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Remarks on models for the J and other ψ particles*

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We make some comments concerning charm-related models, the Schwinger phenomenological theory, and a possible multiplicative t quantum-number scheme for the J and other ψ particles. It is seen that an accurate measurement of the rate $J^0 \to \pi^+ + \pi^- + \gamma$, a search for *narrow-width* $(I^G, J^P) = (1^\pm, 1^\mp)$ particles (with the vector particle probably below 3.1 GeV), and a possible enhanced pair production of (JJ) and $(J\psi)$ in hadron-initiated reactions at high energies remain of substantial interest in sorting out our options.

There now exists fairly convincing experimental evidence[1,2] that the $J(3.1)$ particle and the $\psi(3.7) \equiv \psi'$ particle have both quantum numbers $(I^G, J^P) = (0^-, 1^-)$. [We use the notation ψ to denote the family of particles $\psi(3.1), \psi(3,7), \psi(4.15), \ldots$. For clarity we often denote $\psi(3.1)$ as J, $\psi(3.7)$ as ψ', and $\psi(4.15)$ as ψ''.] The theoretical interpretation remains in a state of flux and we make here some remarks concerning some of the models proposed with an aim to extract out those experimental consequences which will help us to sort out the various options provided by different theories.

I. CHARM-RELATED MODELS

Perhaps the current theoretical favorite is the charmonium[3,4] interpretation which places the $J(3.1)$ and $\psi(3.7)$ as bound $c\bar{c}$ states $1\,^3S_1$ and $2\,^3S_1$ with $I^G = 0^-$ in the general framework of the Weinberg-Salam phenomenology.[5] This same theory would place the broad $\psi(4.15)$ found in e^+e^- annihilation[6] as above $c\bar{c}$ charm threshold with a "phase transition" between 3.7 and 4.1. However, the detailed predictions of this model are not in good agreement with experiment.[7] They can be briefly summarized as follows[8]:

(a) The model predicts $R = \sigma(e^+e^- \to \text{hadrons}) / \sigma(e^+e^- \to \mu^+\mu^-) = \frac{10}{3}$ when color is included. Experimentally e^+e^- annihilation seems to be settling to a new scaling plateau (without marked structure between $s^{1/2} = 4.1$ and 6.8 GeV with $R = 5$.

(b) The model predicts a substantial increase in (K/π) ratio when one passes through the phase transition region ($s^{1/2} \sim 4$ GeV in e^+e^- annihilation. Experimentally, there is perhaps a 10–15% increase but nothing abrupt is observed.

(c) In order to understand one-hadron h inclusive annihilation from $e^+e^- \to h +$ anything with the absence of Bjorken scaling for $x = 2E_h/s^{1/2}$ less than 0.5, the proposal has been made[9] that the small-x region is associated with creation of very slow pairs $X, \bar{X}$ (with charm content) via $e^+e^- \to X + \bar{X}$, each X then decays into two usual hadronic particles (each carrying energy $\sim \frac{1}{4}s^{1/2}$). Hence the breakdown in scaling due to the creation of slow $X, \bar{X}$ is expected to occur for $x = 2E_h/s^{1/2} \lesssim 2s^{1/2}/4s^{1/2} \sim 0.5$, in rough agreement with data. Experimentally the ratio $\langle E_{\text{charged}}/E_{\text{total}}\rangle$ and the charge multiplicity $\langle n_{\text{ch}}\rangle \sim 4$ do not vary very much over the phase transition region around 4 GeV in e^+e^- annihilation. This then creates the "multiplicity crunch" problem for the conventional charm model, since the absence of peaks in $K^+\pi^-$, $K^+\pi^+\pi^-, \ldots$ corresponding to X (or $\bar{X}$) of mass 2 GeV cannot be easily explained away by attributing dominant multiparticle decay modes to these charmed objects since $\langle n_{\text{ch}}\rangle$ is *only* 4. Indeed, assuming that, for instance, the charmed meson[10] D^+ is produced at the level of $\frac{20}{3}$ nb in e^+e^-, and that one might reasonably guess that the branching ratio of $D^+ \to K^-\pi^+\pi^+$ is about $\frac{1}{4}$, then $\sigma(e\bar{e} \to D^+ + X)B((D^+ \to K^-\pi^+\pi^+)/(D^+ \to \text{all})) \sim \frac{5}{3}$ nb. Experimentally there appears to be nothing significant above $\frac{1}{2}$ *nanobarns per channel*.

