SOME MODELS FOR THE MASSIVE NARROW RESONANCES IN e^+e^- ANNIHILATION

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This letter presents several models for the high-mass narrow states recently observed in e^+e^- annihilation. Probably the most satisfactory is that they are e^+e^- resonances strengthened through hadronic lepton cores. Z^0, γ^*, ϕ, U^0, $c\bar{c}$ and coloured mesons and gluons are also discussed as possible identifications.

The three recently-discovered high-mass narrow-width particles (1,2) possess some anomalous properties, which it is the purpose of this Letter to discuss in a number of alternative models. The lowest-lying state (J) has a mass 3.103 ± 0.003 GeV (3) and a width < 1.9 MeV (2). It decays 90% in the multihadron channel and 5% each to e^+e^- and $\mu^+\mu^-$. There are an average of $3.4 \pm .5$ charged particles and $1.6 \pm .1$ γ in the J decay, and other neutrals are usually present. The second state (k) (4) has a mass 3.695 ± 0.004 GeV and a width < 2.7 MeV; its dominant decay mode is J 2π. The third state (L) is broad ($\Gamma \sim 100 - 200$ MeV) and has a mass ~ 4.1 GeV (5). There is no definite reason to assume that L is associated with J and k, but the fact that the three are probably the only large peaks above 2 GeV suggests that they are due to the same phenomenon. No quantum numbers have yet been determined for any of the particles, although there are reports of J photoproduction, predominantly in the forward direction, indicating spin 1.

Discounting angular-momentum barrier effects (6), the narrow J width needs explanation in terms of an interaction somewhat weaker than the pure strong interaction. The recent experimental detection of neutral currents (7) suggests that Z^0 may indeed be physically real, and perhaps identifiable with J. Its lifetime would be $\sim 10^{-18}$ s, within the bounds of present J width determinations, but both its e^+e^- and photoproduction cross-sections would be considerably lower than those observed for J (8). Nevertheless, the J branching ratio for leptonic decay modes is roughly that calculated for Z^0 from the relative strengths of leptonic and hadronic neutral currents. This model would be favoured if a mode such as $e^+\pi^-v_e$ were detected, although these would have low amplitudes. Like π^0,

Z^0 may be a Regge trajectory rather than a strict elementary particle (9), and this might help to renormalize weak interaction theory. $m_k^2 - m_J^2 \sim m_L^2 - m_k^2$ (this is only precise for $m_L = 4.2$ GeV, which is just within experimental error), but this Regge trajectory has a slope of only $\sim\frac{1}{4}$ that for hadrons, which is perhaps due to the semiweak interaction expected in this model. Most of the gauge unified field theories, however, give a Z^0 mass much higher than m_J (10). Also, in any model of J, it is obviously satisfactory if we can account for the observed constancy of the hadron production cross-section in high-energy e^+e^- annihilation (11), and it has been shown that Z^0 exchange would not alone be sufficient to keep it at the observed level ($\sim$25 nb) (12).

A second possibility, that J is a heavy photon (13), is not yet ruled out by QED tests, and the lifetime of 10^{-17} s predicted for γ^* is roughly that estimated for J, but there should be a larger J-e coupling and k and L apparently have no place in this model (14).

The gauge unified field theories (15) predict the existence of the Higgs scalar (16), ϕ, which might furnish simultaneous explanations both of hadron production and of J. If such a particle were an intermediate state in

$$e^+ \quad e^- \longrightarrow \text{hadrons} \qquad (1)$$

then this could enhance the cross-section by a factor of up to 100 (17). Furthermore, C-parity considerations indicate that ϕ should decay more to π^0 than to $\pi^\pm$ (18), thus explaining the steady decrease in charged hadron multiplicity as higher energies are reached. Both the ϕ width and mass are as yet unknown, but taking m_W = 37.4 GeV (19), experiments demonstrate that $m_\phi \gtrsim 3$ GeV (20). Unfortunately, the normal ϕ has a very weak e-coupling, whereas J evidently does not, since it is produced with $\sigma \sim 2500$ nb in e^+e^- collisions. However, in the Georgi-Glashow model, ϕ_2 appears, whose e-coupling is proportional to the heavy-electron mass (21). $m_E > 1$ GeV (22), so that the ϕ_2-e coupling is possibly $\sim g_{Je}$. ϕ_2 would decay to e^+e^-, $\mu^+\mu^-$ and hadrons. k could then be identified with ϕ_1, but the failure to observe a fast decay $k \longrightarrow J\,X$ renders this model unlikely. The presence of any scalar might be tested by observing the t-dependence of the hadron production cross-section in e^+e^- colliding beams (18). Finally, however, the recent forward photoproduction of J probably demonstrates that it has unit spin.

