Conf-820142--4

LA-UR -82-1416

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LA-UR--82-1416

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TITLE: LIGHT COMPOSITE FERMIONS - AN OVERVIEW

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SUBMITTED TO: Proceedings of the Orbis Scientiae 1982

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LIGHT COMPOSITE FERMIONS - AN OVERVIEW*

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*Talk presented at the Orbis Scientiae, Coral Gables, Florida (1982)

OUTLINE

1. Rules
2. Mass Generation Mechanisms
3. Generation Number

1. Rules

I know that Estia Eichten (in these proceedings), has already discussed one set of rules which describe massless composite fermions and the possible breaking of chiral symmetries. I'd just like to spend a few minutes now discussing the status of some rules which have been proposed and also to emphasize a few points. In particular, I will discuss (a) 't Hooft's anomally conditions (and left-right symmetric theories), (b) 't Hooft's decoupling conditions (or persistent mass hypothesis of Preskill and Weinberg[2]), and (c) "tumbling"[3] vs no "tumbling".

(a) 't Hooft's anomally conditions are by now well established.[4] However, the anomally conditions are not sufficient to uniquely determine the spectrum of massless composites. Additional dynamical assumptions (RULES) are necessary in order to obtain an unambiguous spectrum. For example, the anomally conditions are only applicable when the strong interaction dynamics (i.e., the binding forces) preserve the global chiral symmetries of the theory. If they are broken however, then there is no need for massless composite fermions even if the consistency conditions have solutions. The breaking of the chiral symmetries is a dynamical question. This brings us to the subject of left-right symmetric theories such as QCD. In QCD there is an $SU(M)_L \otimes SU(M)_R$ chiral symmetry, where M is the number of left and right-handed quark flavors. Solutions can be found to the anomally conditions for particular values of M. However, we believe that the QCD forces create fermion condensates that break $SU(M)_L \otimes SU(M)_R$ to $SU(M)_{vector}$ giving all M flavors a dynamical mass. The resulting symmetry $SU(M)_{vector}$ does not require any massless composite fermions and there are none.

What evidence do we have that left-right symmetric theories will generically not require massless composite fermions.

1) Coleman and Witten[5] have shown that in the large N limit of an SU(N) gauge theory with fermions in the fundamental representation the chiral symmetries are spontaneously broken.

2) It has been shown that the chiral symmetries are spontaneously broken in an SU(N) lattice gauge theory with fermions in the fundamental representation either by using a self-consistent strong coupling expansion[6] or in Monte Carlo calculations which neglect internal fermion loops.[7,8]

   Thus it is evident that SU(N) gauge theories with M flavors of left-right symmetric fermions in the fundamental representation do not lead to massless composite fermions.

3) The situation for an O(N) gauge group with fermions in the N dimensional representation is not as clear. For example, Banks and Kaplunovsky[9] have found evidence in an O(N) lattice gauge theory that the chiral symmetries are unbroken and that massless composite fermions (solutions to 't Hooft's anomally conditions) exist.*

To summarize, it's a dynamical question whether chiral symmetries remain unbroken in a theory. This question can be answered in some cases with present techniques. It is crucial information which can eliminate certain classes of

*After this talk was given, we received a paper by J. Kogut, et al.[10] who discuss chiral symmetry breaking in lattice gauge theory. They find that for N = 3, the chiral symmetries are in fact spontaneously broken.

theories with regards to their use in constructing models of massless composite fermions.

(b) 't Hooft suggested that the anomaly conditions should be supplemented by the decoupling condition based on the Appelquist-Carrazone theorem. He argued that the Appelquist-Carrazone theorem would imply that if a solution to the consistency conditions is found in which the constituent can obtain a small mass, then the composite fermion would also obtain a small mass (since it must eventually decouple) and one should throw out such solutions on the grounds that they are "unnatural", i.e., if a particle is "naturally" massless, it should remain massless under small changes in parameters. However, it has been realized that the composite fermion may remain massless, even though its constituent has a small mass, and still be consistent with the Appelquist-Carrazone theorem, i.e., if there is a phase transition when $m_{constituent} \sim \Lambda_{binding}$. ($\Lambda_{binding}$ = binding scale.) The persistent mass hypothesis[2] makes it a dynamical principle that such phase transitions don't occur and that $m_{composite}$ is proportional to $m_{constituent}$. Recently Dimopoulos and Preskill[11] and Bars and Yankielowicz[12] have made it very plausible that massless composites can be made of massive constituents. Their analysis relies on the dynamics of subgroup-alignment and I refer you to their papers for the details. To summarize, it is clear that the decoupling condition as phrased in its strictest form is <u>not</u> a direct consequerce of the Appelquist-Carrazone theorem and is probably <u>not</u> valid as a general rule.

