[10] M. L. Perl, SLAC Report No. SLAC-PUB-1592, in Proceedings of the Institute of Particle Physics Summer School, Montreal, Quebec, Canada, 1975 (to be published).

[11] In quite a different context, a similar assignment was considered by A. Zee, Phys. Rev. D 9, 1772 (1974).

[12] The sign convention of γ_5 is such that $(1-\gamma_5)\psi$ is left-handed.

[13] A. Pais and S. B. Treiman, Phys. Rev. Lett. 35, 1206 (1975).

[14] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[15] M. K. Gaillard and B. W. Lee, Phys. Rev. Lett. 33, 108 (1974); G. Altarelli and L. Maiani, Phys. Lett. 52B, 351 (1974).

[16] E. Golowich and B. R. Holstein, Phys. Rev. Lett. 35, 831 (1975).

[17] M. K. Gaillard and B. W. Lee, Phys. Rev. D 10, 897 (1974).

[18] For instance, $m=0$, $m'=2$ GeV, $m^*=5$ GeV, $m^{*\prime}=16$ GeV, $\tan^2\alpha=1$, and $\tan^2\beta=1$.

[19] Y.-S. Tsai, Phys. Rev. D 4, 2821 (1971).

[20] J. D. Bjorken and C. H. Llewellyn-Smith, Phys. Rev. D 7, 887 (1973).

How Many Charm Quantum Numbers are There?*

A. Pais
Rockefeller University, New York, New York 10021

and

S. B. Treiman
Jadwin Physical Laboratories, Princeton University, Princeton, New Jersey 08540

(Received 8 September 1975)

We address the question, how many kinds of new quantum numbers ("charm") are indicated by recent experimental developments in the study of e^+-e^- collision phenomena and dimuon production in neutrino and antineutrino reactions?

A variety of recent developments has led to the expectation that one or more new kinds of quantum numbers ("charm," collectively) are needed for hadron physics. This note addresses the question, how *many* new quantum numbers—new quark types—are required? It is our main purpose to stress the impact which information on antineutrino reactions may have on this question.

It is a widely held view that the recently discovered narrow ψ and ψ' resonances, although they have the quantum numbers of ordinary hadrons, are built up of charmed quark-antiquark pairs. At the present writing the most direct evidence for charm comes from the observation[1] of neutrino-induced reactions in which a pair of oppositely charged muons appears in the final state. The muon energy spectra appear to rule out the possibility that these events arise exclusively from the decay $L^0\to\mu^++\mu^-+\nu$ of a new heavy lepton L^0 produced in the neutrino reaction.[2] This makes a strong case for an alternative interpretation according to which the μ^- is produced directly, the μ^+ arising from semileptonic decay of a short-lived hadron belonging to a new class of particles. Less clear, at this time, is the origin of the recently reported[3] μe events in e^+e^- annihilation.

The case for a least one new quark (beyond the usual triplet u, d, s) was first made in connection with certain theoretical issues of ordinary weak-interaction phenomenology.[4] This led to a certain four-quark SU(2)⊗U(1) gauge model that we shall refer to here as the "standard" model.[5] The new quark, c, introduced in the model was thus available, so to speak, when the ψ and ψ' resonances were discovered; and it could be invoked for a picture in which ψ and ψ' are, respectively, the lowest and first excited $1^{--}({}^3S_1)$ states of the c-$\bar{c}$ system. Similarly, the charged currents of the standard model contain charm-changing pieces, which could be invoked to account qualitatively for charm production, and therefore for dimuon events, in neutrino reactions.

Despite these qualitative successes various authors were led to contemplate modifications of the standard model, including a further proliferation of new quark types.[6] Clearly one has considerable freedom in introducing new quark species if the hadron states which bear the corresponding quantum numbers are too massive to be directly excited at present energies ("very heavy quarks"). However, in this note we concentrate mainly on the issue of new quantum numbers (new quark types) associated with hadronic states of modest mass.

Even in this limited framework there were several considerations that motivated attempts to go beyond the standard four-quark model (insofar as all physical hadrons are color singlets, color tripling does not enter here into our enumeration of quark types). One question is whether the narrow ψ and ψ' resonances are pair states formed out of a *single* species of new quark. For some time, lack of evidence for radiative transitions to additional new quark-pair states anticipated[7] on an assumed single-species origin of ψ and ψ' encouraged speculations that ψ and ψ' and also, perhaps, ψ'' were associated with several new quark types. However some of the anticipated states and radiative transitions have recently been discovered.[8] As a result, the impetus on spectroscopic grounds for introduction of more than one new quark type has somewhat diminished. The search for additional *narrow* resonances in e^+, e^- collisions has by now been extended[9] to a total energy of about 7.5 GeV, with negative findings. Of course, it may be that other families do exist, but that the lowest 1^{--} states lie above 7.5 GeV; or that these states are very broad, presumably because they happen to lie above the threshold for decay into charmed hadrons with the appropriate quantum numbers; or it may be that these states do not couple appreciably to the electromagnetic current and are therefore not excited in e^+-e^- collisions.

