have medium-weak decays

$$\theta \to \text{nucleon} + e^+ + e^- + \text{mesons},$$

and

$$\theta \to \text{nucleon} + \text{mesons}.$$

θ and $\bar{J}$ could be produced in association.

Remarks.—(a) *The sign of $g_{\mu\mu}/g_{ee}$ can in principle be determined by studying the interference between the resonance and background terms in* $ee \to \mu\mu$. We notice here that the background term is due to quantum electrodynamic Bhabha scattering with the annihilation diagram as the only contributing one. This term can be explicitly computed. (It has the opposite sign from the background Bhabha scattering amplitude in $e^+e^- \to e^+e^-$.) The interference term is sizable and has a sign that depends on that of $g_{\mu\mu}/g_{ee}$.

(b) If J has no strong interactions it may be possible to determine the existence or absence of $g_{\nu\nu}$ by accurate measurements of Γ and the partial widths of J. In such a case, it seems to us that it is very difficult to determine $g_{\nu\nu}$ by other experiments.

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Remarks on the New Resonances at 3.1 and 3.7 GeV*

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This is a collection of comments which may be useful in the search for an understanding of the recently discovered narrow resonances at 3.1 and 3.7 GeV.

Several recent experiments[1-3] have revealed a strikingly narrow meson resonance at 3105 MeV (we shall refer to this as the J particle). There are also indications of a narrow resonance[4] at 3695 MeV (we refer to this as the ψ particle), observed in e^+-e^- annihilation.

Let us first briefly recall some of the characteristics of the J particle. The partial widths are estimated to be $\Gamma(J \to e^+ + e^-) \approx \Gamma(J \to \mu^+ + \mu^-) \approx 3$ keV, and for decay into channels containing charged hadrons, $\Gamma(J \to \text{visible hadrons}) \sim 50$ keV. The total width cannot be more[5] than $\sim 4\Gamma(J \to \text{visible hadrons})$. The J particle seems to decay at most only very rarely into states composed exclusively of 4 or 6 charged pions. This suggests assignment of odd G parity to the J particle; and the angular distribution of $e^+ + e^- \to \mu^+ + \mu^-$ under the resonance peak is consistent with a spin-1 assignment to the resonance.

Various possibilities suggest themselves for the theoretical interpretation of the J particle. The view that we wish to explore here is that it is a hadron in the same family as ρ, ω, φ, . . . , but composed of new kinds of quarks. We call these, generically, "charmed" quarks and denote them by the symbol c (they may or may not be the charmed quarks proposed by Glashow and coworkers[6,7] for use in theories of the weak interactions). This picture provides a natural basis for odd G-parity assignment to the J particle. The outstanding problem, of course, is to explain the narrow width for decay of the J particle into hadrons, and relatedly, the smallness of the production cross section as reported in Ref. 1.

Concerning the various alternative interpretations,[8] an important initial issue has to do with the question whether the J particle couples directly to leptons or only indirectly, via a virtual photon. On the latter picture the spin-parity assignment *must*, of course, be 1^-. There is, however, another test. On any picture, decay of the J particle into hadrons presumably takes place predominantly without electromagnetic intervention. However, if the J particle indeed couples directly to a virtual photon in its decay to leptons, then it can sometimes also decay to hadrons through a photon link: $J \to$ virtual $\gamma \to$ hadrons. For $\sqrt{s} \sim 3$ GeV, the branching ratio on this mechanism is about three times that into leptons; and from e^+-e^- annihilation data[9] off the resonance one knows that of the hadronic events about one in twenty involves four charged pions exclusively. Thus, for the J, we would expect a width of about $3\times\frac{1}{20}\times 3$ keV $\simeq 0.5$ keV for decay into four charged pions, or about one such event in a hundred under the J peak. Similarly, about 1% of the events under the peak should have a final state of six charged pions only. If such events were not observed at this level,[10] this would constitute a strong indication against coupling of J to a virtual photon.