In the Pati-Salam unified field theory (23), a host of further states appear, some having properties in common with J, k and L. Propagators such as X and S^o are much too massive ($\sim$ 100 GeV) to be identified with the J complex, but the model also introduces an octet V(8) of neutral coloured vector gluons. Some of these could have m $\sim$ 3 GeV, and would have photon quantum numbers. They would be produced in pairs by the strong interaction, but, on their own, might be quasistable, as their decay would involve colour nonconservation. The failure to observe k in searches at Brookhaven (1,2) possibly indicates pair-production, but further tests are necessary. All three new states could be accomodated in the V(8) octet, showing that the apparent Regge trajectory structure was not significant.

In common with other members of the vector octet, the photon is expected to possess a colour component U^o (23). Such a state would, like J, exhibit standard heavy-photon resonance properties, and would be produced with observable cross-section. It would probably have a small width (assuming the rest of the colour octet to be more massive), as its decays would not conserve colour. The dominant U^o decay mode would be of the form $n\pi^o\gamma$, although e^+e^- and $\mu^+\mu^-$ would appear. In the Pati-Salam model (23), the U^o contribution to (1) is negligible for the q^2 obtainable, but vector gluons and vector-gluon pairs could act as important intermediate states, contributing a term rising with s. k and L would here be standard Regge recurrences of U^o, although heavy γ would have to be suppressed.

J and k could also be standard coloured vector mesons, in which case the constant cross-section for (1) would be explained by simple vector meson dominance, although there may be some difficulties associated with an infinite series of vector mesons (24). L would then be interpreted as an ordinary strong-decaying vector meson resonance. This model could be tested by attempting to observe peaks in the cross-section for (1) at low energies ($\leqslant$ 2 GeV).

Yet another possible identification for J is a charm-anticharm quark ($c\bar{c}$) vector meson (25). However, there is no satisfactory explanation for the failure to observe any trace of a lower-mass $c\bar{c}$ scalar meson in e^+e^- annihilation, rendering this hypothesis unlikely. Furthermore, k appears to be much too stable to be a simple strong-excited state of J.

Perhaps the best model for the J, k and L states is that they are threshold effects occurring in lepton <u>hadronization</u>. QED has been amply tested down to

$\sim 5 \times 10^{-17}$ m (26), but the electron may well possess a hadronic inner core of diameter $\sim 10^{-18}$ m. We may justify this choice of size by remarking that, in analogy to the strong interaction, $\sqrt{G_F} \approx 6 \times 10^{-19}$ m is the characteristic structure size associated with the weak interaction (27). At low energies, e will behave as a pointlike lepton, but, as the interaction energy increases, so the hadronic core becomes more important, causing a corresponding increase in the strength of lepton-lepton and lepton-hadron interactions. This effect could perhaps be described by a strong-interaction form factor (28). As the energy increases, so the density of hadron exchange increases, but at low energies ($E < E_{crit}$), there is no hadron exchange. Thus, unlike the Pati-Salam X-e-q coupling (29), the lepton hadronization model does not produce erroneous contributions to pseudoscalar meson decay branching ratios (30) until high energies are reached, but it does still predict the cross-section for (1) to be ~ 25 nb for $9 < q^2 < 25$ (GeV)^2 if we take the effective interaction core diameter as $\sqrt{(25 \times 10^{-36})/2\pi} \sim 8 \times 10^{-19}$ m.