This last mentioned possibility is interesting in connection with another difficulty that has been perceived for the four-quark model: The ratio R of cross sections for $e^+ + e^- \to$ hadrons and $e^+ + e^- \to \mu^+ + \mu^-$ is predicted to equal $\frac{10}{3}$ (with color tripling) once all four quarks are well excited. However, the observed value at high energies (4–8 GeV) is appreciably larger than this, $R \sim 5.5$ (notice, however, that if heavy lepton pairs are being produced the true value of R would be reduced by one unit for each species of heavy lepton). This circumstance has provided another impulse for the contemplation of further new quark types, but any such proliferation has to confront the nonobservation of additional families of narrow vector resonances. An interesting scheme discussed by Wilczek[10] may be relevant here. It permits one to increase R and yet maintain a lid on additional 1^{--} states that couple to the electromagnetic current.

Let us consider next what we can learn about the number of new quark types from neutrino and antineutrino reactions.[11] According to the standard four-quark model the weak charge-raising current is $j_\mu^{\text{weak}} = \bar{u}\gamma_\mu(1+\gamma_5)d_C + \bar{c}\gamma_\mu(1+\gamma_5)s_C$, where $d_C = d\cos\theta_C + s\sin\theta_C$, $s_C = -d\times\sin\theta_C + s\cos\theta_C$, θ_C being the Cabibbo angle. On a parton-model interpretation of the evidence from $\Delta S = 0$, $\Delta C = 0$ processes, it is well known that deep inelastic lepton scatterin on nucleons is dominated by contributions from the d and u (*valence*) partons. For charmed production by neutrinos ($\Delta C = 1$), production on d-type partons is suppressed by the Cabibbo factor $\sin^2\theta_C \approx 0.04$, and production off s and $\bar{c}$ partons in the *sea* is supposed to be suppressed because of the presumed rarity of sea partons.[12] For $\bar{\nu}$ reactions ($\Delta C = -1$) the valence quarks make no contribution whatsoever, so that only the sea partons $\bar{d}$, $\bar{s}$, and c can participate. Thus, one expects suppressed cross sections for charm production, in both the ν and $\bar{\nu}$ cases. On the parton picture, moreover, one has $\sigma^\nu(\Delta C = 1) \geqslant \sigma^{\bar{\nu}}(\Delta C = -1)$, where the equality holds if the sea contribution dominates the Cabibbo-suppressed valence contribution in the reactions. In any case we surely expect that $\sigma^\nu(\Delta C = 1) \ll \sigma^\nu(\Delta C = 0)$. Indeed, if the sea contributions were negligible, then at very high energies where threshold effects for charm production are unimportant, we would have $\sigma^\nu(\Delta C = 1)/\sigma^\nu(\Delta C = 0) \approx 0.04$. It is hard to imagine that the sea contributions could much more than double this ratio.

The frequency of dimuon events depends on the effective branching ratio B for muonic decay of charmed hadrons. The earliest reports[1] of dimuon production involved mixed $\nu, \bar{\nu}$ beams, however with the ν component dominant. For beam energies > 40 GeV the ratio of $\mu^+\mu^-$ and μ^- events was found to be $\sigma(\mu^+\mu^-)/\sigma(\mu^-) = (9 \pm 3)\times 10^{-3}$. On the interpretation that the dimuon events come principally from the ν component of the beam, we learn that $B\sigma^\nu(\Delta C = 1)/\sigma^\nu(\Delta C = 0) \approx 0.01$. On the standard model we expect that $\sigma^\nu(\Delta C = 1)/\sigma^\nu(\Delta C = 0)$ should be small, less than ~ 0.1 unless the sea contributions are unexpectedly very large. Taking this ratio to be $\lesssim 0.1$, we have $B \gtrsim 0.1$. According to the usual estimates[13] this branching ratio is itself expected to be rather small, and even $B \doteq 0.1$, though perhaps acceptable, seems only marginally plausible. It was partly for this reason that one was led to consider various modifications of the standard model, with a view to arranging for enhanced production of charmed particles in neutrino reactions.

