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LIGHT COMPOSITE FERMIONS

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ABSTRACT

't Hooft's conditions for massless composite fermions are discussed. We then study the various mechanisms through which such composite fermions can acquire a small mass. Two new mass generation mechanisms are proposed.

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The possibility that quarks and leptons are composites of more elementary objects called preons¹⁾ has recently received much consideration²⁾⁻⁶⁾. If the quarks and leptons are indeed composite, two questions arise. First, why are the lepton (and presumably also quark) binding energies⁴⁾ so much larger than their masses? Second, what is the origin of the small masses of quarks and leptons? In answer to the first question, 't Hooft²⁾ has given conditions under which composite fermions are massless. We will review and discuss 't Hooft's conditions. Next, in answer to the second question, we will propose mechanisms by which these composite fermions can acquire a small mass.

Consider the unbroken asymptotically free gauge group G^C with left-handed spin 1/2 fermion representation content:

$$N_1 (n_1) + N_2 (n_2) + \dots + N_k (n_k) \quad (1)$$

We use the name "colour" for the degrees of freedom on which G^C acts, and the name "flavour" for the degrees of freedom on which acts the symmetry group of the colour gauge interactions:

$$G^F = SU(N_1) \times \dots \times SU(N_k) \times U_{11} \times \dots \times U_{k-1} \quad (2)$$

Also, by convention, all fermions are left-handed spin 1/2 whether preons or composites. Let us consider the theory defined by G^C and the fermion representation content (1) at energies well below Λ^C , the scale at which the gauge coupling constant of G^C becomes strong. At those energies, colour is confined: only colourless (and therefore in general composite) degrees of freedom appear. Moreover, the global symmetries of physics at those energies form some subgroup H^F of G^F , since in general G^F has been partly broken down spontaneously at energy scales of order Λ^C :

$$G^F \xrightarrow{\Lambda^C} H^F \quad (3)$$

't Hooft²⁾ pointed out that composite fermions can be kept massless by chiral symmetries in H^F . Moreover, 't Hooft²⁾ postulated the following constraints on the H^F multiplets of massless composite fermions that might appear:

$$1) \quad \text{Tr}_{\Psi} (Q^a \{Q^b, Q^c\}) = \text{Tr}_{\psi} (Q^a \{Q^b, Q^c\}) \quad (4)$$

for any triplet of generators Q of H^F . Ψ represents the set of composites, whereas ψ represents the set of preons.

2) For any explicit preon mass term:

$$\bar{\Psi}^T m \sigma_2 \Psi + \text{h.c.} \quad (5)$$

that breaks $H^f \rightarrow H'^f$, H'^f must be such as to allow mass for all the composites Ψ that contain massive preons ψ .

Equation (4) is thought to follow from general principles and to be a necessary constraint. The second constraint, as Preskill and Weinberg⁶⁾ recently emphasized, follows from the Appelquist-Carazzone decoupling theorem⁷⁾ and the assumption that no phase transition occurs when m is varied from zero to infinity. Since m/Λ^C can be a critical parameter, it is not clear that this assumption is valid.

Solutions^{2),3),5)} to 't Hooft's constraints exist. Moreover, if the second constraint is dropped, numerous solutions^{6),8)} can be found to Eq. (4). Let us thus take for granted the existence of massless composite fermions à la 't Hooft and address the question of how to give them small masses.

Obviously this must be done by introducing a small perturbation that breaks the chiral symmetries in H^f . Let us require that this perturbation be introduced without the use of elementary scalars. We wish to consider theories with gauge fields and spin 1/2 fermions only. We then distinguish three different ways in which composite fermions can acquire small masses.

1. "Unification"

G^C can be the unbroken subgroup of a larger group G :

$$G \xrightarrow{\mu} G^C, \quad \mu > \Lambda^C \quad (6)$$

In general, G will unify several multiplets (1) of G^C into larger multiplets. As a result, H^f will be explicitly violated by the interactions mediated by the G/G^C vector bosons. One can expect composite fermion masses of order $(\Lambda^C)^3/\mu^2$.

As an example, consider $G^C = SU(5)$ and the preons $\{\psi^i, \psi_{ij} = -\psi_{ji}\} \sim (\bar{5}) + (10)$. $G^f = U(1)$ generated by $Q = 3N_5 - N_{10}$. The massless composite $\Psi = \epsilon_{ijklp} (\psi_{ij}^\dagger \sigma_2 \psi_{kl}^\dagger) \psi^p$ reproduces Eq. (4) the preon anomaly³⁾. Now assume unification into $G = O(10)$ at some scale $\mu \gg \Lambda^C$. We introduce an $SU(5)$ singlet ψ_0 to complete the $O(10)$ multiplet: $(16) = (10) + (\bar{5}) + 1$. The four fermion interactions mediated by the $O(10)/SU(5)$ vector bosons:

$$\frac{-1}{\mu^2} J_{ij}^\alpha J_\alpha^{ij} \quad (7)$$

with:

$$J_{ij}^\alpha = \psi_0^\dagger \sigma^\alpha \psi_{ij} + \frac{1}{2} \epsilon_{ijklp} \psi_{ke}^\dagger \sigma^\alpha \psi^p \quad (8)$$

explicitly break the $U^f(1)$ symmetry of $SU^C(5)$. After a Fierz transformation, one of the terms in (7) becomes:

$$\begin{aligned} & -\frac{2}{\mu^2} \epsilon_{ijklp} (\psi_{ke}^\dagger \sigma_2 \psi_{ij}^\dagger) (\psi_0 \sigma_2 \psi^p) + h.c. \\ & \simeq -\frac{(\Lambda^C)^3}{\mu^2} (\Psi^T \sigma_2 \psi_0 + h.c.) \end{aligned} \quad (9)$$

2) H^f can be explicitly broken by gauging some subgroup K^f of G^f . This mechanism has been discussed by several authors⁹⁾. The resulting Ψ masses are of order $e^{-2\pi/\alpha\Lambda^C}$ or $\alpha\Lambda^C$ depending on whether or not K^f instantons are necessary to break the relevant chiral symmetries in H^f [α is the K^f gauge coupling constant at the scale Λ^C]. For completeness, we give an updated version of Weinberg's original example⁹⁾.

