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Pre-quarks and fractional charges

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Abstract. Gluons in a fractionally charged quark model, arising within a non-Abelian unified gauge theory, are likely to be massless if colour SU(3) is to serve as a good classification symmetry. Unless gluons are selectively confined and quarks are not, the absence of massless gluons in weak decays of hadrons would seem to argue against observable fractionally charged quarks. This, however, does not preclude the existence of fractionally charged pre-quarks (preons, objects of which integer-charged quarks may be composed). We remark that if pre-quarks carry charge $\pm e/3$, the flavour symmetry group must be larger than SU(4) (possibly SU(6)), within the context of the Yang–Mills type of unified gauge theories.

Within the context of the Yang–Mills type of unified gauge theories, quarks (objects carrying *both* flavour and colour) can be integer or fractionally charged (Pati and Salam 1974). However, unconfined fractionally charged quarks pose something of a theoretical dilemma. Firstly, if their physical mass is not too large (<5 GeV), they might have been seen in cosmic rays and possibly also in accelerator experiments. But, more important, assuming that the colour degrees of freedom are gauged within the context of a Yang–Mills non-Abelian gauge theory of quarks and leptons, the neutral colour octet of spin-one gluons mediating strong interactions are likely to be massless, for reasons we indicate below. The emission of such massless gluons (despite the fact that they are electrically neutral) should not be too hard to detect via a lack of energy–momentum balance in decays like

$$\pi^+, K^+ \rightarrow \mu^+ + \nu + V^0 + \bar{V}^0$$

$$K^+ \rightarrow \pi^+ + \pi^0 + V^0 + \bar{V}^0$$

$$\Lambda \rightarrow p + \pi^- + V^0 + \bar{V}^0 \quad \text{etc.}$$

The branching ratios for such decays might be expected to be of order α_s^2 ($\alpha_s \approx 0.3$ – 0.5 for such low-momentum processes) multiplied by phase-space ratios and thus be $>10^{-4}$. No such gluons appear to have been detected.

Thus either (i) massless spin-one gluons[†] are selectively confined even when fractionally charged quarks are not, a rather surprising feature which needs theoretical substantiation, or (ii) massless gluons will appear in improved experimental searches (we urge such a search); or (iii) *fractionally charged* quarks carrying *both* colour and

[†] Our remarks do *not* apply to partially (or wholly confining) strong interaction theories mediated by spin-2 particles (Salam and Strathdee 1978a).

flavour do not exist as physical particles. In this paper we remark that for pre-quarks[†] (preons, elementary entities carrying either flavour *or* colour, but not both) of which quarks might be composed, such dilemmas do not arise. The pre-quarks could be fractionally charged and observable and physical gluons massive, provided the quarks themselves are integer-charged.

The reasoning[‡] which leads to masslessness of gluons for the fractionally charged quark-model is based upon the following set of assumptions: (i) the gauge Lagrangian is built upon an underlying unifying local symmetry which is such that no Abelian U(1) piece contributes to electric charge, (ii) quarks and leptons belong to the same multiplet of the local symmetry, (iii) quarks carry *both* attributes of flavour and colour, (iv) masses of gauge particles arise through a spontaneous symmetry breaking mechanism consistent with renormalisability, and finally and crucially (v) colour SU(3) is preserved at least as a good classification symmetry for strong interactions.

What we are asserting is this: assuming that, if quarks are unconfined, so also are gluons, the gluons ought to be massive. Now for the case of fractionally charged quarks, even though one can find elaborate Higgs-Kibble multiplets, which (through the spontaneous symmetry breaking mechanism) permit of these gauge gluons being massive, it has been shown by Mohapatra *et al* (1976) that such multiplets appear to lead to a strong breakdown of colour as a strong interaction classification symmetry. This is assuming that the assumptions (i)–(iv) listed above are satisfied.

