ISTITUTO NAZIONALE DI FISICA NUCLEARE
Laboratori Nazionali di Frascati

LNF-78/43

G. Dattoli, R. Mignani and D. Prosperi: MORE FLAVOURS NOW: AN EIGHT-QUARK MODEL OF HADRONS

Estratto da:
Lett. Nuovo Cimento 22, 701 (1978).

Servizio Documentazione
dei Laboratori Nazionali di Frascati
Cas. Postale 13 - Frascati (Roma)

LETTERE AL NUOVO CIMENTO VOL. 22, N. 17 26 Agosto 1978

More Flavours Now: An Eight-Quark Model of Hadrons.

G. DATTOLI

CNEN, Divisione Nuove Attività, Centro di Frascati - Frascati
Istituto di Fisica dell'Università - Roma

R. MIGNANI

Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

D. PROSPERI

Istituto di Fisica Sperimentale dell'Università - Napoli
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati - Frascati

(ricevuto l'8 Maggio 1978)

In spite of the success of the Glashow-Iliopoulos-Maiani model (1), some very recent experimental results suggest that more than four quarks are needed to account for the present status of hadron physics. Let us summarize them:

i) There is strong evidence for a new heavy lepton τ (2), and indirect evidence for its own neutrino ν_τ (3,4). This, in turn, requires the introduction of at least a new

(1) S. L. GLASHOW, J. ILIOPOULOS and L. MAIANI: *Phys. Rev. D*, **2** 1285 (1970).
(2) M. L. PERL, G. S. ABRAMS, A. M. BOYARSKI, M. BREIDENBACH, D. D. BRIGGS, F. BULOS, W. CHINOWSKY, J. T. DAKIN, G. J. FELDMAN, C. E. FRIEDBERG, D. FRYBERGER, G. GOLDHABER, G. HANSON, F. G. HEILE, B. JEAN-MARIE, J. A. KADYK, R. R. LARSEN, A. M. LITKE, D. LÜKE, B. A. LUN, V. LÜTH, D. LYON, C. C. MOREHOUSE, J. M. PATERSON, F. M. PIERRE, T. P. PUN, P. A. RAPIDIS, B. RICHTER, B. SADOULET, R. F. SCHWITTERS, W. TANENBAUM, G. H. TRILLING, F. VANNUCCI, J. S. WHITAKER, F. C. WINKELMANN and J. E. WISS: *Phys. Rev. Lett.*, **35**, 1489 (1975); A. BENVENUTI, D. CLINE, P. COOPER, M. HEAGY, R. IMLAY, M. E. JOHNSON, T. Y. LING, R. LUNDY, A. K. MANN, P. MCINTIRE, S. MORI, D. D. REEDER, J. RICH, C. RUBBIA, R. STEFANSKI and D. WINN: *Phys. Rev. Lett.*, **38**, 1110 (1977). See also: M. L. PERL: talk at the *Rencontre de Moriond, Flaine, March 1977* (SLAC-PUB-1923); G. FLUGGE: DESY preprint 77/34, June 1977; M. L. PERL: talk at the *International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, August 1977*; S. YAMADA: talk at the *International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, August 1977*; G. KNIES: talk at the *International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, August 1977*.
(3) H. HARARI: preprint WIS-77/56-Ph, November 1977.
(4) J. F. DONOGHUE and L. WOLFENSTEIN: *Phys. Rev. D*, **17**, 224 (1978); H. PIESCHMANN: Lecture at the *Triangle Meeting on Hadron Structure, Strbske Pleso, October 1977*.

quark pair, in order to remove the triangle anomalies (5), so ensuring renormalizability of weak interactions in gauge theories;

ii) The discovery of a large resonant structure around 9.5 GeV in hadron-hadron collision experiments (6) suggests the possible existence of a new $(q\bar{q})$-state family, similar to the J/ψ-one.

Let us also remind that the smallness of parity-violation effects in the atomic level of bismuth (7) does not agree with the theoretical predictions of the standard $SU_2 \otimes U_1$ gauge theory of weak and electromagnetic interactions; many available theories explaining these effects involve more than four quarks (8). In addition, one could take into account the experimental data from inelastic neutrino scattering (*e.g.*, the so-called y-anomaly) (9), which, however, are not confirmed by more recent experiments (9).

