FIVE QUARKS, NEW PARTICLES AND V + A CURRENTS

Y. ACHIMAN
Institut für Theor. Physik, Universität Heidelberg, Germany

K. KOLLER

and

T.F. WALSH
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

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We propose an SU(5) model for the new heavy mesons, with a charge −1/3 fancy quark in addition to a charge + 2/3 charmed quark. Besides interpreting the two narrow vector mesons J/ψ and ψ' as $c\bar{c}$ and $f\bar{f}$ bound states and accounting for present data in a natural way, the model has (i) three new fancy vector mesons in addition to the charmed ones of the SU (4) model, (ii) *at most* two new $C = P = +$ mesons ($c\bar{c}, {}^3P_J, J = 0, 1$) between J/ψ and ψ', with suppressed radiative decays $\psi' \to {}^3P_J + \gamma$, (iii) a state near 4.6 GeV in e^+e^-, decaying mostly to fancy mesons if it is broad or perhaps charmed mesons if it is narrow, (iv) V + A weak currents and a large anomaly in $\bar{\nu}N$ reactions, (v) a possible heavy lepton.

The recent discovery of new narrow vector mesons [1, 2] suggests expanding the SU(3) symmetry of low mass hadrons to some larger and more badly broken group, of which SU(3) is a subgroup. Candidates for new symmetries are SU(4) [3] and SU(3) × SU(3) [4].

There have been other recent proposals for new symmetries [5, 6]. We have looked at a number of models and have come to the conclusion that SU(5) is also a viable alternative for describing the new mesons. This model can naturally accommodate the existence of just two narrow states J/ψ and ψ' and the ratio of their leptonic widths. It presents the striking possibility of V + A weak currents. In an exploratory spirit, we present here the case for SU(5).

We will exploit the full content of the five quark model within the present experimental context, commenting on other possibilities at the end. In addition, we employ the parton model in the discussion.

We add a new quark to the four (u,d,s,c) of SU(4) [3]. One possibility is to choose a quark c′ of charge 2/3; c′ has $C' = 1, I = Y = C = 0$. The usual quarks u,d,s,c have $C' = 0$. We will call this the c–c′ model. A second option has a charge −1/3 quark f. We assign quantum numbers as follows: c and f have a new additive quantum number $M = 1$ ($M = 0$ for u,d,s) and are assigned to a doublet of "*K*-spin", $K_3 = +1/2$ $(-1/2)$ for c(f). This is the c–f model. If it is, we could choose quantum numbers $C = K_3 + M/2$ and $C' = -K_3 + M/2$. The charge operators for the two models are $Q = I_3 + Y/2 + 2(C + C')/3$ for the c–c′ model and $Q = I_3 + Y/2 + K_3 + M/6$ for the c–f model.

Requiring the cancellation of triangle anomalies [7] would lead us to add at least one new heavy lepton doublet to $(\nu_e e^-)_L$ and $(\nu_\mu \mu^-)_L$ for the c–c′ model and one, $(\nu_E, E^-)_R$, for the c–f model, where R and L stand for V + A (V−A) couplings. Thus in either case we have the possibility of new heavy leptons – a possibility, because it is not clear whether the cancellation of anomalies is a necessity or not.

We won't discuss the c–c′ model in detail; it can be handled along the lines of the c–f model, which we take up now.

First we give the assignment of hadron states and some of their phenomenology, then a discussion of weak and electromagnetic interactions.

Hadron states. We suppose that the c and f quarks are very heavy, with f more massive than c, and to zeroth order choose $\psi_c = c\bar{c}$, $\psi_f = f\bar{f}$. The physical states are $\psi = \psi_c \cos\beta + \psi_f \sin\beta$ and $\psi' = \psi_f \cos\beta - \psi_c \sin\beta$. The leptonic width ratio $\Gamma_\psi(e\bar{e}) : \Gamma_{\psi'}(e\bar{e}) = 4.8$ keV: 2.2 keV then leads to $\beta \sim 8^\circ$ or -60°. In conformance with $m_f > m_c$ we choose $\beta \sim 8^\circ$ and thus small deviation from ideal mixing, as for light vector and tensor mesons.

In this way we naturally account for just two narrow vector mesons, each below its respective threshold ($\approx c\bar{c}$ or $\approx f\bar{f}$).