(c) The phenomenon of tumbling (i.e., a gauge group breaking itself by forming fermion condensates in a nontrivial representation) is the consequence of a rule suggested by Dimopoulos, Susskind, and myself.[3] In some cases it has no effect on the spectrum of massless composities whether or not the system actually tumbles. This is a result of a principle of complimentarity[13] which have no time to discuss now. In these cases tumbling manifests itself on the the structure of intermediate scales. There do exist cases however in which tumbling is signalled by the presence of phase boundaries in the system which distinguish the broken and unbroken chiral phases. (These are necessarily non-complimentary examples.)

Consider the gauge group SU(6) with one left-handed multiplet of fermions in the 20-dimensional representation. The fermion field is given by the expression

$$\psi_{[ijk]} \qquad i,j,k = 1,\ldots,6 \tag{1}$$

and [ijk] denotes anti-symmetrization. It is easy to see for this system that it is not possible to break chirality without simultaneously breaking either Lorentz invariance or SU(6). Consider the Lorentz scalar, gauge invariant operator

$$\psi_{[ijk]}\psi_{[rst]}\epsilon^{ijkrst} = 0 \quad . \tag{2}$$

It vanishes by Fermi statistics. The next possible channel in which a condensate might form is then given by the Lorentz scalar

$$\psi_{[ijk]}\psi_{[rst]}\epsilon^{jkrst\ell} = \phi_i^\ell \quad . \tag{3}$$

This is actually the Maximally Attractive Channel as defined in Ref. 3. If ϕ_i^ℓ condenses it will break SU(6). One possible breaking pattern is

$$SU(6) \rightarrow SU(3) \otimes SU(3) \otimes U(1) \quad . \tag{4}$$

In the symmetric phase there are no finite energy fermion states. Whereas in the broken phase there are $SU(3) \otimes SU(3)$ singlet fermions carrying long range U(1) forces. There also exist U(1) monopoles in this phase. Whether or not the system tumbles is thus a dynamical question which deserves further study.

Recently Eichten and Feinberg[14] have argued that tumbling does not occur in four dimensions. They find, in a perturbative approximation, that the gauge contributions to the vacuum energy dominate over the Fermion contributions and tend to preserve the symmetric phase. A. D'Adda, et al.,[15] on the other hand, have studied the non-Abelian generalization of CP^n models in 2 dimensions. These models contain an $SU(\ell)$ local gauge symmetry in addition to a global U(n) invariance. They find, in a 1/n expansion, that the local $SU(\ell)$ gauge group breaks down due to the formation of the fermion bilinear condensate

$$\phi_{(\alpha\beta)} = \langle \bar{\psi}_{R\alpha} \psi_{L\beta} \rangle \neq 0 \quad . \tag{5}$$

$\alpha, \beta = 1, \ldots, \ell$. Clearly, much work must still be done to understand the tumbling phenomenon.

2. Mass Generation Mechanisms

We have all these massless composite fermions flying around and we'd like to give them some small masses $m \ll \Lambda_{binding}$. Recall the reason why they are massless is due to an exact chiral symmetry G_{flavor} which as a result of 't Hooft's anomally conditions protects these fermions from getting mass.* Thus,

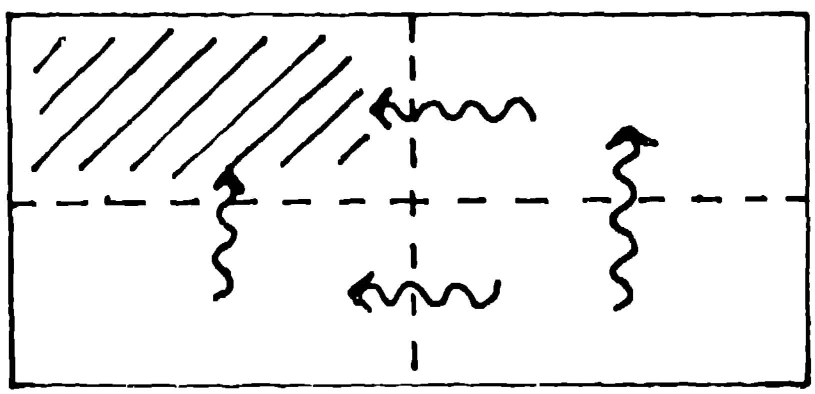
*For a discussion of this point see E. Eichten, in these proceedings.

in order to obtain mass, we must break G_{flavor} and the degree to which G_{fl} is broken determines the ratio $m/\Lambda_{binding}$. I am aware of four mechanisms for this breaking.