Because of a very recent experimental development, however, any attempts along this line have now to face new and severe constraints. It has been found, namely, that dimuon events are produced also in $\bar{\nu}$ reactions[14]; and although it is still too early for any precise comparisons of the ν and $\bar{\nu}$ dimuon cross sections, the preliminary indications are that the two cross sections are at least roughly equal. Insofar as this holds up experimentally, any scheme that enhances (generic) charm production *must do so for both the* ν *and* $\bar{\nu}$ *reactions.*

Let us see what the possibilities are in the context of weak SU(2)⊗ U(1) gauge models. In the standard model there are two weak SU(2) doublets, both left-handed: $(u, d_C)_L$, $(c, s_C)_L$. One can arrange for substantial enhancement of charm production in the ν reactions by adding to the model the right-handed doublet[15]

$$\begin{pmatrix} c \\ d \end{pmatrix}_R .$$

The new current which this introduces allows for charm production in ν reactions off valence d quarks, without Cabibbo suppression factors. Because the new current is right-handed, the ratio of $\Delta C = 1$ and $\Delta C = 0$ cross sections for ν reactions should approach one-third in the deep inelastic region (well-above charm thresholds). The trouble with this scheme, however, is that it has no corresponding provision for enhancement of charm production in $\bar{\nu}$ reactions.

If one wishes to enhance substantially both the ν and $\bar{\nu}$ cross sections for charm production one has inevitably to introduce several new kinds of quarks, hence several kinds of charm. A simple possibility is illustrated by the model

$$\begin{pmatrix} u \\ d_C \end{pmatrix}_L, \begin{pmatrix} c \\ s_C \end{pmatrix}_L, \begin{pmatrix} c' \\ d \end{pmatrix}_R, \begin{pmatrix} c \\ d'' \end{pmatrix}_R,$$

where c' is needed for the Glashow-Iliopoulos-Maiani mechanism[4] but is taken as sufficiently massive so that it is not "excited" in e^+-e^- collisions, and where d'' is the counterpart of c'. The dimuon events are to be associated with charmed hadrons containing c' or d''. In the deep inelastic region, where valence partons are expected to dominate, charm produced in ν reactions is associated with c' quarks; for $\bar{\nu}$ reactions, with the quantum numbers of d''. This model accomodates dimuon production, in both classes of reactions, with a small branching ratio B. The trouble is that the *total* ν and $\bar{\nu}$ cross sections (charm-conserving plus charm-changing) are predicted to become *equal* on isoscalar targets. Experimentally[16] $\sigma_{\text{total}}^{\bar{\nu}}/\sigma_{\text{total}}^{\nu} \approx 0.3 \pm 0.1$, at $E \approx 80$ GeV.

There exists the possibility to moderate these enhancement effects by introducing still more quarks (very heavy ones), mixing them into the right-handed doublets in such a way that the $\nu + d \rightarrow \mu^- + c'$ and $\bar{\nu} + u \rightarrow \mu^+ + d''$ amplitudes are reduced by mixing parameters. This can no doubt be parametrized in an acceptable way within the constraints of the ν and $\bar{\nu}$ data and with a comfortably small value of the branching ratio B. But there remains the problem that two new quarks, c' and d'', have been introduced and associated with charmed hadrons of modest enough mass to be relevant for interpretation of the dimuon data. We thus have two new families of "excitable" hadrons—yet, as discussed earlier, no evidence for this in the e^+-e^- data, at least not in the form of new, *narrow* resonances. In this connection it might be thought that the Wilczek mechanism could be invoked to decouple one of the families from the electromagnetic current, but this in fact cannot be arranged.

Insofar as this "two-family" problem is resolvable we are left with the prediction that the charmed particles produced in $\bar{\nu}$ reactions are predominantly in a different family from those produced in ν reactions. These differences would eventually have to show up as differences in the properties of the charmed particles produced in ν and $\bar{\nu}$ reactions, e.g., different masses for the charmed particles.

The simplest possibility, however, is that only one kind of new quark is involved in the dimuon events both for ν and $\bar{\nu}$ reactions; and that any additional quark types that one may wish to contemplate for other reasons are associated with charmed particles that are too massive to be much excited at present energies in e^+e^- collisions and $\nu, \bar{\nu}$ reactions. Effectively, therefore, we are reduced to a four-quark picture, either the standard model or other nearly equivalent models involving heavy quarks, e.g.,

$$\begin{pmatrix} u \\ d_C \end{pmatrix}_L, \begin{pmatrix} c' \\ s_C \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_R,$$

where c' is a heavy quark and excitable charm is associated with c. For definiteness we will speak of the standard model. If $\sigma^{\nu}(C=1)$ and $\sigma^{\bar{\nu}}(C=-1)$ are indeed comparable, we are forced to conclude that the sea contributions are rather large; also, unless these contributions are *very* large, then the muonic branching ratio of charmed hadrons is itself rather big, $B \gtrsim 0.1$. There is, of course, the welcome feature in all of this that charm production, certainly for $\bar{\nu}$ reactions but also for the ν reactions, provides a sensitive probe of the sea parton distributions, a situation without parallel, quantitatively, in $\Delta C = 0$ reactions.

