}^2-t)^{-1}$. For any other exchange (except charmed mesons), an effective propagator is taken as $(b^2-t)^{-1}$ where b^2 is a parameter determined from the ratio of K^+/π^+ production at large $p_\perp$.

A_L and A_R are assumed to obey Bjorken scaling:

$$A(s',t)=\frac{a^4}{(a^2-t)}\omega\chi(\omega)\xrightarrow[\omega\to\infty]{} s'\frac{a^4}{(a^2-t)^2}\,, \quad (2.2)$$

where $\omega\equiv s'/(a^2-t)+1\approx 2m\nu/Q^2$, $\chi=(\omega-1)^3/\omega^3$, and m is the mass of the exchanged particle. The parameter a^2 is determined by fitting the π spectrum (from $p_\perp=0.2$ GeV/c to 9.0 GeV/c). An overall normalization constant is found for the π spectrum after which the K, ρ, and J (ψ) spectra are fixed.

The integral, Eq. (2.1), can be expressed as an integral[10] over s_L', s_R', t_L, and t_R and in that form can be calculated on a computer.

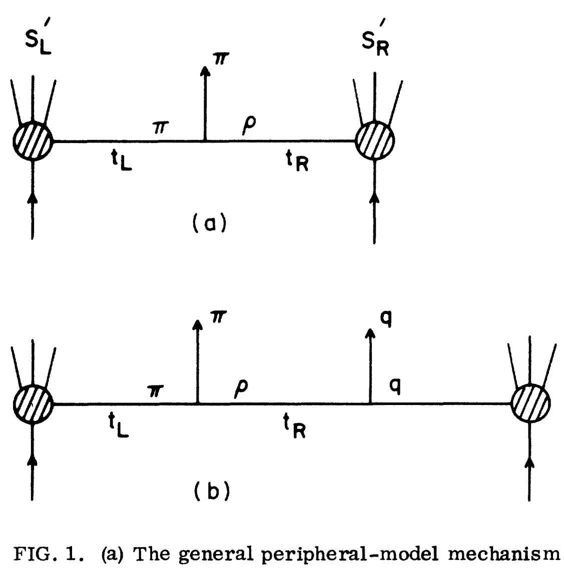

FIG. 1. (a) The general peripheral-model mechanism for production of a pion with momentum p by the exchange of particles such as ρ and π ($pp\to\pi$ +anything); (b) an equivalent parton model view of the same process. At large $p_\perp$, t_R is the large momentum transfer ($q \equiv$ quark-parton).

III. THE CROSS SECTIONS AT LOWER ENERGIES

The calculation of J (ψ) production involves additional assumptions. Since J (ψ) is assumed to be a $\mathcal{P}'\bar{\mathcal{P}}'$ meson, only diagrams such as Fig. 2(a) obeying the Zweig-Iizuka rule[15] are "allowed." As a result only charmed particles couple strongly to J (ψ) and in Fig. 1(a) the exchanged mesons must be charmed mesons. However, since no charmed quarks were present in the incoming particles, they must be in the outgoing particles. For pp scattering, the lowest-mass final state with a J (ψ) is one with a proton, a J (ψ), a charmed meson, and a charmed baryon whose total mass is estimated[8,9,16] to be approximately 8 GeV whereas at BNL with $E_{\rm lab}$ = 30 GeV, $\sqrt{s}$ is 7.6 GeV so that this process *cannot* occur (or for lower-mass estimates, is negligible). For higher energies this process is not forbidden and further discussion is given in Sec. IV.

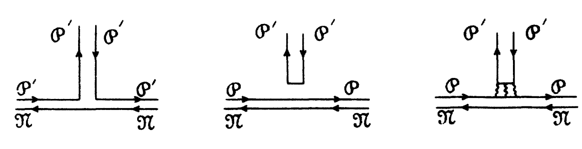

FIG. 2. The central vertex from Fig. 1(a): (a) obeying the Zweig-Iizuka rule; (b) violating the Zweig-Iizuka rule; (c) a possible mechanism for violation of the Zweig-Iizuka rule (three-gluon exchange).