The minimal quark model needed to explain these new data seems, therefore, one with $2N = 6$ flavours. Six-quark models of hadrons have been already proposed, in the past, by some authors (10,11). One of their most interesting features is that they naturally account for CP-violation (12,13). However, DE RUJULA, GEORGI and GLASHOW have recently raised arguments in favour of a flavour number higher than six (precisely, 8, 10 or 12) (14), in the framework of a $SU_{2L} \otimes SU_{2R} \otimes U_1$ gauge theory.

Therefore, in this letter, we want to do a further (theoretical) step toward the « quark proliferation », by proposing an eight-flavour model of hadrons, based on the introduction of two quartets of quarks (and thus similar to Harari's six-quark model (11)).

Our basic assumption is that the eight building blocks of hadrons are accommodated in two quartets, which differ from one another by a new additive quantum number, the « heaviness » H. In addition to the usual SU_4 quartet of « light quarks » (q^l = u, d, s, c), with $H = 0$, we have a new quartet of « heavy quarks » (q^h = t, b, r, v) with $H = 1$. Quarks t and b belong to an isodoublet, while r and v are isosinglets. The situation is displayed in fig. 1*a*) and *b*), where use is made of the « planar representation » $(\tilde{Y}, I_3)$ of the weight diagrams (15) (it is $\tilde{Y} \equiv Y + C$). The new quartet appears to be an « heavy » repetition of the old « light » one. We further assume that all quarks come in the usual three colours, but no coloured hadrons exist.

---

(5) C. BOUCHIAT, J. ILIOPOULOS and P. MEYER: *Phys. Lett.*, **38** B, 519 (1972); D. GROSS and R. JACKIW: *Phys. Rev. D*, **6**, 477 (1972).

(6) S. W. HERB, D. C. HOM, L. M. LEDERMAN, J. C. SENS, H. D. SNYDER, J. K. YOH, J. A. APPEL, B. C. BROWN, C. N. BROWN, W. R. INNES, K. UENO, T. YAMANOUCHI, A. S. ITO, H. JÖSTLEIN, D. M. KAPLAN and R. D. KEPHART: *Phys. Rev. Lett.*, **39**, 252 (1977); W. R. INNES, J. A. APPEL, B. C. BROWN, C. N. BROWN, K. UENO, T. YAMANOUCHI, S. W. HERB, D. C. HOM, L. M. LEDERMAN, J. C. SENS, H. D. SNYDER, J. K. YOH, R. J. FISK, A. S. ITO, H. JÖSTLEIN, D. M. KAPLAN and R. D. KEPHART: *Phys. Rev. Lett.*, **39**, 252 (1977).

(7) P. E. G. BAIRD, M. W. S. M. BRIMICOMBE, G. J. ROBERTS, P. G. H. SANDARS, D. C. SOREIDE, BOUCHIAT and C. C. BOUCHIAT: *Phys. Lett.*, **48** B, 111 (1974); M. W. S. M. BRIMICOMBE, C. F. LOWING and P. G. H. SANDARS: *J. Phys. B*, **1**, 237 (1976); E. M. HENLEY and L. WILETS: *Phys. Rev. A*, **14**, 1411 (1976); D. C. SOREIDE, P. E. G. BAIRD, M. W. S. M. BRIMICOMBE, G. J. ROBERTS, P. G. H. SANDARS, E. N. FORTSON, L. L. LEWIS and E. G. LINDAHL: *Phys. Rev. Lett.*, **36**, 352 (1976).

(8) See, *e.g.*, A. DE RUJULA, H. GEORGI and S. L. GLASHOW: *Ann. of Phys.*, **109**, 242 (1977), and references therein.

(9) See, *e.g.*, B. C. BARISH: CALTECH-preprint CALT 68-621 (September 1977), and references therein.

(10) R. M. BARNETT: *Phys. Rev. Lett.*, **34**, 41 (1975).

(11) H. HARARI: *Phys. Lett.*, **57** B, 265 (1975); *Ann. of Phys.*, **94**, 391 (1975).

(12) M. KOBAYASHI and K. MASKAWA: *Prog. Theor. Phys.*, **49**, 652 (1973).

(13) L. MAIANI: *Phys. Lett.*, **62** B, 183 (1976); S. PAKWASA and H. SUGAWARA: *Phys. Rev. D*, **14**, 305 (1976); J. ELLIS, M. K. GAILLATD and D. V. NANOPOULOS: *Nucl. Phys.*, **109** B, 213 (1976).