The hadronization model appears to agree with experiment on a number of further points. In $p\bar{p}$ interactions at 5 GeV c.m.s., the hadron production cross-section is ~ 100 mb (31), about 10^6 times that in lepton-like collisions. The nucleon core diameter is $\sim 10^{-15}$ m, and the model takes the electron core diameter as $\sim 10^{-18}$ m. Under the reasonable assumption that hadron yield $\propto$ hadronic core area, we predict the observed factor 10^6. Furthermore, the energy distribution of the resultant π, $E_\pi (d\sigma/d^3p)/\sigma_{had}$, near 90°, is almost identical in high energy ee and pp collisions (11,32), indicating a similar structure in the two cases, and disagreeing with the predictions of standard models. Together with baryon and lepton number violation (33), lepton hadronization may also be of importance in models of the early history of the universe. It could help to explain the high $\nu\bar{\nu}$ interaction rate and subsequent hadron formation in the first second after the 'big bang'. Again, there are recent reports (34) of e^+e^- production with a cross-section as much as 5 times that predicted from parton models (35) in 200 GeV pp interactions, indicating large ep couplings at high energies, typical of an e-hadronization situation. Finally, the completeness of the gauge unified field theories requires (23) that the asymmetric behaviour of leptons and hadrons to the strong interaction will cease at high energies.

Within this framework of hadronic lepton cores, we can derive a very satisfactory model for the J complex. At the high energies involved in J production, electrons are markedly hadronic, so that the effective strength of the e^+e^- interaction is radically increased. Hence the formation of a <u>quasistrong</u> e^+e^- resonance may occur, with properties very similar to those of J. Its width would be small, and it would possess both hadronic and leptonic decay modes. Assuming the value of 4.1 GeV for m_L to be correct, we find that the Regge trajectory connecting k and L has a slightly steeper slope than that connecting J and k. Such a phenomenon is typical of that expected from an interaction whose strength is increasing. Furthermore, $\Gamma_L > \Gamma_K \geqslant \Gamma_J$, again suggesting an interaction of increasing strength. The hadronization effect would produce larger hadron decay branching ratios from L and k than from J, and this is absolutely consistent with the experimental data. The abundant photon component in J decay may arise primarily from final-state interactions, such as $e^+e^- \longrightarrow \gamma$. In k decay, less will appear, since the products have higher momenta. Experimental tests of the hadronization model would include observations on high-energy ep, $\mu^+\mu^-$ (36) and e^+v_e interactions, in which there should be excess hadron production and resonant peaks (scaling violation). It has also been suggested (37) that the presence of anomalous lepton interactions could be detected in precise measurements of the circular polarization of x-rays from muonic atoms and comparisons between e^-p and e^+p cross-sections at high energies.

The effective weak interaction coupling constant should remain as G_{Fermi} until a critical energy $E_{crit} \sim 2$ GeV is reached. At the point, the hadronic core should begin to affect it, so that it rises exponentially (with slight damping at various points because of the Regge structure of strong-interaction propagators) up to a maximum value $\sim 10^{-3}\ G_{strong}$, the interactions of the hadronic core being restricted by its smallness. One explanation for the existence of a critical energy for hadron exchange would be that the propagators are held in the core by some strong but saturated force until they attain a critical 'breakaway' energy. This force could possibly arise from gluon exchange in and around the central quark-parton core. If the range of the superstrong gluon interaction were $\sim 10^{-18}$ m, then hadron propagators would be restricted to the core at low energies in leptons but not in hadrons, in agreement with experiment (38).

Thus we may conclude that the most satisfactory model for J, k and L is that they are hadronized-lepton resonances, although their properties might also be accounted for if they were coloured.

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(1) J.J.Aubert et al, Phys. Rev. Lett. 33 (1974) 1404; J.E.Augustin et al, Phys. Rev. Lett. 33 (1974) 1406; C.Bacci et al, Phys. Rev. Lett. 33 (1974) 1408.

(2) G.S.Abrams et al, Phys. Rev. Lett. 33 (1974) 1453.

(3) Weighted average of estimates in ref. 1.

(4) J is also called $\psi(3105)$ and k also $\psi(3695)$.

(5) Announced by SPEAR Jan. 1975.

(6) If J did have an exotic spin, then we should a production cross-section lower than $\sim$ 2500 nb.