1) Weak gauging I[16]

In this scenario G_{fl} is assumed to spontaneously break to a subgroup H_{fl} as a result of the strong interaction dynamics. Consider an irreducible representation under G_{fl} of massless composite fermions--solutions to the anomaly conditions for G_{fl}. This becomes a reducible representation under the subgroup H_{fl}. Not all of these states are protected by H_{fl} and in fact it is easy to see that some obtain mass either directly from the many fermion condensate that broke G_{fl} to H_{fl} or via instantons and the condensate.

$$D(G_{fl}) = \sum_{\oplus i} D_i(H_{fl})$$



(Fig. 1)

The solid box represents the irreducible representation $D(G_{fl})$ and the small boxes are $D_i(H_{fl})$. The shaded area is the irreducible representation of H_{fl} with mass of order $\Lambda_{Binding}$.

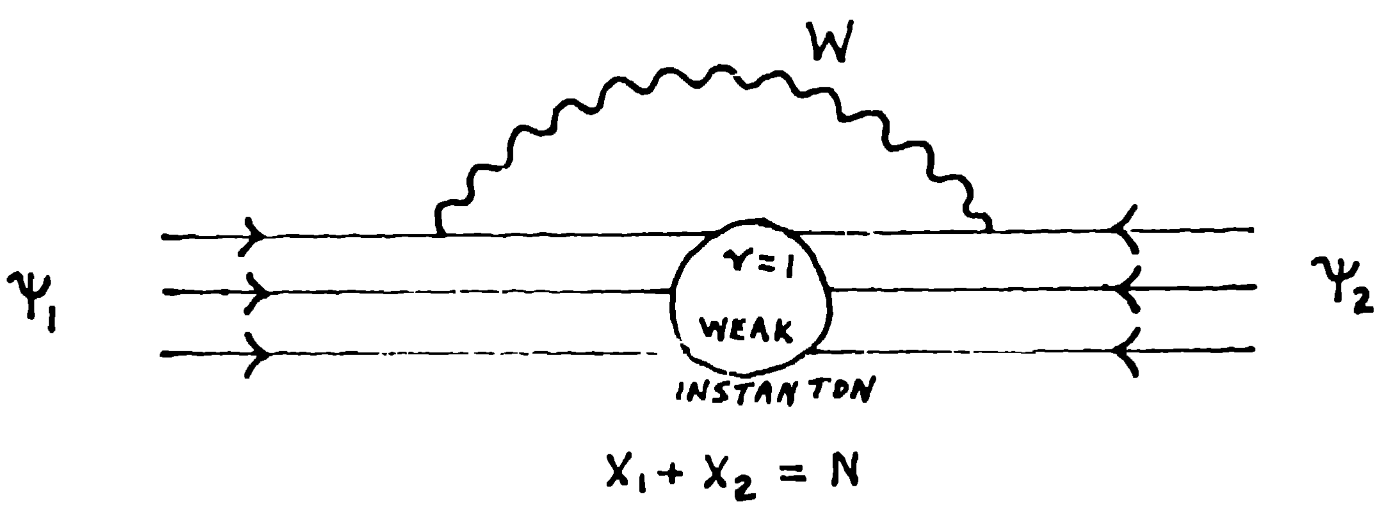
Now imagine weakly gauging a subgroup G_w of G_{fl} so that G_w is not contained in H_{fl}, but explicitly breaks H_{fl}. Then the fermions which are protected by H_{fl} will obtain mass radiatively via weak exchanges. This is represented by the wiggly lines in the figure above, i.e., the weak exchanges take massless states into massive ones. These corrections will typically be of order

$$m \sim \alpha\Lambda_{binding},\ \alpha^2\Lambda_{binding} \qquad (6)$$

where α is the weak fine structure constant.