(14) A. DE RUJULA, H. GEORGI and S. L. GLASHOW: *Ann. of Phys.*, **109**, 258 (1977).

(15) G. DATTOLI, G. MATONE and D. PROSPERI: *Nuovo Cimento*, **45** A, 187 (1978).

The first straightforward result of our scheme is that, below the threshold for the production of heavy mesons, it is $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-) = 10/3$ (*), while above this threshold $R = 20/3$. This is clearly in qualitative agreement with the present experimental data ([16]), provided that the heavy mesons are produced well above $\sqrt{s} \sim 4$ GeV.

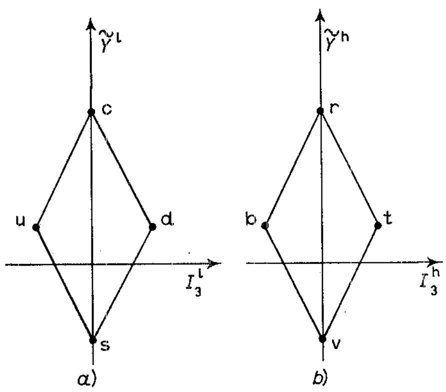

Fig. 1. – Planar representation $(\tilde{Y}, I_3)$ of the two fundamental quartets of quark $(\tilde{Y} = Y + C)$; fig. *a*) shows the usual «light» quarks (u, d, s, c), whose heaviness is $H = 0$; fig. *b*) shows the new «heavy» quarks (t, b, r, v), with $H = 1$.

The Gell-Mann–Nakano–Nishijima formula now reads

$$Q = I_3 + \tfrac{1}{2}\tilde{Y}\,, \tag{1}$$

where $I_3 = I_3^l + I_3^h$, $\tilde{Y} = \tilde{Y}^l + \tilde{Y}^h$ and the indices l and h label the light and heavy quarks, respectively.

The most general group symmetry to be taken into account is $U_8 \otimes SU_3$, where SU_3 acts on colour indices. Apart from colour, the group has 64 generators, but the relevant physical features of the model can be described by suitable subalgebras of U_8. A possible choice is the following one (see the U-scheme of ref. ([11])):

$$SU_4^l \otimes SU_4^h \otimes U_1^H \otimes U_1^B\,, \tag{2}$$

where SU_4^l (SU_4^h) generates the strong symmetries of light (heavy) quarks, while U_1^H and U_1^B describe the heaviness and baryon number, respectively. Alternatively, we can assume that the additive quantum numbers of light and heavy quarks are not separately conserved, but $Y = Y^l + Y^h$ and $I_3 = I_3^l + I_3^h$ are the good quantum numbers;

(*) Let us remind that, according to the usual quark-parton model, it is $R_\infty = \sum Q_q^2$.

([16]) See, *e.g.*, B. RICHTER: *Proceedings of the XVII International Conference on High-Energy Physics* (London, 1974); J. E. AUGUSTIN, A. M. BOYARSKI, M. BREIDENBACH, F. BULOS, J. T. DAKIN, G. J. FELDMAN, G. E. FISCHER, D. FRYBERGER, G. HANSON, B. JEAN-MARIE, R. R. LARSEN, V. LÜTH, H. L. LYNCH, D. LYON, C. C. MOREHOUSE, J. M. PATERSON, M. L. PERL, B. RICHTER, R. F. SCHWITTERS, F. VANNUCCI, G. S. ABRAMS, D. BRIGGS, W. CHINOWSKY, C. E. FRIEDBERG, G. GOLDHABER, R. J. HOLLEBEEK, J. A. KADIK, G. H. TRILLING, J. S. WHITAKER and J. E. ZIPSE: *Phys. Lett.*, **34** B, 764 (1975).

the good symmetry of the model turns out to be the diagonal SU_4 algebra within $SU_4^1 \otimes SU_4^h$ (*O-scheme* of ref. [11]). In this case, we have to take the following subalgebra of U_8:

(3) $$SU_4 \otimes U_1^H \otimes U_1^B \subset O_8 \subset U_8 .$$

In the O-scheme, the fundamental octet can be written in the form

(4) $$[8] = [4, 0] \oplus [4, 1] ,$$

where the adopted notation is $[m, H]$, m being the multiplicity of the SU_4 representation.