(7) F.J.Hasert et al, Phys. Lett. 46B (1973) 138.

(8) N.Cabibbo, R.Gatto, Phys. Rev. 124 (1961) 1577; R.W.Brown, L.B.Gordon, K.O.Mikaelian, Phys. Rev. Lett. 33 (1974) 1119; R.F.Cahalan, Phys. Rev. D9 (1974) 257.

(9) C.Iso, Ann. Phys., 23 (1963) 304.

(10) Most of the gauge theories give $m_Z \sim 76$ GeV; e.g. J.C.Pati, A.Salam, Phys. Rev. D10 (1974) 275.

(11) A.Litke et al, Phys. Rev. Lett. 30 (1973) 1189; G.Tarnopolsky et al, Phys. Rev. Lett. 32 (1974) 432.

(12) C.H.Llewellyn Smith, D.V.Nanopoulos, CERN rep. (unpubl.).

(13) R.Blankenbecler, L.F.Cook, M.L.Goldberger, Phys. Rev. 128 (1963) 2440.

(14) If they are Regge reccurrences, then we should expect others at 2008 MeV, 2839 MeV, etc. (there is $A_4(1960)$ with $J^P = 1^-$, but we should expect copious production in e^+e^- beams.

(15) E.g. S.Weinberg, Phys. Rev. Lett. 27 (1971) 1668.

(16) P. Higgs, Phys. Lett. 12 (1964) 132.

(17) E.Ma, Phys. Rev. D10 (1974) 1576.

(18) T.Goldman, P.Vinciarelli, Phys. Rev. Lett. 33 (1974) 246.

(19) T.D.Lee, Phys. Rev. Lett. 26 (1971) 801.

(20) M.Conversi, S.D'Angelo, R.Gatto, L.Paoluzi, Phys. Lett. 46B (1973) 269.

(21) J.D.Bjorken, C.H.Llewellyn Smith, Phys. Rev. D7 (1973) 887.

(22) M.Bernardini et al, Nuovo Cimento 17A (1973) 383.

(23) E.g. J.C.Pati, A.Salam, Phys. Rev. D10 (1974) 275.

(24) J.J.Sakurai, Phys. Lett. 46B (1973) 207.

(25) R.Walgate, New Scient. 64 (1974) 861.

(26) E.g. J.Bailey et al, Nuovo Cimento 9A (1972) 369.

(27) O.W.Greenberg, G.B.Yodh, Phys. Rev. Lett. 32 (1974) 1473.

(28) R.Chanda, Lett. Nuovo Cimento 11 (1974) 593.

(29) J.C.Pati, A.Salam, Phys. Rev. Lett. 32 (1974) 1083.

(30) J.D.Davies, J.G.Guy, R.K.P.Zia, Nuovo Cimento 24A (1974) 324.

(31) Particle Data Group (V.Chaloupka et al), Phys. Lett. 50B (1974).

(32) J.W.Cronin et al, Phys. Rev. Lett. 31 (1973) 1426.

(33) J.C.Pati, A.Salam, Phys. Rev. Lett. 31 (1973) 661.

(34) P.L.Jain et al, Phys. Rev. Lett. 32 (1974) 797.

(35) E.g. G.Altarelli, N.Cabibbo, L.Maiani, R.Petronzio, Nucl. Phys. B69 (1974) 531.

(36) Preliminary data from $\mu^+\mu^-$ scattering at high energies indicates scaling violation (D.J.Fox et al, Phys. Rev. Lett. 33 (1974) 1504), but the situation will be more complex with μ than with e, as μ probably has a composite structure (D.K.Ross, Nuovo Cimento 9A (1971) 254).

(37) M.A.B.Beg, G.Feinberg, Phys. Rev. Lett. 33 (1974) 606.

(38) A highly-speculative variation on the hadronization model presented here would be that the weak interaction arises as a low-energy effect involving the weak long-range exchange of vector gluons from the core. At high energies, full-strength core-core gluon-mediated interactions could occur, resulting in high hadron yield and resonant behaviour. There is still no definite reason to exclude the identification of e^-, v_e, and v_μ with the quarks. v_μ would be taken as strange.