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Possible Interactions of the *J* Particle*

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We discuss some possible interaction schemes for the newly discovered particle J and their experimental implications, as well as the possible existence of two J^0's like the K_S-K_L case. Of particular interest is the case where the J particle has strong interactions with the hadrons. In this case J can be produced by associated production in hadron-hadron collisions and also singly in relative abundance in ep and μp collisions.

A new particle J with a mass of 3.1 GeV was recently discovered.[1-3] We shall analyze in this note the properties of J. In view of its small width we shall assume that J is not coupled singly to hadrons. That is, we assume that there are no strong couplings of the form J(hadrons). However, strong couplings of the form JJ(hadrons) may be present, causing J to interact strongly with hadrons. We discuss the cases where J does not and does have such strong interactions. Our analysis is mostly phenomenological, with a minimum of theoretical prejudices about specific schemes of hadron structure.

Let M_J, Γ_{ee}, $\Gamma_{\mu\mu}$, $\ldots$, Γ be the mass, the partial widths, and the total width of J. We shall assume that it is coupled to the $\bar{e}e$, $\bar{\mu}\mu$, and other fields through the effective Hamiltonians

$$\mathcal{H} = ig_{ee}[\bar{e}\gamma_\lambda(1+\gamma_5)e]J_\lambda + ig_{\mu\mu}[\bar{\mu}\gamma_\lambda(1+\gamma_5)\mu]J_\lambda + \mathcal{H}_{\text{other}}, \tag{1}$$

or

$$\mathcal{H} = ig_{ee}[\bar{e}\gamma_\lambda e]J_\lambda + ig_{\mu\mu}[\bar{\mu}\gamma_\lambda\mu]J_\lambda + \mathcal{H}_{\text{other}}. \tag{2}$$

J_λ is chosen Hermitian and all g's are real. We assumed the spin of J to be 1. However, we do not speculate in this paper about the origin of these effective Hamiltonians. In particular, we do not assume that (2) is necessarily electromagnetic in origin. The decay widths are

$$\begin{aligned} &\Gamma_{ee} = \tfrac{2}{3}M_J\beta_{ee}, \quad \Gamma_{\mu\mu} = \tfrac{2}{3}M_J\beta_{\mu\mu}, \quad \text{for (1);} \\ &\Gamma_{ee} = \tfrac{1}{3}M_J\beta_{ee}, \quad \Gamma_{\mu\mu} = \tfrac{1}{3}M_J\beta_{\mu\mu}, \quad \text{for (2),} \end{aligned} \tag{3}$$

where

$$\beta_{ee} = (4\pi)^{-1}g_{ee}^2, \quad \beta_{\mu\mu} = (4\pi)^{-1}g_{\mu\mu}^2. \tag{4}$$

The integrated resonance cross section ($\bar{e}e \rightarrow$ all) is

$$\int \sigma^{(J)}(\bar{e}e \rightarrow \text{all})\,dE = b\pi^2 M_J^{-2}\Gamma_{ee}. \tag{5}$$

Notice that the cross section at M_J for (channel

$i) \to$ (channel 0) is

$$4\pi\lambda\!\!\!^{-2}(\tfrac{3}{4})\Gamma_i\Gamma_0/\Gamma^2. \tag{6}$$

An easy way to derive these formulas is to compute the elastic cross section $e^+e^- \to e^+e^-$ by Feynman diagrams with an imaginary part given to the mass of J. If the lepton masses are ignored, the angular distributions for both $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$ are

$$(1+\cos\theta)^2 \text{ for (1)}, \quad 1+\cos^2\theta \text{ for (2)}. \tag{7}$$

If the e^+ and e^- beams are independently polarized, these angular distributions are not changed.

We estimate the left-hand side of (5) to be ~9000 nb MeV. [Of this total, 8000 comes from a numerical integration of Fig. 1(a) of Ref. 2, and 500 comes from estimated contributions from each of the other two figures of the same paper. Purely neutral channels are assumed to contribute little.] Thus

$$\Gamma_{ee} \sim 4 \text{ keV}, \quad \Gamma \sim (9000/500)\Gamma_{ee} \sim 70 \text{ keV}, \tag{8}$$

for both (1) and (2), while the coupling constant β_{ee} is

$$\beta_{ee} \sim 2\times10^{-6} \text{ for (1)}, \quad \beta_{ee} \sim 4\times10^{-6} \text{ for (2)}. \tag{9}$$

These estimates for Γ_{ee} and β_{ee} are insensitive to the value of 500 nb MeV used here.