There remains the matter of like-sign muon pairs. For the ν reactions[1] the ratio $\sigma^\nu(\mu^-\mu^-)/\sigma^\nu(\mu^+\mu^-)$ is roughly 0.1; in the $\bar{\nu}$ case two $\mu^+\mu^+$ events have been recorded out of a total of seven dimuon events.[14] One interesting interpretation[15] of the like-sign phenomenon relies on effects, analogous to $K^0, \bar{K}^0$ mixing, which produce transitions between $D^0 \equiv (c\bar{u})$ and its conjugate $\bar{D}^0 \equiv (\bar{c}u)$. In the standard model, however the ratio of like-sign to opposite-sign events is expected[17] to be small, $\lesssim 10^{-3}$; but it is possible to arrange for substantial mixing through introduction of very heavy quarks.[18]

Alternatively, we might rely on associated production of pairs of charmed particles in $\Delta C = 0$ charged current reactions. The like-sign pair arises when the hadron of appropriate quantum number ($C = -1$ for $\bar{\nu}$ reactions) decays muonically. On this interpretation one should also occasionally see trimuonic events at a rate, relative to like-sign dimuon events, which might well be of order 0.1.

---

*Work supported in part by the U. S. Energy Research and Development Administration under Contract No. E-(11-1)-2232B.

[1] A. Benvenuti *et al.*, Phys. Rev. Lett. 34, 419 (1975); B. C. Barish, Colloq. Int. CNRS 245, 131 (1975); A. Benvenuti *et al.*, Phys. Rev. Lett. 35, 1199, 1203 (1975).

[2] A. Pais and S. B. Treiman, Phys. Rev. Lett. 35, 1206 (1975).

[3] M. L. Perl *et al.*, Phys. Rev. Lett. 35, 1489 (1975).

[4] B. J. Bjørken and S. L. Glashow, Phys. Lett. 11, 255 (1964); S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[5] For general reviews see, e.g., S. Weinberg, Rev. Mod. Phys. 46, 255 (1974); A. De Rújula, H. Georgi, S. L. Glashow, and H. R. Quinn, Rev. Mod. Phys. 46, 391 (1974); M. A. B. Bég and A. Sirlin, Annu. Rev. Nucl. Sci. 24, 379 (1974); M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. 47, 277 (1975).

[6] The vast literature can be traced from some of the more recent contributions: R. Barnett, Phys. Rev. Lett. 34, 41 (1975); H. Harari, SLAC Reports No. SLAC-PUB-1568, 1975 (unpublished), and No. SLAC-PUB-1589, 1975 (unpublished); A. De Rújula, H. Georgi, and S. L. Glashow, Phys. Rev. Lett. 35, 69 (1975), and to be published; F. Wilczek, A. Zee, R. Kingsley, and S. B. Treiman, Fermilab Report No. 75/44 THY (to be published); H. Fritzsch and P. Minkowski, preprint CALT-68-503, 1975; S. Pakvasa, W. Simmons, and S. F. Tuan, Phys. Rev. Lett. 35, 702 (1975).

[7] C. Callan *et al.*, Phys. Rev. Lett. 34, 52 (1975); T. Appelquist *et al.*, Phys. Rev. Lett. 34, 365 (1975); E. Eichten *et al.*, Phys. Rev. Lett. 34, 369 (1975); B. Harrington, Phys. Rev. Lett. 34, 706 (1975).

[8] W. Braunschweig *et al.*, Phys. Lett. 57B, 407 (1975); G. Feldman *et al.*, Phys. Rev. Lett. 35, 821 (1975).

[9] A. Boyarski *et al.*, Phys. Rev. Lett. 34, 762 (1975); see also J. Aubert *et al.*, Phys. Rev. Lett. 35, 416 (1975); and unpublished works.

[10] F. Wilczek, to be published.

[11] Many of the points considered here have already appeared in the literature; see Ref. 5; also M. K. Gaillard, paper presented at the Tenth Recontre de Moriond, Méribel-lès-Allues, France, 1975 (to be published).

[12] For estimates see, e.g., G. Farrar, Nucl. Phys. B77, 429 (1974).

[13] See Gaillard *et al.*, Ref. 5.

[14] A. Benvenuti *et al.*, Phys. Rev. Lett. 35, 1249 (1975).

[15] For some of the implications in neutrino reactions see V. Barger, T. Weiler, and R. Phillips, Phys. Rev. Lett. 35, 692 (1975).

[16] R. Imlay, in *Proceedings of the Seventeenth International Conference on High Energy Physics, London, England, 1974,* edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975), p. IV-100; F. Sciulli, *ibid.*, p. IV-105.

[17] See Wilczek *et al.*, Ref. 6.

[18] See, for example, model *D* in Ref. 17.