Consider QCD with three massless quarks $\{u,d,s\}_{L,R} \sim 3(3)_L + 3(3)_R$ of $SU^C(3)$. $G^f = SU_L(3) \times SU_R(3) \times U_V(1)$. Let us consider a scenario where $\langle \bar{s}s \rangle \simeq (\Lambda^C)^3$ but $\langle \bar{u}u \rangle = \langle \bar{d}d \rangle = 0$. $H^f = SU_L(2) \times SU_R(2) \times U_V(1) \times U_V^8(1)$. The massless composites $p = (u_i \bar{d}_j) u_k \epsilon^{ijk}$ and $n = (u_i \bar{d}_j) d_k \epsilon^{ijk}$ reproduce the quark anomalies with respect to H^f [C is the 4×4 charge conjugation matrix]. The other members of the baryon octet (Λ, Σ, Ξ) have masses of order Λ^C .

Now let us gauge $K^f = SU_V(3)$. The vacuum aligns in such a way that $SU_V(3) \xrightarrow{\Lambda^C} SU_V(2) \times U_V^8(1)$. The gauging of $SU_V(3)$ explicitly breaks the axial symmetries in H^f that keep the p and n massless. p and n acquire a mass of order $\alpha\Lambda^C$ through self-energy diagrams with an $SU_V(3)/SU_V(2)$ vector boson and a Λ or Σ baryon inside the loop.

3) Metatechnicolour:

The gauging of a subgroup J^f of H^f can lead to the spontaneous breaking of chiral symmetries in H^f . The mechanism combines the ideas of "metacolour"²⁾ and "technicolour"¹⁰⁾ to produce an alternative to "extended technicolour"¹¹⁾. Let us thus rename: $G^C \rightarrow G^{mc}$ for metacolour, $G^f \rightarrow G^{mf}$ for metaflavour, $H^f \rightarrow H^{mf}$ and $J^f \rightarrow G^{tc}$ for technicolour. G^{tc} is a subgroup of H^{mf} . One can produce composite fermion masses of order $(\Lambda^{tc})^3/(\Lambda^{mc})^2$.

As an example, consider $SU(5)$ with $\{\psi_{\alpha}^i, \psi_{ij}^{\rho}\} \sim N(\bar{5}) + N(10)$. $\alpha, \rho = 1, \dots, N$; $i, j = 1, \dots, 5$. $G^{mf} = SU_5(N) \times SU_{10}(N) \times U(1)$ where the Abelian generator is $Q = 3N_5 - N_{10}$. As a result of a "tumbling" scenario³⁾, $H^{mf} = O(N) \times U(1)$ where $O(N)$ is the diagonal subgroup of $O_5(N) \times O_{10}(N)$. The massless composites $\Psi_{\alpha} = (\psi_{ij}^{\rho\dagger} \sigma_2 \psi_{kl}^{\rho\dagger}) \psi_{\alpha}^p \epsilon_{ijklp} \sim (N)_5$ of $O(N) \times U(1)$ reproduce the preon anomalies [Eq. (4)]. Now, let us gauge a $O^{tc}(M)$ subgroup of $O(N)$. Ψ_r ($r = 1, \dots, M$) are technifermions; Ψ_a ($a = M + 1, \dots, N$) are "ordinary" fermions. We expect the technifermions to condense:

$$\left\langle \sum_{r=1}^M \Psi_r \sigma_2 \Psi_r \right\rangle \simeq (\Lambda^{tc})^3 \quad (10)$$

thereby spontaneously breaking the $U(1)$ symmetry that keeps the "ordinary" fermions massless. The latter acquire mass as a result of residual four fermion interactions between metacolour composites (these are analogous to baryon-baryon interactions in QCD). In our model, we expect the $O(N) \times U(1)$ symmetric residual interaction:

$$\frac{1}{(\Lambda^{mc})^2} (\Psi_{\alpha} \sigma_2 \Psi_{\alpha}) (\Psi_{\alpha} \sigma_2 \Psi_{\alpha})^{\dagger} \quad (11)$$

to be present. A mass term for the "ordinary" fermions:

$$\frac{(\Lambda^{tc})^3}{(\Lambda^{mc})^2} \sum_{a=M+1}^N \Psi_a \sigma_2 \Psi_a + h.c. \quad (12)$$

results.

We feel that as far as mass generation for the quarks and leptons is concerned, the first and third mechanisms are more promising than the second. The extended technicolour mechanism¹¹⁾ appears to run into problems with flavour changing neutral currents¹²⁾ (FCNC). Equation (11) clearly shows that FCNC will also be present in the metatechnicolour mechanism. However, in a model more realistic than the example we gave, the residual interactions between ordinary fermions (quarks and leptons) might be suppressed relative to the residual interactions between ordinary fermions and technifermions by such mechanisms as the OZI rule¹³⁾. The problem of FCNC in models of dynamical symmetry breaking might thus be avoided.

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