The basic reason for this breakdown lies in the dichotomy of fractionally charged quarks carrying *both* flavour and colour, but at the same time their charge operator not receiving contributions symmetrically from these two attributes of colour and flavour. If this dichotomy is removed—i.e. if quarks are integer-charged (regardless of whether they are composites of pre-quarks or not) with the charge operator made up symmetrically of both colour as well as flavour pieces, there is no conflict between the generation of masses for the octet of colour gluons (through non-vanishing expectation values of appropriate sets of Higgs-Kibble scalar fields) and the preservation of an effective global SU(3) symmetry, respected by strong interactions and broken only by order $\alpha = e^2/4\pi$ corrections[§].

The conclusion of this argument is that, unless massless gluons are observed, *unconfined* quarks carrying both colour and flavour are unlikely to carry fractional charges, if we believe the present ideas underlying the Yang-Mills type of spin-one unified gauge theories. However, pre-quarks can exist, with fractional charges (and massive gluons), together with an effective global colour-classification symmetry.

Now with the assumption of no Abelian U(1) pieces contributing to the electric charge operator, the pre-quarks ('flavons' and 'chromons') can carry only specified

[†] The pre-quark (preon) hypothesis in the context of unified gauge theories was motivated by Pati and Salam (1974) and Pati *et al* (1975). In a general context several authors (J D Bjorken, O W Greenberg, B Krolkowski, C H Woo and others) have considered similar ideas, published and unpublished. See, for example, Greenberg (1975) and references therein.

[‡] This has been outlined in detail elsewhere (Mohapatra *et al* 1976). We present simply the basis of the arguments here for completeness.

[§] The mathematical argument leading to this conclusion is given by Mohapatra *et al* (1976). It holds to our present level of understanding of the symmetry-breaking mechanism. The basic strategy of preserving an effective global symmetry, while breaking the local symmetry, utilised by Mohapatra *et al* (1976) in a general context, stems from the work of Bardacki and Halpern (1972), DeWitt (1973) and Bars *et al* (1973). The work of de Rújula *et al* (1977), which gives a theory of massive gluons with fractionally charged quarks, utilises a U(1) symmetry contained in $SU(2) \times U(1) \times SU(3)_{\text{colour}}$ consistent with the conclusions of Mohapatra *et al* (1976).

values of fractional electric charges depending on the symmetry group and the charge formula. To be specific, if the symmetry group were $SU(2)_{\text{flavour}} \times SU(2)_{\text{colour}}$ with only two flavons and two chromons, and with $Q_{\text{em}} = (I_3)_{\text{flavour}} + (I_3)_{\text{colour}}$, the pre-quarks could only carry charges $\pm \frac{1}{2}$. For the symmetry group $SU(3)_{\text{flavour}} \times SU(3)_{\text{colour}}$ with three flavons and three chromons and $Q_{\text{em}} = (F_3 + F_8/\sqrt{3})_{\text{flavour}} + (F_3 + F_8/\sqrt{3})_{\text{colour}}$ the charges on flavons and chromons could only be $(\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3})$ and $(-\frac{2}{3}, \frac{1}{3}, \frac{1}{3})$.

Quite clearly, if the charge contains no U(1) piece, a group like SU(4) for flavour (descending to the GIM subgroup) will not yield[†] flavons of charges $\pm \frac{1}{3}$. Thus, if indeed such values ($\pm \frac{1}{3}$) of elementary charges have already been discovered[‡]—and this of course will need much more substantiation—and assuming that composite quarks are integer-charged, so that both flavons and chromons carry charges of same magnitudes ($\pm \frac{2}{3}, \mp \frac{1}{3}$)—one would infer, from the chain of arguments above—that the flavour group must be larger than SU(4), perhaps SU(5) or SU(6) or larger. With inclusion of lepton numbers as additional colours, the colour group would also be larger than SU(3), for example $SU(4)_{\text{colour}}$ with one type of lepton number, or $SU(6)_{\text{colour}}$ with three lepton numbers (electronic, muonic and ζ leptonic). The important point is that the arguments given above about the masslessness or otherwise of strong colour gluons are independent of the existence of these additional leptonic colours. All in all, a symmetry group of choice with six flavons and (symmetrically to this) six chromons may be the group $SU(6)_{\text{flavour}} \times SU(6)_{\text{colour}}$ with $Q_{\text{em}} = (F_3 + F_8/\sqrt{3})_{\text{flavour}}^{I+II} + (F_3 + F_8/\sqrt{3})_{\text{flavour}}^{I+II}$. Here the elementary flavon and chromon charges are $(\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3}, \frac{2}{3}, -\frac{1}{3}, -\frac{1}{3})$ and $(-\frac{2}{3}, \frac{1}{3}, \frac{1}{3}, -\frac{2}{3}, \frac{1}{3}, \frac{1}{3})$ with altogether 18 composite quarks and 18 leptons. Here the superscripts I and II for flavour symmetry refer to SU(3) subgroups acting on (p, n, λ) and (c, b, b') indices respectively; likewise for colour.