The coupling shown in Fig. 2(b) is forbidden by the Zweig-Iizuka rule; however, since the J (ψ) does, in fact, decay into noncharmed hadrons,[3] some mechanism must exist to allow a small violation of the rule. An example of such a mechanism is the color-singlet state of three gluons, shown in Fig. 2(c), which is found in the quark-gluon model of Appelquist and Politzer.[7] Only the existence, not the nature of the mechanism is assumed here. Inserting such a mechanism into Fig. 1(a), one finds that J (ψ) can be produced (even at $E_{\rm lab}=30$ GeV) with the exchange of mesons such as ρ and π, although the effective coupling of ρ and π to J (ψ) is much smaller than the usual strong SU(3) couplings.

To calculate the suppression due to the violation of the Zweig-Iizuka rule without invoking additional unsubstantiated theoretical input, it is assumed that the ratio of the effective coupling to the usual SU(3) [or SU(4)] coupling is given very approximately by

$$R_g=\frac{\Gamma(J\ (\psi)\to \text{hadrons})}{\Gamma(\rho\to\text{hadrons})}\left[\frac{p_\pi^3/m_\rho^2}{m_{J\ (\psi)}}\right]\approx 10^{-4}\,, \tag{3.1}$$

where p^3/m^2 is the usual p-wave threshold factor [for J (ψ), $p^3/m^2\approx m_{J\ (\psi)}$]. It should be emphasized that this result is approximately the same whether $\rho\to$hadrons, $\varphi\to$hadrons, or $\rho'\to$hadrons (etc.) is used.

Since all experiments (at this time) in pp scattering have observed J (ψ) through the $\mu^+\mu^-$ or e^+e^- decay mode, all calculated cross sections must be multiplied by the branching ratio[17]

$$R_b=\frac{\Gamma(J\ (\psi)\to e^+e^-)}{\Gamma(J\ (\psi)\to\text{anything})}\approx 0.07\,. \tag{3.2}$$

With the factors R_g and R_b and Eq. (2.1) we calculate J (ψ) production at $x=0$. Then one observes that the x dependences of $\pi, K, \bar{p}$ production in pp collisions are substantially the same. The $p_\perp$ dependences are also roughly independent of x. Since much of the cross section comes from the central region, and if it is assumed that J (ψ) has an x dependence roughly similar to that of other particles, one can obtain the cross sections by normalizing to the results at $x=0$. In the fragmentation ($x\neq 0$) regions, it is expected that there would be significant contributions in addition to that in Fig. 1(a). Therefore, using the single-particle spectrum at $x=0$, we have

$$\left(E\frac{d\sigma}{d^3p}\right)_{J\ (\psi)}\Bigg/\left(E\frac{d\sigma}{d^3p}\right)_{\pi^+}\approx\frac{\sigma(J\ (\psi))}{\sigma(\pi^+)}\,, \tag{3.3}$$

where $\sigma(\pi^+)$ means $\langle n_{\pi^+}\rangle\sigma_{\rm total}$.

From Eqs. (2.1), (3.1), (3.2), and (3.3), the cross section for J (ψ) production at $E_{\rm lab}=30$ GeV is found to be

$$\sigma(J\ (\psi)\to e^+e^-)=4.7\times 10^{-34}\ \text{cm}^2\,. \tag{3.4}$$

The experimental data[2] with which this result must be compared require [in addition to some assumption about the x dependence equivalent to Eq. (3.3)] an assumption about the $p_\perp$ dependence of J (ψ) production since the results at BNL were obtained at very small $p_\perp$. The cross section reported by Aubert *et al.*[2] (10^{-34} cm^2) was found assuming an $\exp(-6p_\perp)$ behavior similar to pions (but not K or $\bar{p}$). However, the spectrum from the peripheral model can be parameterized by $\exp(-3.6p_\perp^2)$. Using this $p_\perp$ dependence to extrapolate and integrate the data, the "experimental" result is then approximately 3×10^{-34} cm^2, and our theoretical result of 4.7×10^{-34} cm^2 [Eq. (3.4)] is entirely consistent. A more detailed discussion of $p_\perp$ dependence is given in Sec. IV.