For the remaining discussion we adopt the view that the J particle is a hadron, pictured to be a ^3S bound state of $c\bar{c}$ and analogous to the φ meson, similarly regarded as a ^3S bound state of $\lambda\bar{\lambda}$. The decay $\varphi \to 3\pi$ is known to be highly suppressed, presumably in accordance with the semiempirical "hairpin" rule of Zweig[11] and others. A measure of this suppression is provided by the ratio $\Gamma(\varphi \to 3\pi)/\Gamma(\omega \to 3\pi) \simeq 7\times 10^{-2}$. On the basis of various mass formulas to be discussed below we expected charmed hadrons ($c\overline{\mathcal{P}}$, $c\overline{\mathfrak{N}}$, $c\bar{\lambda}$, etc.) to have masses in the range ~ 2 GeV and greater, so that the analog of $\varphi \to K + \bar{K}$ decay is not available for J decay. In this way one may estimate that $\Gamma(J \to \text{hadrons}) \approx$ (typical, unsuppressed hadron width ~ 200 MeV)$\times 7\times 10^{-2}\xi \approx 14\xi$ MeV, where ξ is an extra suppression factor which reflects the presumed heaviness of the charmed quarks, $m_c \sim m_J/2$. To obtain the observed J width one needs a considerable extra suppression indeed, $\xi \sim 5\times 10^{-3}$. Various attempts[12] have been made to explain this, none completely convincing. For present purposes we simply accept the fact. What is especially puzzling, and no doubt significant, is that this suppression does not seem to be operative for annihilation of J into a virtual photon, i.e., the width for J decay into leptons is "normal" in the sense that it is comparable to that for $\varphi \to e^+e^-$ decay.

Because decay into ordinary hadrons is strongly suppressed, for whatever reason, certain decay modes which might otherwise be expected to be minor may become significant. In particular, if we accept that the J particle is a ^3S state of $c\bar{c}$, we may expect that there exists a pseudoscalar ^1S state, call it J_p, with mass comparable to that of J. If the mass is in fact below that of the J, as might be expected, the possibility arises of $J \to J_p + \gamma$ decay. On the present picture this would be a pure spin-flip transition, whose amplitude, expressed in terms of the magnetic moment of the charmed particles, can be estimated fairly reliably. We find $\Gamma(J \to J_p + \gamma) \simeq \frac{4}{3}\alpha Q^2\mu^2\omega^3/m^2$, where $Q = \frac{2}{3}$ is the presumed charge of the charmed quark, $m_c \sim 1500$ MeV is the mass, μ is the magnetic moment in units of $Qe/2m_c$, and ω is the photon energy. Calculations of this sort give a reasonable value[13] for the width of $\omega \to \pi^0 + \gamma$ decay. Taking $\mu = 1$ we find that the interesting range 1 keV $\lesssim \Gamma(J \to J_p + \gamma) \lesssim 100$ keV[5] corresponds to 80 MeV $\lesssim M_J - M_{J_p} \lesssim 400$ MeV.[14]

Concerning decays of the hypothetical J_p particle, whose G parity is even and isospin zero on the present picture, the allowed hadronic channels include states with an even number of pions (but the two-pion state is forbidden by parity considerations), $K\bar{K}\pi$, etc. However, the same mechanism that suppresses J decay into hadrons would be expected to be operative here also, so that modes which would otherwise be minor could become significant here, in particular the mode $J_p \to \gamma + \gamma$. The analogous process $\eta \to \gamma + \gamma$ has a width of about 1 keV. For $J_p \to \gamma + \gamma$, an estimate based on unbroken SU(4) for dimensionless coupling constants (with η taken to be a pure octet and J_p taken to be a state formed out of quarks of charge two-thirds) gives $\Gamma(J_p \to \gamma + \gamma)/\Gamma(\eta \to \gamma + \gamma) \sim \frac{32}{3}(m_{J_p}/m_\eta) \approx 60$. It would seem that a conservative lower limit is provided by equating the two widths, so $\Gamma(J_p \to \gamma + \gamma) \sim 1$ keV. At the other extreme, purely dimensional considerations would suggest a scaling according to the cube of the mass, so $\Gamma(J_p \to \gamma+\gamma)/\Gamma(\eta \to \gamma+\gamma) \sim (m_{J_p}/m_\eta)^3$. This leads to an enormous width, ~2 MeV, for $J_p \to \gamma+\gamma$ decay. All in all, a width of several tens of keV does not seem unreasonable. As for $J_p \to \gamma+\pi+\pi$ we appeal to the small width for the analogous $\eta \to \gamma+2\pi$ process to suggest that this may not be too significant.