(d) The charmonium picture[11,12] places the $\psi(3.7)$ in a radially excited $2\,^3S_1$ state from the ground $1\,^3S_1$ $J(3.1)$ state; hence an $M1$ γ transition of the $\psi(3.7)$ to the $1\,^1S_0$ parastate partner of the $J(3.1)$ expected also in the neighborhood of 3.1 GeV should be much in evidence. A more serious problem is the theoretical prediction of $E1$ transitions from $\psi(3.7)$ to $^3P_2$, $^3P_1$, $^3P_0$ states expected in the neighborhood of 3.5 GeV with typical width of order 200 keV. Experimentally these transitions appear to be absent at the 15-keV level.[7] Although two or more states[13] have been observed in the 3.4–3.5 GeV region, the photonic rates are not consistent with expectations of a charmonium radial-excitation picture. The $1\,^1S_0$ has also been observed[13] but at a much lower mass than expected (2.85 GeV rather than 3.1 GeV).

(e) In a radial-excitation model, the matrix element for $\psi' \to \psi\pi^+\pi^-$ should be suppressed[14] at large $m_{\pi\pi}{}^2$ owing to the orthogonality of ψ' and ψ wave functions. No such suppression is seen.[2]

In a context outside of $e\bar{e}$ annihilation, Barger, Weiler, and Phillips[15] pointed out that the dilepton anomaly in neutrino interactions[16] could be understood in terms of charm production if scattering off the quark sea component is the dominant ingredient. The recent broad $v = xy$ distribution data[17] indicate instead production off the valence quarks. Finally, De Rújula and Glashow[3] suggest that the thermodynamical model[18] predicts, for the production of a particle with mass M,

$$\sigma(pp \to M + \ldots)/40\ \text{mb} \sim (M/m_\pi)^{3/2} e^{-M/T} = H(M)\,, \tag{1}$$

where $T = 160$ MeV. For orthocharmonium $J(3.1)$, Eq. (1) yields 2×10^{-33} cm^2, or 10^{-34} cm^2 for e^+e^- production via the resonance, agreeing with experiment.[19] It seems to us that the Hagedorn formula (1) assumes that the particle M has normal strong interactions with the usual hadrons ($g_{Mh}^2/4\pi \sim 1$). For $J(3.1)$, the production cross section given by (1) needs at least to be supplemented by multiplicative factor $g_{Jh}^2/4\pi \sim 6\times10^{-5}$; hence

$$\begin{tikzcd}[column sep=tiny] \sigma(pp \to & J \arrow[dr] & (3.1) + \ldots) = 6\times10^{-39}\ \text{cm}^2\,. \\ & & e^+e^- \end{tikzcd}$$

It is our opinion that because the $J(3.1)$ is such a long-lived particle (medium-weak coupling to the normal hadrons), Hagedorn thermodynamics in strong interactions is inapplicable for *singly*-produced "orthocharmoniums" $J(3.1)$ and $\psi(3.7)$ (Ref. 12) (even though it is formally ascribed with strong interaction properties with h) via hadron-initiated reactions. This does not rule out alternative mechanisms for producing $J(3.1)$ singly as has been proposed recently.[20]

Of course some of the problems (such as the ratio R) facing the "charm" picture can be solved by inventing more or different quarks[4] and/or invoking heavy leptons.[21]