Of the eight-orders-of-magnitude difference between the J (ψ) and π cross sections, five are accounted for by the factors Eqs. (3.1) and (3.2), and three by the mass difference between J (ψ) and π.

IV. CROSS SECTIONS AND $p_\perp$ DEPENDENCES

The above result assumed the exchange of noncharmed mesons [Fig. 2(c)] because charmed-meson exchange [Fig. 2(a)] was not possible at low energies. At higher energies, however, it is likely that charmed exchange will dominate over the Zweig-Iizuka-rule-suppressed noncharmed exchange. The exchange of particles of such large mass forces the introduction of new assumptions. The parameter b^2 associated with the effective propagator can no longer be obtained from other reactions and is assumed to be on the scale of the mass of the charmed mesons. It is taken as $b^2=4.0$ GeV^2. It is possible that the parameter a^2 associated with the form factor should no longer be $a^2=1.4$ GeV^2. However, the energy and $p_\perp$ dependence are not very sensitive to the parameters a^2 and b^2 for heavy particles such as J (ψ) (for reasonable values of a^2 and b^2).

The magnitude of the cross section from charmed exchange is, however, sensitive to those parameters and, therefore, is expected to be correct only to a factor of 3 or 4. Since some of the data (such as Ref. 2) are being collected at very small $p_\perp$ (and $x=0$), the calculated results of the model, in Table I, are given for both $p_\perp=0.1$ GeV/c and integrated over $p_\perp$. Once normalized to the data at any given energy, the results for the charmed-exchange cross sections are expected to be accurate. SU(4) couplings were used for the central vertex. As is discussed below, the $p_\perp$ dependence is quite flat and a significant fraction of the cross section is found at $p_\perp>1.0$ GeV/c.

Table I also contains the calculated results for

TABLE I. Calculated J (ψ) cross sections and experimental K and $\bar{p}$ cross sections. (a) The calculated J (ψ) cross sections at $p_\perp = 0.1$ GeV/c in arbitrary units; (b) the calculated J (ψ) cross section (integrated over $p_\perp$) in units of 10^{-34} cm^2 (first row is multiplied by 3/4.7); (c) the experimental relative K and $\bar{p}$ cross sections (see Ref. 20) at $p_\perp = 0.5$ GeV/c (normalized to 3. at $E_{lab} = 25$ GeV).

(a)	$E_{lab} = 30$	100	300	1500 GeV
Noncharmed exchange	3.0	21.	24.	33.
Charmed exchange	0	0.5	8.	30.

(b)	$E_{lab} = 30$	100	300	1500 GeV
Noncharmed exchange	3.	30.	50.	95.
Charmed exchange	0.	2.	50.	200.

(c)	$E_{lab} = 25$	70	300	1500 GeV
(K/π) times 70	3.	4.1	4.3	4.7
($\bar{p}/\pi$) times 470	3.	6.0	7.2	11.2

J (ψ) production via noncharmed-meson exchange (Sec. III). The suppression of J (ψ) relative to π or ρ is due to three factors (in addition to the branching ratio): (1) the large mass of J (ψ), (2) the threshold factors for the associated charmed particle production, and (3) the exchange of charmed mesons (via the parameter b^2). Each of the three factors is one to three orders of magnitude (depending on energy). The value of the cross section at $E_{lab} = 30$ GeV is discussed at the end of Sec. III. Section (c) of Table I is given for comparison; it shows the expected suppression of large-mass particles at lower energies. The only surprising result is the predicted rise of the cross section from 3×10^{-34} cm^2 at $E_{lab} = 30$ GeV to about 300×10^{-34} cm^2 at $E_{lab} = 1500$ GeV. This sharp increase is largely a result of the associated production of the heavy charmed particles with the J (ψ), which suppresses J (ψ) production at lower energies. The difference between the cross sections with noncharmed-meson exchange and with charmed-meson exchange is, of course, due to the small effective coupling of J (ψ) to noncharmed mesons.

From Sec. (b) of Table I one sees that the associated production of chrmed particles with the J (ψ) is unequivocally expected in this model at lab energies at and above 300 GeV. [If charmed exchange is, for some reason, greatly suppressed, the results for noncharmed exchange are still expected to be correct and (see Table I) also give sharply rising cross sections though no associated charm production.]