According to the estimates described above, if J_p is appreciably less massive than J, one should encounter the chain $J \to J_p+\gamma \to \gamma+\gamma+\gamma$ which would affect the estimate of the widths.[5] These events would have a dramatic signature, involving one monochromatic low-energy photon and two others nearly monochromatic and nearly back-to-back.

An interesting question arises in connection with possible decay processes of the type $J \to \gamma$ + ordinary hadrons. Under "normal" circumstances one would expect the widths for $J \to$ hadrons, $J \to \gamma+$hadrons, $J \to e^+ + e^-$ to stand roughly in the ratio $1:\alpha:\alpha^2$, where $\alpha = \frac{1}{137}$. In fact, the absolute width for $J \to e^+ + e^-$ does have the normally expected magnitude, whereas the hadron width is greatly suppressed. This leaves open, for $J \to \gamma$ + hadrons, whether it is to be scaled by the appropriate factor of α relative to $J \to$ hadrons or to $J \to e^+ + e^-$, or neither. The "hairpin" rule would perhaps suggest the first alternative, so that $J \to \gamma$ + hadrons would be insignificant, even relative to $J \to e^+ + e^-$; but the uncertainty, *a priori*, is enormous. For φ decay the branching ratios into $\pi^0+\gamma$ and $\pi^+ + \pi^- + \gamma$ are small, with respective *upper* limits 0.35% and 0.7%. The limits are not yet decisive, considerably exceeding as they do the branching ratio for $\varphi \to e^+e^-$. On the other hand, the branching ratio for $\varphi \to \eta + \gamma$ is 3%, which is smaller than that for $\varphi \to 3\pi$ only by a factor of 5. Since η has a substantial $\lambda\bar{\lambda}$ quark content this decay is analogous to $J \to J_p + \gamma$, which we have argued might be substantial if the mass difference is appreciable. The evidence from φ decay therefore suggests that $J \to \gamma$ + ordinary hadrons should be suppressed relative to $J \to J_p + \gamma$.

The suppression of the coupling of J to ordinary hadrons reflects itself not only in the small decay width but also in the smallness of the cross section reported for J production in nucleon-nucleon collisions.[1] On the other hand, on the picture under present discussion J couples with normal strength to virtual photons. This suggests that J production could be substantial in diffractive photoproduction, comparable—at given momentum transfer t—to photoproduction of φ mesons. The only effect, *a priori*, that works against J photoproduction arises from the large J mass, hence the larger value for $|t_{\min}|$. Even so, for $E \gtrsim 20$ GeV the photoproduction cross section,[15] almost wholly diffractive, could well lie in the range of a few microbarns.