Case of no strong interaction for particle J.—We first consider this case, i.e., the case where J interacts with hadrons only through couplings of the order of its decay interactions. In this case if coupling (1) is found to be valid, J very much resembles the neutral component of the intermediate boson[4] W that has been proposed to mediate weak interactions, since the coupling constant β_{ee} above is of the same order of magnitude as that of intermediate bosons. If on the other hand coupling (2) is found to be valid, then J resembles a heavy photon. However, it is interesting to observe that the coupling of J to hadrons cannot be exactly proportional to the photon coupling to hadrons, because otherwise one would have

$$R_J = R_{\text{background}},$$

where R is the ratio of hadron channels to the $\bar{\mu}\mu$ channel. Experimentally,[2] $R_J \sim 20$ while $R_{\text{background}} \sim 3$. Thus if interaction (2) obtains, an attractive possibility is that J is a massive Abelian gauge field generated by some conserved quantity other than the charge,[5] such as a combination of the baryon number and lepton numbers, with a small coupling constant.

Case of strong interaction for particle J.—The presence[6] of a strong interaction of the form

$$JJ(\text{hadrons}) \tag{10}$$

has many extremely interesting experimental consequences. These will now be separately discussed.

(A) J can be produced in hadron collisions through the inverse of its decay channel $J \to$ hadrons. We shall call this process the weak production process. If (10) is present, then J can also be pair produced. This resembles the associated-production mechanism of Pais[7] in a different context. The observed J production cross section at Brookhaven National Laboratory[1] is $\sim 10^{-34}$ cm^2, leading to the ratio $J/\pi \sim 10^{-9}$. If (10) is absent, this ratio is likely to remain at this order of magnitude at higher energies. On the other hand, if the observed J production cross section is due to associated production, then *the ratio J/π may rise to considerably larger values at high energies*. The reason is that the Brookhaven energy is low and it requires the Fermi motion of the nucleons inside the Be target nucleus to make pair production possible. We note here that a sizable J/π ratio could contribute to, and may even account for, the observed ratios e/π and μ/π at high transverse momenta, as recently extensively studied. [Cf. following discussion of additional quantum numbers.]

(B) A coupling

$$g_{\nu\nu}[(\bar{\nu}\nu)J] \tag{11}$$

with a strength comparable with the $(\bar{e}e)J$ coupling would lead to copious productions of J in ν collisions with nucleons through the process illustrated in Fig. 1(a), if the energy of ν is above J production threshold. The total cross section of νp would then be very much larger than the observed values. Hence one concludes that *the*

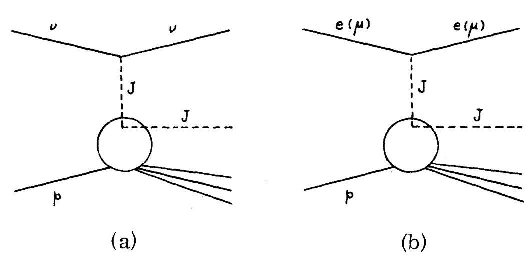

FIG. 1. J production in νp and ep collisions if J interacts strongly with hadrons.

presence of strong interaction (10) implies that $|g_{\nu\nu}| \ll |g_{ee}|$.

(C) The presence of the coupling (10) implies that

$$e\ (\mu) + p \rightarrow e\ (\mu) + J + \text{hadrons}, \tag{12}$$

as shown in Fig. 1(b). For large values of q^2, the branching ratio of (12) as compared with $e\ (\mu) + p \rightarrow$ all may be estimated by comparing (9) with α^2. Experimental search of the process (12) through the leptonic decay modes of J is thus of great interest. For $|q|^2 \gtrsim M_J{}^2$, the branching ratio is very roughly

$$\frac{e\ (\mu) + p \rightarrow e\ (\mu) + \bar{l}l + \text{hadrons}}{e\ (\mu) + p \rightarrow \text{all}} \sim 10^{-2} \text{ to } 10^{-3}, \tag{13}$$

where $\bar{l}l$ stands for $\bar{e}e$ or $\bar{\mu}\mu$ at the J mass.