II SCHWINGER'S MODEL

Exciting as the experimental prospects of dileptons are (especially $\mu^-\mu^-$) with an origin couched in varying degrees of charm, we must consider also the possibility of a more conservative solution. For instance, Schwinger[22] asks the question whether one can exhibit a mechanism for avoiding unwanted ($\Delta S = 1$) neutral currents that refers largely to experimentally recognized types of particles, and sketches an affirmative answer. The Schwinger proposal rejects the Cabibbo rotation in favor of a mixing, between two types of unit-spin mesons, that is produced by the SU(3)-symmetry-breaking interaction. As an example, the accustomed set of vector mesons (ρ, ω, ϕ) will be supplemented by another set $(\tilde{\rho}, \tilde{\omega}, \tilde{\phi}) = \tilde{V}$, with an analogous situation holding also for the 1^+ sets. The second sets of hadronic fields have disparate roles in strong interactions, in that they are postulated to have *only slight couplings to the quasi-stable hadrons*. Indeed it was remarked[22] *prior to the discovery of J and the other ψ particles* that the apparent discrepancy between the Cabibbo factor $\cos\theta_C \cong 0.98$ and unity could be removed if for instance the $\tilde{V}$ particles had an effective coupling to hadrons ~ 2% of that for ρ^0 meson, to wit, $\Gamma(\tilde{V})/\Gamma(\rho^0) = (0.02)^2 = 70\ \text{keV}/150\ \text{MeV}$. Although the $\tilde{V}$ has normal electromagnetic couplings, decays into $\gamma + \pi^0$, $\gamma + \eta^0$, $\gamma + \eta'^0$, etc., are suppressed relative to its electromagnetic decay into lepton pairs because $(0.02)^2\alpha < \alpha^2$ by an order of magnitude. Hence the predicted $\tilde{V}$ does appear to have the gross characteristics[23] of the recently found $J(3.1)$ particle, and is perhaps the only phenomenological theory which clearly *anticipated* particles with the observed general characteristics (normal electromagnetic coupling, suppressed hadronic interaction). Of course (in common with the charmonium picture) the decay of $\tilde{V}(3.1) \to \nu\bar{\nu}$ is weak whereas its decay into charged lepton pairs is electromagnetic; thus $(\tilde{V} \to \nu\bar{\nu})/(\tilde{V} \to l^+l^-)$ is of order[24] $G_F^2/\alpha^2 \sim 10^{-6}$ and this decay mode would not be seen in the SLAC-SPEAR experiment with respect to the 3.1-GeV object.

There is now some evidence[7] that the $J(3.1)$ is dominantly an SU(3) singlet ($J \not\to K\bar{K}$ though the $K\bar{K}^*$ mode is seen), hence it appears unlikely that the 3.1-GeV object is a mass-degenerate superposition of $\tilde{\rho}$ and $\tilde{\omega}$, as suggested by some magnetic models.[25] Since Schwinger's phenomenological theory[22,23] requires complements for $(\rho^0, \omega^0, \phi^0)$, it is suggestive to assign the $I^G = 0^-$ $\psi(3.7)$ as dominantly belonging to an SU(3) octet. *A search for a narrow*[26] *$I = 1$ $\tilde{\rho}$ in this general mass range will be a critical test of the theory.* There are already indications that the 3.1- and 3.7-GeV objects are the only narrow states[27] in the mass region of 3.2 to 5.9 GeV for e^+e^- annihilation. Hence a search for the $\tilde{\rho}$ member might well be conducted in the mass region below 3.1 GeV, a fact also motivated somewhat by the analogy with the (ρ, ω, ϕ) case in which the $I = 1$ member also lies lower than its $I = 0$ partners. Another test would be a search for *narrow* axial-vector mesons $\tilde{A}$(either $I = 0$ or $I = 1$). Analogous to the decay of the A_1, the $\tilde{A}(I = 1)$ would decay into J (or ψ') + π. Since the decay of $\psi' \to J + 2\pi$ is a large fraction of all ψ' decays, $\tilde{A}(I = 1)$ would be expected to have a large branching ratio for the J (or ψ') + π decay mode. Thus the $\tilde{A}(I = 1)$ would clearly show itself on a J(or ψ') + π mass plot in the experiment

$$\begin{tikzcd}[column sep=tiny] pp \to & \tilde{A} \arrow[dr] & + X \\ & & J\ (\text{or } \psi') + \pi\,. \end{tikzcd}$$

Similarly, the $\tilde{A}(I=0)$ could be found, although its decay modes would be more complicated [e.g., $\tilde{A}(I=0)\rightarrow J+\eta$].

III. PAIR PRODUCTION AND *t* QUANTUM NUMBER

A particularly interesting question concerning the J and other ψ particles is whether they have pairwise strong interactions with the normal hadrons. Considerations of the photoproduction of these states[28] suggest that the cross section for $J(3.1)+N \rightarrow J(3.1)+N$ is about 1 mb. This in turn suggests via crossing symmetry that $JJ \longleftrightarrow N\bar{N}$ coupling is of medium-strong strength. Medium-strong pair interactions with ordinary hadrons is further indicated by the relatively large width[7] of between 100 and 400 keV (quite comparable to strong decay $\eta' \rightarrow \eta^0+\pi\pi$) for the process $\psi(3.7)\rightarrow J(3.1)+2\pi$ in spite of the small available phase space.[29] Hence, independent of any specific model, pair production of (JJ), $(J\psi')$, and perhaps $(\psi'\psi')$ might be enhanced over single production of these particles in hadron-hadron collisions at sufficiently high energy when diffractive dissociation mechanism of production is expected to be operative.[20] This possibility could well be supported by the rapid increase of $J(3.1)$ production rate in going from 30 GeV (Ref. 19) to 250 GeV in $n+\text{Be} \rightarrow J(3.1)+X$, seen recently.[30] However, it should be examined by looking for *pairs of dileptons* both with 3.1 GeV mass (or alternatively with 3.1 and 3.7 GeV masses). If a systematic search for such pairs of dileptons in hadron-initiated reactions should yield a null result, we might be more inclined to accept the thermodynamics interpretation[18] of pair production where $\sigma(pp\rightarrow M+M+\ldots)/40\ \text{mb} \simeq H^2(M)$ and hence is *minuscule* for $M=3.1$ or 3.7 GeV. Note that since (JJ) and $(J\psi')$ have pair-wise *medium-strong interaction* with the usual hadrons, the pair-production process is more amenable to Hagedorn thermodynamics than singly produced J or ψ', which are essentially of *medium-weak* strength in their coupling with normal hadrons.