If the "usual" $\mathcal{P}, \mathcal{N}, \lambda$ quarks are indeed supplemented by charmed quarks, and if J can indeed be pictured as a $c\bar{c}$ state, then the J particle should belong to a family containing 1^- charmed hadrons of various sorts. The Gell-Mann–Okubo mass formula for the ordinary vector-meson nonet (supplemented by the assumption that $\varphi = \lambda\bar{\lambda}$) may then be extended to yield $m_H^2 = (m_J^2 + m_\rho^2)/2$, $m_L^2 = (m_J^2 - m_\rho^2)/2 + m_{K^*}^2$, where H denotes the charmed vector mesons with quark content $c\bar{\mathcal{P}}$, $c\bar{\mathcal{N}}$, and where L denotes a strange and charmed vector meson with quark content $c\bar{\lambda}$. There is of course the age-old dilemma of choosing between a quadratic mass formula, as given above, and a linear mass formula. Here, in fact, in the picture that J is a loosely bound, nonrelativistic system, the linear formula might well be more appropriate. With the quadratic formula we find $m_L \approx m_H \approx 2.3$ GeV; with the linear formula $m_L \approx 2.05$ GeV, $m_H \approx 1.95$ GeV. We do not enter here into a discussion of the possible decay and production properties of the charmed hadrons, a subject which has already been extensively discussed in the literature.[16] To estimate the mass of the J_p particle, discussed earlier, we may extend various ideas from the lore of Regge recurrences and of SU(6). Thus we extend the mass formula $m^2(K^*) - m^2(\rho) = m^2(K) - m^2(\pi) = m^2(K_2^*) - m^2(A_2)$ to read $m^2(J) - m^2(K^*) = m^2(J_p) - m^2(K)$. This leads to $m(J_p) \approx 3$ GeV. A linear version of this formula would produce a mass splitting $m_J - m_{J_p} \approx 400$ MeV. To discuss L-excited states of the $c\bar{c}$ system we propose an extension of the string model[17] in which the charmed quark masses at the ends of the string are given a finite value, m_Q. The energy and angular momentum of a rotating string are then given by

$$E = \frac{2m_Q}{(1-\omega^2R^2)^{1/2}} + 2\int_0^R dr \frac{T_0}{(1-\omega^2r^2)^{1/2}}$$

and

$$L = \frac{2m_Q\omega R^2}{(1-\omega^2R^2)^{1/2}} + 2\int_0^R dr\, T_0 \frac{\omega r^2}{(1-\omega^2r^2)^{1/2}},$$

where ω is determined by $\omega R = (1 + m_Q/T_0R)^{-1/2}$. From the observed Reggeon slope of ordinary hadrons (with $m_Q = 0$) we infer that $2\pi T_0 \approx 1$ GeV^2. For the low angular momentum excitations the nonrelativistic approximation is quite adequate and we find

$$E(L) = 2m_c + (2T_0^2/m_c)^{1/3} L^{2/3}.$$

Thus, the $L=1$ excitations of the loaded string (corresponding to J^{pc} 0^{++}, 1^{++}, 2^{++}, 1^{+-} mesons) have a mass ~3400 MeV, while the $L=2$ (1^{--}, 2^{--}, 3^{--}, 2^{-+}) excitations have a mass ~3600 MeV.

It is tempting to identify[18] the $L=0$ daughter of the $L=2$ excitation at 3600 MeV with the $\psi(3700)$ resonance discovered at SPEAR, thus interpreting ψ as a radially excited ^3S state of the $c\bar{c}$ system, with odd G parity and spin and parity 1^-. On this interpretation, the processes $\psi \to J + 2\pi$ and $\psi \to J_p + \gamma$ could well be important among the various decay modes of the ψ particle. Although the decay $\psi \to J + 2\pi$ is suppressed in the soft-pion limit on consideration of partial-conservation of axial-vector current and current algebra ideas, a corresponding suppression for the analogous decay $E \to \eta + \pi + \pi$ does not seem to be operative; for both reactions the pions are not that "soft." Of course, for $\psi \to J + 2\pi$ and for ψ decay into ordinary hadrons we still have to invoke the suppression implied by the hairpin rule but this would be expected to be less strong for $\psi \to J + 2\pi$ if ψ and J have the same quark content.[19] The process $\psi \to J_p + \gamma$ is analogous to the reaction $J \to J_p + \gamma$ discussed earlier, but for the ψ decay case there is ample available phase space. Recall, other things being equal, that the width grows cubically with the photon energy. One encounters here a radial overlap integral $\langle \psi_{J_p} | e^{i\vec{k}\cdot\vec{x}} | \psi_\psi \rangle$ whose magnitude depends on the characteristic radius R of the orbits of the $c\bar{c}$ system. Since $|\vec{k}| = \omega$ is large however, ωR could well be substantial and the overlap integral, therefore, might be of order unity. For the purpose of estimating the width we assume a simple harmonic oscillator potential between c and $\bar{c}$ with spring constant adjusted to give the observed mass difference. The overlap integral (taking $m_{J_p} \sim m_J$, so $m_\psi - m_{J_p} \sim 600$ MeV) turns out to be $\sim\frac{1}{4}$, corresponding to a width of ~25 keV. The upper limit to the width would be ~400 keV corresponding to the maximum overlap of 1. The radiative decay of ψ into $L=1$ states may be very significant. On the basis of the loaded string we estimated the mass of these states at 3400 GeV; the harmonic oscillator model mentioned above gives roughly the same. With the harmonic oscillator model a rough estimate (based on the electric dipole approximation) for the decay width yields $\Gamma \approx \frac{32}{27}\alpha\omega^2/m_c^2 \approx 500$ keV. An alternative possibility is that the ψ particle is the ^3S ground state of another kind of charmed quark-antiquark pair, $c'\bar{c}'$. The Glashow-Iliopoulos-Maiani mechanism is easily extended to such a proliferation of charmed quark types. In such a model the decay $\psi \to J +$ hadrons would not be expected to be significant.