Let us now discuss, in this scheme, the meson spectrum ($q\bar{q}$ states). We have

(5) $$[8] \otimes [\bar{8}] = [4 \otimes \bar{4}, 0 \otimes 0] \oplus [4 \otimes \bar{4}, 0 \otimes \bar{1}] \oplus [4 \otimes \bar{4}, 1 \otimes 0] \oplus [4 \otimes \bar{4}, 1 \otimes \bar{1}] .$$

The most general representation belonging to $[8] \otimes [\bar{8}]$ can therefore be written as $[4 \otimes \bar{4}, R^H]$, where $R^H = 0 \otimes 0,\ 0 \otimes \bar{1},\ 1 \otimes 0,\ 1 \otimes \bar{1}$ (*). Usual mesons belong to the $R^H = 0 \otimes 0$ ($H = 0$) multiplet, while to the other multiplets belong mesons built up by heavy quarks, with $H = -1, +1$ and 0, respectively.

Let us pay attention to the «new» meson states. The wave functions of mesons belonging to the $1 \otimes \bar{1}$ multiplet can be simply obtained from the usual ones by substituting the light quarks in their $(q^l\bar{q}^l)$ structure with the corresponding heavy ones ($d \to b$, $u \to t$, $c \to r$, $s \to v$). We propose for these $(q^h\bar{q}^h)$ mesons the notation $\gamma(x)$, where x is the usual symbol for the corresponding $R^H = 0 \otimes 0$ meson: for instance, $\gamma(\varrho^+)$ denotes the $(t\bar{b})$ vector meson. Analogously, the notation $\beta(x)$ will be adopted for any $(q^l\bar{q}^l)$-meson belonging to the $R^H = 0 \otimes \bar{1}$ multiplet: for instance, $\beta(D^{*+})$ corresponds to the $(r\bar{d})$ vector meson.

We want now briefly to mention some possible interpretations of the recently discovered resonance $\Upsilon(9.4)$ [9]. Among the heavy mesons, only the neutral ones with $C = S = H = 0$ directly couple to the photon. If we assume $SU_3 \otimes U_1^C \otimes U_1^H$ wave functions, these mesons are

(6) $$\begin{cases} |\gamma(\omega)\rangle = \dfrac{|b\bar{b}\rangle + |t\bar{t}\rangle}{\sqrt{2}}, & |\gamma(\rho)\rangle = \dfrac{|b\bar{b}\rangle - |t\bar{t}\rangle}{\sqrt{2}}, \\ |\gamma(\varphi)\rangle = -|v\bar{v}\rangle, & |\gamma(\psi)\rangle = |r\bar{r}\rangle . \end{cases}$$

However, if—according to the current ideas—we assume the new 1^--meson to be a bound state of fundamental isosinglets, we are left only with the $\gamma(\varphi)$ and $\gamma(\psi)$ candidates. Moreover, the preliminary analyses [17] of the available experimental data seem to favour the assignment of $-\frac{1}{3}$ for the charge of the fundamental constituent of $\Upsilon(9.4)$. Therefore, we must identify the new resonance with $\gamma(\varphi)$ (**). From the results

(*) Let us notice that the above notation is not the standard one, since usually the U_1 representations are labelled by the values of the conserved quantum number. However, we adopt it to distinguish between states with $H=0$ but compound by different (light or heavy) kinds of quarks.

(**) However, on the basis of the present data, we cannot wholly rule out the hypothesis that $\Upsilon(9.4)$ be a $\gamma(\rho^0)$- or $\gamma(\omega^0)$-state, or a superposition of all four states.

of ref. ([17]), it follows that a nonrelativistic mass $m_\Upsilon \sim 4.5$ GeV has to be attributed to the heavy v-quark.

It is out of our purposes to go beyond with the $\Upsilon(9.4)$ interpretation. Postponing a more careful analysis of this problem when more exhaustive experimental data will be available, we want now to discuss briefly the weak decays of the new heavy quarks and mesons, in the framework of a $SU_{2L} \otimes SU_{2R} \otimes U_1$ gauge theory of weak and electromagnetic interactions ([14]).