2) Weak gauging II[17]

In this scenario G_{fl} does not spontaneously break. However, by gauging a subgroup G_w of G_{fl} we can explicityly break G_{fl} to $G_w \otimes U(1)_X$ where $U(1)_X$ is a global chiral symmetry. $U(1)_X$ is then broken by weak instantons to the discrete symmetry $e^{i\frac{X2\pi}{N\nu}}$ where $N = \sum_i X_i$, X_i is the charge of the i^{th} fermion emitted by an instanton with topological charge $\nu = 1$. The massless composites then obtain mass via weak exchanges in conjunction with a weak instanton.



(Fig. 2)

The mass is of order

$$m \sim \alpha(\Lambda_{Binding})\, e^{-4\pi/\alpha(\Lambda_{Binding})}\, \Lambda_{Binding} \quad . \tag{7}$$

3) Strong gauging[18]

We gauge a subgroup G_{TC} of G_{fl} such that at some scale $\Lambda_{TC} << \Lambda_{Binding}$ the forces associated with G_{TC} become strong. It is also assumed that at the scale Λ_{TC} those massless composite fermions carrying the strong force condense and obtain dynamical masses of order Λ_{TC}. We now argue that even those massless composite fermions which do not feel TC forces will obtain a mass

$$m \sim \frac{\Lambda^3_{TC}}{\Lambda^2_{Binding}} \quad . \tag{8}$$

This is because at energies $E << \Lambda_{Binding}$ there probably exist residual non-renormalizable interactions among the massless composities. For example, there can be four Fermi interactions of the form

$$\frac{1}{\Lambda^2_{Binding}} \psi\psi\psi\psi \tag{9}$$

with the global symmetry G_{fl}. Clearly, if two of the states carry G_{TC} forces and condense, we obtain a mass for the other two of the form

$$\frac{1}{\Lambda^2_{Binding}} \langle \psi_{TC}\psi_{TC} \rangle \psi\psi$$

or (10)

$$m \sim \frac{\Lambda^3_{TC}}{\Lambda^2_{Binding}} \quad .$$

4) Unification

This scenario includes the extended Technicolor ideas as a simple example (see Ref. 19 for further discussion). One just imagines that all the fermions in an ETC scenario are bound states of some strong interaction with a binding scale much larger than Λ_{ETC}.

In addition, we have the following possibility discussed recently by Abbott, et al.[20] Consider a strong group $G_{S1} \otimes G_{S2}$ where G_{Si} are simple groups. Include fermions transforming under $G_{S1} \otimes G_{S2}$ such that there exists a global chiral symmetry G_{fl}. As a result of $G_{S1} \otimes G_{S2}$ the elementary fermions bind at a scale $\Lambda_{Binding} \sim \Lambda_{S1} \sim \Lambda_{S2}$ forming massless composite fermions which transform under G_{fl}. If we now unify $G_{S1} \otimes G_{S2}$ into a simple group $G_S \supset G_{S1} \otimes G_{S2}$ at a scale $\Lambda_u >> \Lambda_{Binding}$ and at the same time break G_{fl}, then some of the composite fermions will obtain mass. As an example, consider $G_S \equiv SU(5) \supset G_{S1} \otimes G_{S2} = SU(3)_S \otimes SU(2)_L$ where $SU(2)_L$ can be thought of as a strong version of the standard weak $SU(2)_L$ [21] and $SU(3)_S$ is a new strong interaction not to be confused with $SU(3)_{color}$. The breaking $SU(5) \to SU(3)_S \otimes SU(2)_L$ occurs at a scale $\Lambda_u >> \Lambda_{Binding} \sim \Lambda_S \sim \Lambda_{2L}$. Consider the following left-handed fermion states with their $SU(3)_S \otimes SU(2)_L$ quantum numbers:

$$
\begin{array}{lll}
T_{Si} & (3,2) & S = 1,2,3 \; \varepsilon \; SU(3)_S \\
 & & i = 1,2 \quad \varepsilon \; SU(2)_L \\
\bar{A}^S & (\bar{3},1) & \\
\bar{B}^S & (\bar{3},1) & \\
\psi_i & (1,2) & \bar{e} \qquad (1,1)
\end{array}
\tag{11}
$$