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[18]If the force between c and $\bar{c}$ may be approximated by a harmonic oscillator potential then the first radial excitation with $L=0$ is degenerate in energy with the lowest state with $L=2$.

[19]We note that the decay $\psi \to J+\eta$, which might otherwise be expected to be a strong competitor with $\psi \to J+2\pi$, should be suppressed because the available phase space is limited and the decay takes place only in the P wave. Moreover the process violates SU(3) symmetry.

COMMENTS

Intermediate Boson in the Fermion-Current Model of Neutral Currents*

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The intermediate-boson version of the earlier proposed fermion-current model of neutral currents is discussed. In particular I speculate on the possibility that the recently discovered 3.105-GeV particle may be identified with the intermediate boson of the fermion-current model.

Shortly after the discovery of neutrino-induced neutral-current reactions it was proposed that the hadronic piece of the neutral current be identified with the unitary singlet baryon current.[1] In the same paper I also speculated that all neutral-current phenomena are due to an extremely simple universal Fermi interaction of the form

$$\mathcal{L}_{\text{eff}} = (G\lambda/\sqrt{2})\, j_\lambda^{(\text{F})} j_\lambda^{(\text{F})}, \tag{1}$$

with

$$j_\lambda^{(\text{F})} = i\left[\bar{e}\gamma_\lambda e + \bar{\mu}\gamma_\lambda\mu + \bar{\nu}_e\gamma_\lambda\nu_e + \bar{\nu}_\mu\gamma_\lambda\nu_\mu + \bar{u}\gamma_\lambda u + \bar{d}\gamma_\lambda d + \bar{s}\gamma_\lambda s\right], \tag{2}$$

where the notation of the uncolored quark model is used for hadrons. In view of the recently reported evidence for a narrow-width boson in e^+e^- production[2] and in e^+e^- annihilation,[3] it is of some interest to make a few comments on the intermediate-boson version of the "fermion-current model."

I propose that the effective interaction (1) applicable to low-q^2 phenomena arises from a more fundamental intermediate-boson coupling as follows:

$$\mathcal{L} = gZ_\mu j_\mu^{(\text{F})}, \tag{3}$$

where Z_μ is a neutral spin-1 field of mass m_Z. Clearly we have

$$g^2/4\pi = 2(\lambda/4\pi)(G/\sqrt{2})m_Z^2, \tag{4}$$

where the factor 2 is necessary because the interaction (1) represents the product of two identical currents so that a typical term like $(\bar{e}e)(\bar{u}u)$ appears twice.[4] The partial decay width for the Z boson decaying into a lepton pair can easily be calculated to be

$$\Gamma(Z\to e^+e^-) = \Gamma(Z\to \mu^+\mu^-) = \tfrac{1}{3}(g^2/4\pi)m_Z \simeq (10^{-5}/\sqrt{2})(\lambda/6\pi)(m_Z^3/m_p^2). \tag{5}$$

As for the hadronic decay modes of the Z boson, let us first observe that the quantum numbers of the final states are characterized by

$$J^{PC} = 1^{--}, \quad I^G = 0^-. \tag{6}$$

This quantum number assignment leads to numerous predictions some of which will be discussed