(D) If $J^{\pm}$ exists (see below), and is quadratically coupled strongly to hadrons as in (10), then by an entirely similar reasoning as under (B) above, one would conclude that $J^{+}(\bar{\nu}e)$ coupling is very small. Thus in this case $J^{\pm}$ cannot be the mediator for β decay.

(E) S. C. C. Ting and his group have informed us that they have discussed for several weeks the possibilities of the existence of $J^{\pm}$, and decays such as

$$J^{\pm} \rightarrow (\text{hadrons} + \text{photons})^{\pm} e^{+} e^{-}, \tag{14}$$

and

$$J \rightarrow (\text{hadrons} + \text{photons})^{0} e^{+} e^{-}. \tag{15}$$

They are working on their data to see whether they have already discovered (14) and (15). If (15) exists with a rate comparable with that for $J \rightarrow e^{+}e^{-}$ except for phase-space factors, then one can conclude that the coupling (10) exists as a strong interaction.[8] The converse is also true.

Decay (15) if it exists with sizable branching ratios, may in fact be a significant part of Fig. 1(a) of Ref. 2. If that is true, there is the intriguing possibility that the ratio of the pure hadron width to $\mu\mu$ width of J is only

$$R_J \approx 3 \approx R_{\text{background}}. \tag{16}$$

Possible existence of additional quantum numbers.—For a Hermitian field J the quadratic strong coupling JJ(hadron) implies that J has a *multiplicative* quantum number $t = \pm 1$, and that t is conserved in strong interactions. While this is possible, *additive quantum numbers* are probably more appealing. Additive quantum numbers would result if there are two J^0's (like in the K^0-$\bar{K}^0$ case). One would then have a strong interaction

$$J^0 \bar{J}^0(\text{hadrons}), \tag{17}$$

where

$$J^0 = J_1 + iJ_2, \tag{18}$$

with J_1 and J_2 both Hermitian. The observed J is then some linear combination of J_1 and J_2. In this case one has a new additive quantum number t, an integer, which is conserved in strong interactions: $t = 1$ for J^0 and $t = -1$ for $\bar{J}^0$; $t = 0$ for the pre-J-discovery particles. Notice that the narrow width of J is consistent with the proposal that t is conserved also in electromagnetic interactions and that $t = 0$ for the photon.

The presence of (10) as a strong interaction implies that J has an isotopic spin. An intriguing possibility is then that $J^{+}J^{0}$ and $\bar{J}^{0}J^{-}$ form two isotopic spin doublets. In this case the well-known formula $Q = I_z + \frac{1}{2}Y$ should be extended to read

$$Q = I_z + \tfrac{1}{2}(B + S) + \tfrac{1}{2}t. \tag{19}$$

The symmetry group for the strong interactions[9] in such a case should have a higher rank than SU(3).

The J_1-J_2 complex is then quite similar to the K_S-K_L complex. The mass difference between them is perhaps of the order of the larger of the two widths (~ 100 keV). Interesting interference effects might then be detectable in the $e^{+}e^{-}$ colliding-beam experiments.

CP violation is very likely involved in the decay of J_1-J_2, and the situation is quite similar to that of the $W_a{}^0$-$W_b{}^0$ complex discussed in Ref. 4.

The general picture that emerges, if these discussions turn out to be relevant, is that there are new quantum numbers that cause the stability of J, and that there is a new class of medium-weak interactions of strengths $\sim 10^{-6}$ that cause the decay of J. Because of the discussions in (B) and (D) above, it seems unclear that these medium-weak interactions are related in any way to the square root of the usual weak interactions.

The new quantum numbers could also stabilize other hadrons. *It would be interesting to search for these narrow hadrons.* For example, there could be a particle θ with baryon number $B = 1$, $S = 0$, and $t = 1$, with a narrow decay width ~ 100 keV. Its mass should be between $3.1 - 0.94 = 2.16$ GeV and $3.1 + 0.94 = 4.04$ GeV to stabilize against the decay of J and θ into each other. It would 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