As first emphasized to us by Schwinger,[31] the medium-strong decay $\psi'\rightarrow J+2\pi$ can at first sight create a problem for any interpretation of the 3.7 as a $J^P=1^-$ particle with normal electromagnetic coupling $3.7 \longrightarrow \gamma$. By itself, nothing in the original picture[22] prevents paired couplings of $\tilde{V}$ with normal hadrons. They are also anticipated in charm-related models though one must keep in mind here the caveat of Pati and Salam.[32] Namely, writing the decay $3.7\rightarrow 3.1+\pi^+ +\pi^-$ in the effective coupling form $g\psi'_\mu J_\mu \phi_\pi^\dagger \phi_\pi$ (essentially a phase-space model), we obtain ${g_{\psi' J}}^2/4\pi \gtrsim 8$, a medium-strong coupling when compared to the large enhancement ${g_{\rho'\rho}}^2/4\pi \sim 400$ for $\rho'(1600)\rightarrow \rho+\pi^+ +\pi^-$. If the familiar Okubo-Zweig-Iizuka rule [suppression of $J(3.1)$ and $\psi(3.7)\rightarrow$ normal hadrons by about 10^{-3} in the amplitude][33] also applies to $\psi(3.7)\rightarrow J(3.1)+2\pi$, then even with the ρ' enhancement we would expect ${g_{\psi' J}}^2/4\pi \approx 10^{-6}\times 400 = 4\times 10^{-4}$ as opposed to 8. The situation will, of course, alter if deviation from the Okubo-Zweig-Iizuka rule for $(\psi'\rightarrow J+\pi+\pi)$-type decays could be understood consistently (perhaps because they carry $c\bar{c}$ content in both initial and final state?). Irrespective of models, Schwinger[31] pointed out that if the decay $3.7\rightarrow 3.1+2\pi$ is compatible with medium-strong decay, then a normal electromagnetic coupling $3.7 \longrightarrow \gamma$ would imply that the decay $J(3.1)\rightarrow \pi^+ +\pi^- +\gamma$ occurs at too large a rate. To wit, the chain[34,35]

$$\begin{tikzcd} & \pi^+\pi^- J \arrow[dr] & \\ J^0 \arrow[ur] \arrow[dr] & & \pi^+\pi^-\gamma\,, \\ & \pi^+\pi^- \psi' \arrow[ur] & \end{tikzcd} \tag{2}$$

with three-meson intermediate states $\pi^+\pi^- J$ and $\pi^+\pi^-\psi'$ (J and ψ' in intermediate state are off-mass-shell) dominating,[36] would yield bv a dimensional argument[37]

$$\Gamma(J\rightarrow \pi^+\pi^-\gamma) \sim 10^{-2}\,\alpha M_J = 220\ \text{keV}\,. \tag{3}$$

Here the factor 10^{-2} is introduced to take into account the medium-strong nature of $(\pi\pi JJ)$ and $(\pi\pi J\psi')$ vertices. Equation (3), if taken literally, would suggest that this one single radiative mode would more than account for the total width of $J(3.1)$. Nevertheless, to the extent that such estimates have been reasonably reliable for $\omega^0\rightarrow \pi^0+\gamma$, *we urge accurate measurement of the rate* $J^0\rightarrow \pi^+\pi^-\gamma$ *for a possibly large anomaly. In this connection we speculate that a substantial fraction of the unidentified 43% of* $\psi(3.7)$ *decay*[7] *may also involve radiative transitions to* $\gamma+h$ *final states via chain* $3.7\rightarrow 3.7$ *(or 3.1)* $+h\rightarrow \gamma+h$.

