Van Royen-Weisskopf quark model and the new particles*

P. J. O'Donnell and C. L. Ong
Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7 Canada
(Received 28 May 1975; revised manuscript received 20 August 1975)

We show that the Van Royen-Weisskopf quark-model assumption can be extended to include the new particles provided the charm quark has charge $-4/3$.

The discoveries[1] of the narrow resonances J/ψ and ψ' with masses of 3.1 GeV and 3.7 GeV, respectively, indicate the existence of at least one new hadronic degree of freedom. Various schemes[2,3] have been proposed to fit the J/ψ and ψ' into multiplets of SU(4) or higher symmetry groups, which have led to extensive calculations of the masses of other charmed particles and the decay rates of various decay modes. Due to the large masses of the J/ψ and ψ', the effect of symmetry breaking is expected to be large. This suggests that the quark-model approach might have some advantages over the symmetry-group approach. This is the point of view we shall adopt in the present paper.

It is well known that a few additional assumptions, besides the SU(6) multiplet assignment, are needed to make the old quark model function properly. These additional assumptions include Zweig's rule, which plays a key role in ruling out certain processes allowed by symmetry consideration, and the Van Royen-Weisskopf[4] assumption $|\psi(0)|^2 \propto M$, i.e., the square of the internal wave function of the quark-antiquark system at the origin is proportional to the mass of the meson, which is important when applying the old quark model to leptonic decays of mesons. While these assumptions have not found their theoretical derivations within the old quark model, it is instructive to see if they work for the new quark(s). In this note we shall examine the Van Royen-Weisskopf assumption in the light of the experimental data on the leptonic decays of the new resonance J/ψ.

At first glance, it would look as if the Van Royen-Weisskopf assumption would no longer be valid, for, as Yennie has pointed out,[5] comparison of the widths for the decay of vector mesons to the e^+e^- pair has the result

$$\frac{\Gamma(\rho\to e^+e^-)}{9}:\frac{\Gamma(\omega\to e^+e^-)}{1}:\frac{\Gamma(\phi\to e^+e^-)}{2}:\frac{\Gamma(\psi\to e^+e^-)}{8}=0.72\pm 0.10:0.76\pm 0.08:0.67\pm 0.07:0.65\pm 0.07$$

$$=\frac{|\psi_\rho(0)|^2}{M_\rho{}^2}:\frac{|\psi_\omega(0)|^2}{M_\omega{}^2}:\frac{|\psi_\phi(0)|^2}{M_\phi{}^2}:\frac{|\psi_\psi(0)|^2}{M_\psi{}^2}, \tag{1}$$

i.e.,

$$\frac{|\psi_\rho(0)|^2}{M_\rho}:\frac{|\psi_\omega(0)|^2}{M_\omega}:\frac{|\psi_\phi(0)|^2}{M_\phi}:\frac{|\psi_\psi(0)|^2}{M_\psi}\approx 1.0:1.1:1.2:3.6.$$

However, one should note that Yennie's result (1) is based on the assumption that J/ψ is a pure charm-quark-antiquark bound state with the charm quark having electric charge $+\frac{2}{3}$. The relation between the leptonic decay width and the qurk-antiquark wave function is given by

$$\Gamma(V\to l\bar{l})\cong\frac{8\pi}{27}\alpha^2 C_V\frac{|\psi_V(0)|^2}{M_V{}^2} \tag{2}$$

in the naive quark model, where C_V, resulting from the combination of Clebsch-Gordan coefficients and quark charges, gives the numbers 9, 1, 2, etc.

Now if we insist on the Van Royen-Weisskopf assumption we get from Eq. (2)

$$\frac{\Gamma(V\to e^+e^-)}{C_V}\propto\frac{1}{M_V}. \tag{3}$$

For the present we consider only the J/ψ and regard it as purely a $c\bar{c}$ bound state. We find

$$\frac{1}{m_l}:\frac{1}{m_\omega}:\frac{1}{m_\phi}:\frac{1}{m_\psi}\simeq 1:1:0.8:0.25$$

to be compared with

$$\frac{\Gamma_I}{9}:\frac{\Gamma_\omega}{1}:\frac{\Gamma_\phi}{2}:\frac{\Gamma_\psi}{32}\simeq 1:1:0.8:0.21. \qquad (4)$$

A value of $C_\psi = 32$ implies that the absolute value of the electric charge of charm quark is $\frac{4}{3}$. By the hypothesis that all physical states should have integral electric charge, we can further rule out the possibility that $Q_c = +\frac{4}{3}$; otherwise we would expect to have charmed mesons and baryons with fractional electric charge. Thus we come to the conclusion that $Q_c = -\frac{4}{3}$. It is encouraging to know that this charge assignment has also appeared in several gauge theories which are free of strangeness-changing neutral currents in the lowest order.[6] If we extend the above analysis to include the ψ' we find $C_{\psi'} = 16$, which does not have a simple implication. This is to be expected if we think of ψ' as an excited bound state.