$\bar{e}$ is a spectator to the strong interactions. The flavor symmetry is

$$G_{fl} = SU(2)_{AB} \otimes U(1) \tag{12}$$

where the U(1) has no strong anomalies. 't Hooft's anomally conditions can be solved and we find the massless composites

$$\bar{A}^{S^*} T^*_{Si} \psi_i \qquad \bar{B}^{S^*} T^*_{Si} \psi_i \tag{13}$$

transforming as a doublet under $SU(2)_{AB}$. Note that according to the scenario of a strong $SU(2)_L$,[21] these massless composites are to be associated with, for example, the ν e doublet and the standard weak interactions are associated with the residual 4 Fermi interactions which result from the binding forces $SU(3)_S \otimes SU(2)_L$. In this context, the singlet $\bar{e}$ is to be associated with the left-handed positron. We now show that the broken SU(5) interactions generate an electron mass. Under SU(5) the states of Eq. (11) transform as follows:

$$10 \supset \bar{A}\, T\, \bar{e}$$
$$\bar{5} \supset \bar{B}\, \psi \quad . \tag{14}$$

The broken SU(5) forces then induce the following mass term

$$\frac{1}{\Lambda_u^2}\, \bar{e}^{*}(T_{Si}\bar{B}^{S}\psi_i^{\gamma})$$

or (15)

$$m_e \sim \frac{\Lambda^3_{Binding}}{\Lambda_u^2} \quad .$$

To summarize, we have discussed four mechanisms to give a small mass $m \ll \Lambda_{Binding}$ to massless composite fermions. These are the tools for constructing realistic models. We note finally that they have been discussed separately for pedagogical purposes but clearly they can be used in tandem when building models.

3. Generation Number

The origin of the different generations of quarks and leptons is a long-standing puzzle. In the context of composite models, the three generations of quarks and leptons must appear in the first approximation as three sets of massless composite fermions in identical representations of a continuous flavor symmetry G_{fl} with a conserved generation number distinguishing them. In addition, the generation symmetry is preferrably a discrete one in order to avoid massless Goldstone bosons that would occur if we would spontaneously break a continuous symmetry. Harari and Seiberg[22] have shown that in a class of rishon models there exist U(1) generation symmetries that are automatically broken to a discrete generation symmetry due to strong interaction instantons. Recently Eichten and Preskill[23] have found solutions to the anomally conditions with this property. I'd like to conclude this talk with one of their examples. We consider the strong interaction group $G_S = SU(N)$ with $N = 4(2m + 1)$, m a positive integer. The left-handed fermions are

$$
\begin{aligned}
&\phi^{(ij)} \\
&\chi_{[ij]} \\
&\psi_{ia} \qquad a = 1,\dots,8
\end{aligned}
\tag{16}
$$

where $i,j = 1,\dots,N \in SU(N)$. The symbols () ([]) mean (anti-) symmetrization. The flavor symmetry G_{fl} of the model is

$$G_{fl} = SU(8)\otimes U(1)\otimes U(1)$$

which we assume is spontaneously broken to $H_{fl} = SU(8)\otimes U(1)_G$ where the generation number G is given by

$$G = 8(m + 1)N_\phi - 8mN_\chi - 6(2m + 1)N_\psi \quad ,$$

and N_ϕ counts ϕ states, etc. The solutions to the anomally conditions for H_{fl} are the massless composites

$$\phi^{ij}\psi_{ia}\psi_{jb} = \xi^{1}_{[ab]}$$

$$\phi^{ij}(\chi\phi)_j{}^{\ell}\psi_{ia}\psi_{\ell b} = \xi^{2}_{[ab]}$$

$$\vdots$$

$$\phi^{ij}[(\chi\phi)^{2m}]_j{}^{\ell}\psi_{ia}\psi_{\ell b} = \xi^{2m+1}_{[ab]} \quad .$$

We thus find 2m + 1 generations in the 28 dimensional representation of SU(8) with generation numbers $G = -4(4m+1), -4(4m-1), \ldots, -4$. If we now let $m = 1$ and $N = 12$, we find 3 generations. Preskill[23] has then shown one way for obtaining a nontrivial mass spectrum for these states by gauging the flavor group SU(8) in an extended Technicolor scenario. We note that when SU(8) is gauged, instantons of the strong Technicolor ($SU(8) \supset G_{TC} = SU(4)$) forces break $U(1)_G$ to the discrete symmetry

$$e^{2\pi iG/\Delta G}$$

where $\Delta G = 54$ and the 3 generations have multiplicative charges $e^{-2\pi i(20/54)}$, $e^{-2\pi i(12/54)}$, $e^{-2\pi i(4/54)}$. The discrete generation symmetry is then spontaneously broken by the strong Technicolor forces, enabling all the fermions to obtain mass.

To conclude, much progress has been made in understanding light composite fermions. Clearly, much more work is necessary before we shall obtain a realistic model of composite quarks and leptons.

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