As is well known, in gauge theories the (Cabibbo-rotated) quark fields (d′, s′, ...; u′, c′, ...) are defined as the eigenvectors of the quark mass matrix. Let us denote by (u, d, ...) the basis where the weak currents are flavour-diagonal. The two different bases (*) are related by unitary transformations of the kind

$$\begin{pmatrix} d' \\ s' \\ b' \\ v' \end{pmatrix}_{L(R)} = \mathscr{R}^{d}_{L(R)} \begin{pmatrix} d \\ s \\ b \\ v \end{pmatrix}_{L(R)}, \qquad \begin{pmatrix} u' \\ c' \\ t' \\ r' \end{pmatrix}_{L(R)} = \mathscr{R}^{u}_{L(R)} \begin{pmatrix} u \\ c \\ t \\ r \end{pmatrix}. \tag{7}$$

The 4×4, orthogonal matrices $\mathscr{R}^\sigma$ ($\sigma = $ u, d) depend on 16 real parameters, of which 7 can be absorbed into the definitions of the quark states, and the others are divided in 6 rotation angles and 3 phases. Thus, our model, too, can account in a natural way for CP-violation.

If we denote by Γ_μ any linear combination of γ_μ and $\gamma_5\gamma_\mu$ matrices, the neutral quark weak current can be written in the form

$$J^n_\mu \sim \bar{u}'_i \Gamma_\mu u'_i - \bar{d}'_i \Gamma_\mu d'_i = \bar{u}_i \Gamma_\mu u_i - \bar{d}_i \Gamma_\mu d_i\,, \tag{8}$$

where the orthogonality of the $\mathscr{R}^\sigma$ matrices ($\mathscr{R}^{\sigma *}_{ik} \mathscr{R}^{\sigma}_{ij} = \delta_{kj}$) has been taken into account. Therefore, neutral currents are free from flavour-changing parts, *i.e.* from $\Delta S = \Delta C = \Delta H \neq 0$ components.

The relevant strength of the $d_i \rightleftarrows u_j$ (charged) semileptonic weak transition is given by

$$\mathscr{R}^{u*}_{li} \mathscr{R}^{d}_{lj} \equiv \mathscr{R}_{ij}\,, \tag{9}$$

where $\mathscr{R}$ is a very complicated unitary matrix depending on 12 weak mixing angles and 6 phases. By making suitable assumptions on the Cabibbo-like angles entering $\mathscr{R}$, and taking into account some recent theoretical predictions ([18]) on their magnitudes, it is possible to draw definite (preliminary) conclusions on the decays of the new quarks.

([17]) E. Eichten and K. Gottfried: *Phys. Lett.*, **66** B, 286 (1977); J. Ellis, M. K. Gaillard, D. V. Nanopoulos and S. Rudez: CERN preprint TH-2346, July 1977; C. E. Carlson and R. Suaya: *Phys. Rev. Lett.*, **39**, 908 (1977); T. Hagiwara, Y. Kazama and E. Takasugi: Fermilag preprint PUB-77/72-THY (August 1977).

(*) In fact, gauge theories do not require that the weak currents and the mass matrix are simultaneously flavour-diagonal.

([18]) H. Fritzsch: *Phys. Lett.*, **70** B, 436 (1977); CERN preprint TH-2433 (December 1977); H. Terazawa: preprint INS-Rep.-298, Institut Nuclear of Study, Tokyo (October 1977); G. Dattoli, R. Mignani and D. Prosperi: *Quark mass matrix and Cabibbo-like angles* (in preparation).

For instance, if we assume a well-defined mass scale for the quarks in the heavy sector (precisely, in analogy with the light sector, $m_t \sim m_b \leqslant m_v \leqslant m_r$), one finds (*):

a) The weak decays of all heavy quarks into the u and d quarks are strongly unfavoured;

b) Both the v- and b- down quark are likely to decay into the c-quark;

c) Conversely, the transitions r $\rightleftarrows$ s and t $\rightleftarrows$ s are expected to be favoured (**);

d) The lifetimes of all heavy mesons under weak decays are predicted to be smaller than those of charmed particles.

A deeper analysis of the model proposed in this letter will be given by the same authors in a forthcoming paper.

* * *

Useful discussions with F. BUCCELLA and P. CAMIZ are gratefully acknowledged.

(*) Detailed calculations will be exploited elsewhere.

(**) From points *b*) and *c*) it clearly follows that the s/c weak decay branching ratio could be a sensible test to clarify the nature of the heavy quarks building up the $\Upsilon(9.4)$ resonance.