It is worthwhile to note that the Van Royen-Weisskopf assumption has a function of specifying how symmetry breaking is to be applied. Thus it is not surprising that Weinberg's spectral-function sum rule with "proper" choice of pole dominance and symmetry can sometimes lead to identical results obtained by the Van Royen-Weisskopf assumption.[7] However, this does not mean that one of them can be derived from another; the Van Royen-Weisskopf assumption is of a more specific character. Furthermore, within the framework of the quark model the wave function of the quark-antiquark pair is a more natural concept. So it is important that the above analysis shows that the Van Royen-Weisskopf assumption holds for the charmed quark model, while at the same time indicates that the charge of the charm quark is $-\frac{4}{3}$.

Within the context of this article such a charge assignment can be regarded either as a condition for the Van Royen-Weisskopf assumption to be valid for a charmed quark model, or as a consequence of applying the Van Royen-Weisskopf assumption to the charmed quark model. One should look elsewhere for evidence for or against such an assignment.

As examples we mention here three simple but distinct features of the four-quark model which has a charm quark with charge $-\frac{4}{3}$.

(i) It predicts the existence of doubly charged mesons and multiply charged (+2 to −4) baryons.

(ii) It predicts $R \equiv \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-) \rightarrow \frac{22}{3}$ asymptotically.

(iii) In processes which have the elementary transition $c \rightleftharpoons d, s$, where d, s, c denote "down," "strange," and "charm" quarks, there is a selection rule $\Delta C = -\Delta Q$.

There are many less simple consequences of such a charge assignment, most of which depend on other model assumptions.

(a) We can abstract from the leptonic width a photon–vector-meson coupling constant for the J/ψ. Following the usual vector-dominance method we obtain

$$\frac{\sigma(\gamma N \rightarrow \psi N)}{\sigma(\gamma N \rightarrow \phi N)} \sim 1.7\frac{\sigma_T{}^2(\psi N)}{\sigma_T{}^2(\phi N)} \sim 0.02, \qquad (5)$$

the latter number following from Pomeron models.[8] Using $\sigma(\gamma N \rightarrow \phi N) \sim 0.6\ \mu b$ gives a prediction of $\sigma(\gamma N \rightarrow \psi N) \sim 12$ nb, in reasonable agreement with experimental indications.[9,10] However, the methods used in obtaining Eq. (5) are too crude to allow it to rule out other charge assignments.

(b) The weak-interaction problem obviously invokes a weak-interaction model.[6] It would appear necessary to have at least six quarks in a model of the type considered here since a four-quark model would most naturally use a triplet representation $(u, d\cos\theta + s\sin\theta, c)$. This representation destroys neutron-β-decay–μ-decay universality by a factor of $\sqrt{2}$; extra quarks allow a way to avoid this conclusion. Higher-order weak-interaction effects of $O(G\alpha)$ appear in $K_L \rightarrow \mu\bar{\mu}$ and in the K_L-K_S mass-difference calculations if $m_{\text{quark}} \ll m_W$. The phenomenology of the weak decay processes of charmed particles will be very much altered. Distinct differences among the various charge assignments will possibly be most easily detected via sign-selected neutrino beams.

---

*Work partially supported by the National Research Council of Canada.

[1]J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974); J. J. Aubert *et al.*, *ibid.* 33, 1404 (1974); C. Bacci *et al.*, *ibid.* 33, 1408 (1974); G. S. Abrams *et al.*, *ibid.* 1453 (1974).

[2]S. Borchardt, V. S. Mathur, and S. Okubo, Phys. Rev. Lett. 34, 38 (1975); A. De Rújula and S. L. Glashow, *ibid.* 34, 46 (1975); E. Eichten, K. Gottfried, T. Kinoshita, J. Kogut, K. D. Lane, and T.-M. Yan, *ibid.* 34, 369 (1975).

[3]D. H. Boal, R. H. Graham, J. W. Moffat, and P. J. O'Donnell, Phys. Rev. Lett. 34, 541 (1975).

[4]R. Van Royen and V. Weisskopf, Nuovo Cimento 50A, 617 (1967); 51A, 583(E) (1967).

[5]D. R. Yennie, Phys. Rev. Lett. 34, 239 (1975).

[6]A number of weak-interaction models have appeared in recent months, which have a charge assignment of

$-\frac{4}{3}$. With four quarks there are the papers of T. Goto and V. Mathur [Phys. Lett. 59B, 153 (1975)] and K. Sarma and G. Rajasekaran [Tata Institute, Report No. TIFR/Th/75-19) (unpublished)]. With six quarks there are the papers of C. Albright and R. Oakes [Fermilab Report No. 75-53 (unpublished)] and F. Close and E. Colglazier [CERN report (unpublished)].

[7]A. Dar and V. Weisskopf, Phys. Lett. 26B, 670 (1968).

[8]C. E. Carlson and P. G. O. Freund, Phys. Lett. 39B, 349 (1972); R. Carlitz, M. B. Green, and A. Zee, Phys. Rev. Lett. 26, 1515 (1971).

[9]B. Knapp *et al.*, Phys. Rev. Lett. 34, 1040 (1975).

[10]D. E. Andrews *et al.*, Phys. Rev. Lett. 34, 1134 (1975); J. F. Martin *et al.*, *ibid.* 34, 288 (1975).