But whatever the larger symmetry group, the point we wish to make is that *with our assumption of no U(1) piece contained in the composition of the charge operator, a discovery of elementary charges $\pm 1/3$ without a simultaneous appearance of massless gluons would denote, not a discovery of quarks, but possibly of pre-quarks, with a flavour group which is larger than SU(4)*. Such pre-quarks may not be excessively massive. A dynamical indication of their physical existence would be signalled by a massive breakdown of scaling for energies and momentum transfers commensurate with the gauge and other masses relevant to their theory. Thus one may distinguish three regions:

(i) Relatively low energies and low momentum transfers (obtaining for example at SLAC and possibly even at Fermilab and SPS) when quarks appear like point particles

[†] In this case electric charge is constrained to have the form $Q = (F_3 + F_8/\sqrt{3} - \sqrt{2/3}F_{15})_{\text{flavour}} + (F_3 + F_8/\sqrt{3} - \sqrt{2/3}F_{15})_{\text{colour}}$, which yield charges $\pm \frac{1}{2}$ for flavons and chromons.

[‡] The notion that pre-quarks should carry fractional charges has been indicated in earlier work by Pati *et al* (1975). The present note has been stimulated by the recent announcement of a discovery of elementary charge $\pm \frac{1}{3}$ by La Rue *et al* (1977, 1979).

§ Speculatively one might consider the possibility of a simple non-Abelian symmetry group like SU(12) of which the 6 + 6 flavons plus chromons form a fundamental representation. A local gauging of its descended subgroup $SU(6)_{\text{colour}} \times SU(6)_{\text{flavour}} \times U(1)$ may, in addition to the non-Abelian gauge particles, also yield a universal gluon corresponding to the U(1) Abelian subgroup. Such a U(1) would not contribute to charge, but the universal gluon would be coupled oppositely (in sign) to flavons and chromons. Thus flavons and chromons may form quark and leptonic composites, but not two flavons or two chromons. The hypothesis of leptons being composites needs additional dynamical considerations. The present utilisation of $SU(6)_{\text{colour}} \times SU(6)_{\text{flavour}}$ for describing the intersections of composite quarks and leptons is then giving us an effective Lagrangian, relevant up to energies at which the quarks and leptons begin to exhibit their composite structure.

and there is no dynamical indication of pre-quarks. Scaling violations are controlled by logarithmic factors originating from asymptotic freedom[†].

(ii) An intermediate region, when composite quarks are described by their form factors, controlled by the range of binding forces, in the pre-quark theory. Scaling violations may be massive.

(iii) The pre-quark regime, where scaling may once again be established, the pre-quarks manifesting themselves as point particles. The situation would be described by a pre-quark parton model on the pattern of the quark parton model, except that it is the pre-quark distribution functions which would be the objects of interest.

(iv) And then do we start again perhaps with pre-pre-quarks . . . ? Following the mathematician Augustus de Morgan (1808–1871), one may find that

Big quarks have Pre-quarks
 In their Bags to bite them
 Pre-quarks have pre-pre-quarks
 'And so, ad infinitum'.

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[†] Asymptotic freedom holds for massive colour-gluon theories at least in the 'temporary sense', to the extent that quartic couplings of relevant scalar fields are $\ll e$. Alternatively one may use the mechanism suggested by Salam and Strathdee (1978b), where Higgs couplings are all induced couplings mediated by gluon exchanges and there are no bare Higgs couplings. There is no breakdown of asymptotic freedom in theories of this type.