Of the other states in the model, $D^0 = c\bar{u}$, $D^+ = c\bar{d}$ and $F^+ = c\bar{s}$ are as in the SU(4) scheme [3], with very nearly the same masses. The new meson states in SU(5) are an SU(3) antitriplet $X^0 = f\bar{d}$, $X^- = f\bar{u}$, $Y^0 = f\bar{s}$ and charged partners of J/ψ and ψ', $\psi^+ = c\bar{f}$ and $\psi^- = f\bar{c}$. All these come in assorted J^{PC}. We will not discuss the baryons here. For the vector meson masses we find in addition to the SU(4) relations [3]

$$D^*-\rho = F^*-K^* = \tfrac{1}{2}(\psi_c-\rho)$$

also

$$X^*-\rho = Y^*-K^* = \psi^\pm-D^* = \tfrac{1}{2}(\psi_f-\rho) \tag{1}$$

where the symbols stand for mass or $(\text{mass})^2$ depending on prejudice. Numerically, the quadratic mass formula gives

$$M_{X^*} = 2.66\ \text{GeV}, \qquad M_{Y^*} = 2.70\ \text{GeV}, \qquad M_{\psi^\pm} = 3.40\ \text{GeV}$$

and the linear mass formula

$$M_{X^*} = 2.10\ \text{GeV}, \qquad M_{Y^*} = 2.22\ \text{GeV}, \qquad M_{\psi^\pm} = 3.26\ \text{GeV}.$$

With our choice of mixing, $M_{\psi_c} = 3.11$ GeV and $M_{\psi_f} = 3.67$ GeV.

Among the higher vector mesons produced in e^+e^-, we assign the broad $\psi''(4.15)$ to be the first radial excitation of J/ψ; presumably it decays to pairs of mesons containing c quarks. If we use the $J/\psi-\psi'$ separation to infer the spacing of $f\bar{f}$ levels, we expect the first radial excitation somewhere near 4.6 GeV. This state would be broad if well above the $f\bar{f}$ threshold, and narrow if near or below the threshold. In the latter case it can decay to charmed mesons through its $c\bar{c}$ component. The corresponding width should be small. If the mixing is as for $J/\psi-\psi'$ we expect $\Gamma(\text{ee}) \sim \frac{1}{2}\Gamma_{\psi'}(\text{ee})$ and the state may have been overlooked. The next (mostly $c\bar{c}$) state should be near 4.8 GeV and broad.

For an harmonic oscillator potential, we obtain $C = P = +\ {}^3P_J$ states (mostly $c\bar{c}$) with center of gravity halfway in $(\text{mass})^2$ between J/ψ and ψ' – i.e. near ψ' [8]. With only spin-orbit forces in the quark model, *at most two* of these states could be between J/ψ and ψ' (the $J = 0,1$ states; that with $J = 2$ then lies *above* ψ'). Of course, there is also a ${}^1S_0$ state near J/ψ, and one near ψ'.

At least one candidate for such an intermediate state (P_c) has been found at DESY [9]. Notice that these states are mostly $c\bar{c}$, so that decays $\psi' \to {}^3P_J + \gamma$ and $\psi' \to {}^1S_0 + \gamma$ are suppressed because the ψ' is mostly $f\bar{f}$. By contrast, ${}^3P_J \to \psi + \gamma$ is *not* suppressed. This may explain why $\psi' \to P_c + \gamma$ is small [10], and comparable to $\psi' \to P_c + \gamma \to J/\psi + \gamma\gamma$ [9]. The situation here is similar to that in some color models [4, 11]. For a recent discussion of the charm case, see ref. [12].

Besides J/ψ and ψ', we have states $\psi^\pm$ which can be pair produced if K_3 is conserved, or singly produced if it is not. In the c–c′ model there is a neutral pair near 3.4 GeV. For this model the leptonic widths give $J/\psi = 0.981\ c\bar{c} + 0.189\ c'\bar{c}'$, $\psi' = 0.981\ c'\bar{c}' - 0.189\ c\bar{c}$ and $m(c\bar{c}) = 3.15$ GeV, $m(c'\bar{c}') = 3.66$ for the quadratic mass formula.

The small width of J/ψ and ψ' requires either a small mixing of heavy quark states with states made out of light quarks (u,d,s) or some similar dynamical mechanism [3]. In our case, some of the suppression of $\Gamma(\psi' \to J/\psi\pi\pi)$ and $\Gamma(\psi' \to J/\psi + \eta)$ (e.g. relative to $\Gamma(\rho' \to \rho\pi\pi)$ is due to the small $J/\psi-\psi'$ mixing. Since $\Gamma(\psi' \to J/\psi\pi\pi) \sim \Gamma_{J/\psi}$, this means that mixing of heavy and light quark states must become larger as the mass of the hadron system in question decreases. This already happens in the "charmonium" version of SU(4) [13], and appears unobjectionable. One consequence is that we expect larger decay widths for J/ψ or ψ' to a photon and low mass SU(3) singlet hadrons than one would have in a strict SU(4) model. The widths are difficult to estimate, but it appears likely that a measurable fraction of $\Gamma_{J/\psi}$ and $\Gamma_{\psi'}$ could be due to radiative decays. We also expect $\Gamma(\psi'' \to J/\psi\pi\pi)$ larger than for SU(4).