The $p_\perp$ dependence calculated for J (ψ) at high energies is quite different[18] from that found for light-mass particles and is consistent with the trend for increasing mass in existing data.[19] A parameterization of this $p_\perp$ dependence is given in Table II, and a comparison is made with the data[20] for other particles. There are three effects evident in Table II: (1) At lower energies the phase space at larger $p_\perp$ is more limited so that the cross sections fall off more rapidly; (2) with increasing mass, larger values of the momentum transfer squared, t, are needed, but the process is damped in t; at large $p_\perp$ mass effects are much smaller so that the slope B decreases with increasing mass; (3) the difference in values of B for noncharmed exchange and for charmed exchange is due to the associated production of charmed particles in the latter case (it is a threshold effect in s_L' and s_R').

From Table I, one sees that at very small $p_\perp$ the noncharmed exchange is more dominant than at large $p_\perp$ and as a result, one expects B to be somewhat larger at very small $p_\perp$.

Again it should be emphasized that these results for the $p_\perp$ dependences are not very sensitive to the parameters a^2 and b^2 (for reasonable values). They are, however, sensitive to the relative admixture of the two production mechanisms. One assump-

TABLE II. Parameterizations of the calculated J (ψ) production and the observed π, K, and $\bar{p}$ production. (a) B in an $\exp(-Bp_\perp^2)$ parameterization of the calculated J (ψ) production; (b) parameterizations of the data (see Ref. 19) for $p_\perp$ dependence of particle production at E_{lab} = 500 GeV and $x = 0$.

(a)

E_{lab}	For noncharmed exchange	For charmed exchange	For noncharmed and charmed
30	3.6		3.6
100	2.5	0.9	2.4
300	1.3	0.6	0.9
1500	0.9	0.5	0.6

(b)

π	$\exp(-6.04\,p_\perp)$
K	$\exp(-3.6\,p_\perp)$
$\bar{p}$	$\exp(-1.2\,p_\perp - 2.0\,p_\perp^2)$

tion which could conceivably be wrong is that at large $p_\perp$, J (ψ) and π have the same $p_\perp^{-n}$ behavior; but π and K do have the same behavior, and there is no evidence that other mesons have different behaviors.

V. OTHER RESULTS

In the region $x \approx 0$, results for πp and Kp scattering should be very similar to those for pp scattering. However, in the fragmentation regions, one might expect in analogy with φ production a larger J (ψ) production cross section in πp and Kp scattering than in pp scattering.

Another question of interest is the production cross section into e^+e^- of the 3.7 GeV resonance relative to the 3.1 GeV resonance, since at E_{lab} = 30 GeV it has not been seen to a level of 1% of the yield of the 3.1 GeV resonance (to e^+e^-). The model predicts that at E_{lab} = 30 GeV the ratio (including all decay modes) of the 3.7 GeV to the 3.1 GeV resoance is 1/7 and that at E_{lab} = 300 GeV it is 1/2. However, the branching ratios to e^+e^- of the 3.1 GeV and 3.7 GeV resonances are not the same; using current results[17] the resulting ratio to e^+e^- at E_{lab} = 30 GeV is between 1/44 and 1/175. The latter resonance is hypothesized[7-9,21] by some to be a radial excitation of the first, and it is possible that this is a factor suppressing its production; it is also possible that the radial excitation hypothesis is wrong and that there are other factors. If the bump at 4.1 GeV is a resonance, its branching ratio to e^+e^- is extremely small, and in addition it is suppressed by a factor of $\frac{1}{4}$ at E_{lab} = 300 GeV according to the model.

At the lower energies the cross section for production of such heavy particles is extremely sensitive to energy. If the energy is decreased from E_{lab} = 30 GeV to 20 GeV, the cross section for production of J (ψ) drops by a factor of seven.

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[18]See B. Knapp *et al.*, Phys. Rev. Lett. 34, 1044 (1975); the straight lines in Fig. 3(b) of this paper are mislabeled and should be labeled $e^{-p_\perp^2}$ and $e^{-2p_\perp^2}$ instead of $e^{-2p_\perp^2}$ and $e^{-6p_\perp^2}$, respectively.
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