Schwinger's suggestion[31] that the ϵ model with a scalar meson in the scheme $3.7\rightarrow 3.1+(\epsilon\rightarrow \pi^+\pi^-)$ be applied also to the process $J^0\rightarrow \pi^+\pi^-\gamma$ has stimulated a number of detailed calculations[34,35] of this process. The conclusion is that in both the ϵ model and for an effective structureless local $\psi' J\pi^+\pi^-$ coupling model, the rate $\Gamma(J^0\rightarrow \pi^+\pi^-\gamma)$ can be < 1 keV and hence, if confirmed by experiment, removes the difficulty raised by Eq. (3). Similarly the rate[34] $\Gamma(\psi^{0\prime}\rightarrow \pi^+\pi^-\gamma)$ is ~0.675 $\Gamma(J^0\rightarrow \pi^+\pi^-\gamma)$. However, implicit in these calculations is the assumption that the *far-off-mass-shell* character of the intermediate J and ψ' in Eq. (2) does not seriously affect the medium-strong couplings $g_{\pi\pi JJ}$, $g_{\pi\pi J\psi'}$ and the couplings $f_{\gamma - J}$ and $f_{\gamma-\psi'}$ at γ-J and γ-ψ' vertices.

Of course application of the ϵ model to the on-mass-shell decay $3.7 \rightarrow 3.1 + (\epsilon \rightarrow \pi^+\pi^-)$ is unambiguous; indeed, the predicted invariant mass distribution of the final-state pions[37,38] are in good agreement with preliminary experimental data from SLAC.[2] We do not believe, however, that application of the ϵ model to $\psi' \rightarrow J + 2\pi$ is an unvarnished triumph for the charmonium model. For instance, if we use the ϵ model and normalize to the bona fide strong decay $\rho' \rightarrow \rho + \epsilon$ (where Schwinger *et al.* estimate[37] $g_{\rho'\rho\epsilon}{}^2/4\pi \sim 2$), the expected $g_{\psi' J \epsilon}{}^2/4\pi$ according to the charmonium model supplemented by the Pati-Salam rule[32] should be 2×10^{-6}—rather different from the value $g_{\psi' J \epsilon}{}^2/4\pi = (1.7 \text{ to } 9) \times 10^{-3}$ obtained purely *phenomenologically* by Harrington *et al.*[38] from the ϵ model. Indeed the over-all characteristics of the medium-strong decay $\psi \rightarrow J2\pi$ can be best parametrized by a multiplicative t-quantum number[39,29] conserved in strong interactions (e.g., $t = -1$ for J and ψ' and $t = +1$ for all previous hadrons h). Since γ-J^0 and γ-ρ^0 couplings exist, the electromagnetic interaction appears not to conserve t. Speculations along this line (with small or null linear interactions between the J and ψ' and ordinary hadrons) have been proposed by several authors.[29,34]

IV. CONCLUSIONS

(a) An anomalously large rate for $J^0 \rightarrow \pi^+\pi^-\gamma$, say a substantial fraction of the total width, will create difficulties for models discussed here with normal electromagnetic couplings for the J and ψ' particles. Accurate measurement of this decay together with a search for a possibly large radiative decay of $\psi(3.7) \rightarrow \gamma + h$ is of *great* interest.
(b) If the rate $J^0 \rightarrow \pi^+\pi^-\gamma$ should prove to be acceptably small ($\lesssim$ a few keV), the Schwinger phenomenological theory can be distinguished from charm-related models not only by the absence of exotic dileptons with varying degrees of charm, but also by the positive identification of an $I = 1$ $\tilde{\rho}$ state of comparable narrowness to the $I = 0$ J and ψ' very likely in the mass region below 3.1 GeV and of axial-vector partners of J, ψ' and $\tilde{\rho}$. (c) A multiplicative t-quantum-number scheme is supported by both the medium-strong nature of decay $\psi' \rightarrow J2\pi$ and $JN \rightarrow JN$ scattering inferred from photoproduction as well as by the small (perhaps null) linear interaction of J and ψ' with normal hadrons. If this hypothesis were correct, it would have important consequences for the pair production of (JJ) and $(J\psi')$ in hadron-hadron collision. In particular, we expect pair production to be *large at high energies*, while J and ψ' radiative decays should also be *substantial*. Examination of pairs of dileptons both with 3.1 GeV mass (or with 3.1 and 3.7 GeV masses) in high-energy reactions where the diffractive dissociation mechanism for generating large pair-production cross sections might be operative, together with the identification of a threshold for pairs, remains of high interest.

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