Asymptotically, we expect that in e^+e^-, $R = \Sigma Q_i^2 = 11/3$ ($R = \sigma(\text{had})/\sigma_{\mu\bar{\mu}}$ [14]) for the c–f model and $4\frac{2}{3}$ for the c–c′ model. Below the new particle threshold R is near 2.5 [2], so above the threshold it may well be larger than the value 3.7 expected in the c–f model. If a heavy lepton exists and is being produced at present energies it would raise R by one unit for $\sqrt{s} \gg 2m_L$. Anomalous e–μ events have been seen at SPEAR by the SLAC-LBL group, and one possible interpretation is that they are due to heavy lepton production [15].

Weak and electromagnetic interactions. In inclusive deep inelastic electroproduction the small f quark charge leads to only small corrections to the SU(4) scheme. This is no longer so for weak processes. We take weak quark doublets $(u,d_c)_L$, $(c,s_c)_L$ and $(u,f)_R$ [e.g. (16)]; the other combinations are singlets. Of course, we have other options for the weak current (a term (c,f) has some interesting consequences), but let us confine ourselves to this choice. Now $J_{ch} = (\bar{u}d_c)_L + (\bar{c}s_c)_L + (\bar{u}f)_R$ defines the SU(2) piece of the weak neutral current to be

$$2J_3 = (\bar{u}u + \bar{c}c - \bar{d}d - \bar{s}s)_L + (\bar{u}u - \bar{f}f)_R \,. \tag{2}$$

Conventionally, the SU(2) × U(1) neutral weak current (which we adopt) reads $J_{neut} = J_3 - 2\sin^2\theta_w J_{em}$ [17]. In general, $\sin^2\theta_w$ can be a parameter unconnected to weak boson masses.

This SU(5) model respects the near exact cancellation of $|\Delta S| = 1$ neutral current amplitudes [18]. It has dramatic consequences for deep inelastic antineutrino scattering. Above the new particle threshold we have two sorts of contributions not present below threshold: (i) from the $c\bar{c}$ and $f\bar{f}$ "sea" in the target nucleon we expect effects of order 5–15% averaged over $x = 2M\nu/Q^2$ and $y = \nu/E$ [16], (ii) from the right-handed piece of J_{ch} ($u \to f$), we expect a contribution dominant over (i). In a simple model where the nucleon consists of u and d valence quarks alone we have (deuteron target)

$$\begin{aligned} \frac{d\sigma^{\nu}}{dx\,dy} &= \frac{18}{5}\frac{G^2ME}{\pi}F_2^{ed}(x) \\ \frac{d\sigma^{\bar{\nu}}}{dx\,dy} &= \frac{18}{5}\frac{G^2ME}{\pi}F_2^{ed}(x)\left[(1-y)^2 + \begin{Bmatrix} 0 \text{ below threshold} \\ 1 \text{ asymptotically} \end{Bmatrix}\right] \end{aligned} \tag{3}$$

The transition depends on the location of the fancy threshold, and the rapidity with which scaling is re-established above this threshold. At the very least we expect a dramatic increase in $\bar{\nu}$N cross sections when W^2 and Q^2 are selected to be large. Of course, there is also the likelihood that fancy baryons will be produced in $\bar{\nu}$N.

Detaching ourselves from a specific gauge theory for a moment, we ought to note that V + A and V–A currents can be present with different strengths at low Q^2.

Experimentally, there appears to be an anomaly in $\bar{\nu}$N [19]; its nature is still unclear.

Below the new particle threshold, neutral current cross sections differ slightly from those in the SU(4) model [20], due to the extra $(\bar{u}u)_R$ term in J_{neut}.

This model is in at least qualitative agreement with present data, and has features which make it vulnerable to experiment – e.g. the presence of V + A currents *. If it turns out that SU(4) is the correct symmetry at present energies, there is still the heretical possibility that some new symmetry like SU(5) will be unveiled at still higher energies. Perhaps new narrow resonances in e^+e^- will be presaged by the discovery of a heavy lepton.

* After working this out, we received a number of papers dealing with V + A currents [21], after submitting this letter, we received still more related work [22].

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