IC/83/78

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

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INTERNATIONAL ATOMIC ENERGY AGENCY

UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

1983 MIRAMARE-TRIESTE

International Atomic Energy Agency
and
United Nations Educational Scientific and Cultural Organization

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ABSTRACT

Using the supersymmetry and R-breaking mechanism induced by $N = 1$ supergravity, we develop the minimal flavon-chromon preonic model where spin 1/2 and spin 0 components of four preonic chiral multiplets correspond to flavons and chromons, from which quarks and leptons are made as composites. The emergence of the concepts of flavour and colour, in this minimal model, is synonymous with R and supersymmetry breaking. This breaking also gives a heavy mass to the gaugino, which is necessary for the implementation of the model.

MIRAMARE - TRIESTE
July 1983

* To be submitted for publication.

** Supported in part by the US National Science Foundation.

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1. This is an addendum to an earlier paper [1], in which we considered the hypothesis that supersymmetry may be the symmetry associated with preonic matter, breaking at the level of energies at which composites of preons (quarks and leptons) are formed.

Among the models considered, we displayed one which we believe is conceptually particularly attractive. This model considers spin-1/2 and spin-0 components of a chiral supersymmetric field as flavons and chromons respectively. Quarks and leptons are two-body composites of flavons and chromons. Thus at the supersymmetric stage flavour and colour quantum numbers are not distinguished - their distinction is simply the distinction associated with the R-quantum number [*], which for a chiral multiplet essentially counts the fermion number of the component fields.

It is at the stage of supersymmetry breaking - more precisely, R-breaking - that flavour and colour are distinguished. The composites are formed after this stage and correspond to quarks, leptons, W's, Z's, etc.

*) This was the context in which this number was introduced by Abdus Salam and J. Strathdee (Ref.2) who designated it as the F-(fermion)-number. The R transformation introduced independently by P. Fayet (Ref.3) differs from the F transformation by phase factors.

The problem which we left unresolved in the earlier paper was that of the mechanism of supersymmetry and R-breaking. With the recently introduced ideas of this breaking being possibly associated with the breaking of $N = 1$ supergravity, we can now solve this problem and below we exhibit one solution of this.

To show the essentials of the model, consider the simple case of U(1) gauging of one left-handed (S) and one right-handed chiral superfield multiplet (T) carrying $R = +1$ and -1 respectively.

Following Cremmer, Fayet and Girardello [4], we introduce a kinetic energy term which is canonical for the chiral multiplet, but for the gauge multiplet one permits a non-canonical generalized kinetic energy term of the form

$$e^{-1} \mathcal{L}^{(gauge)}_{kinetic} = -\frac{1}{4} \mathrm{Re}\, f_{ab} F^{a}_{\mu\nu} F^{b}_{\mu\nu} + \frac{1}{4} \mathrm{Im}\, f_{ab} F^{a}_{\mu\nu} \tilde{F}^{b}_{\mu\nu} - \frac{1}{2} \mathrm{Re}\, f_{ab} \bar{\lambda}^{a} D \lambda^{b} , \quad (1)$$

where D denotes covariant derivative with respect to the gauge group and $f_{ab} = \delta_{ab}[1 + \sqrt{2/3} (\frac{m_\lambda}{m_{3/2}}) \kappa Z]$. Here $\kappa = (1/M_p)$; Z is the scalar part of the "hidden" supermultiplet; and m_λ and $m_{3/2}$ are the two mass-parameters which one can introduce into the theory. These two mass-parameters correspond, after implementation of the super-Higgs effect, to the masses of the gaugino (λ) and the gravitino respectively. With an appropriate choice of the superpotential for the theory, involving the hidden (Z) as well as the manifest fields (S,T), the $N = 1$ supergravity interactions induce standard soft supersymmetry - and R-breaking terms for "low-energy"-physics. Cremmer, Girardello and Fayet [4] show that the supersymmetry-breaking effective potential for the matter scalar-fields t and s reads:

$$V(s,t) = \frac{e^2}{2}\left|s^+s - t^+t\right|^2 + \left|m_{3/2}t\right|^2 + \left|m_{3/2}s\right|^2 \tag{2}$$

while the "low-energy" Lagrangian acquires a mass-term for the gaugino:

$$\mathcal{L}^{mass}_{gaugino} = \frac{1}{2} m_\lambda \bar{\lambda}\lambda \quad . \tag{3}$$

The last term (3) breaks R-invariance and supersymmetry. The scalars s and t have mass $m_{3/2}$ while their spinor compansions are massless.

In the model presented above, the mass of the gaugino is an arbitrary parameter. Following a suggestion of Ferrara, Girardello and Nilles [5] (FGN) it is attractive to consider a variant where local supersymmetry as well as R-invariance may break dynamically through (a) the formation of the gaugino-condensate $\langle\lambda\lambda\rangle \equiv \mu^3 \neq 0$ in the presence of gauge-forces (abelian or more generally non-abelian *)), plus (b) the presence of the non-minimal gauge kinetic terms such as $f_{ab} = \delta_{ab}(1 + \sigma Z/M_p)$. In this case, especially with non-abelian gauge-forces, the mass m_λ of the gaugino, which would be of order μ, is determined by the scale-parameter of the underlying Yang-Mills force. The super-Higgs-effect is induced through four-Fermi interaction of the form $\sim (\psi_\mu \gamma_\mu \chi)(\lambda\lambda)$, which appears in the action together with the assumption of the existence of the $\langle\lambda\lambda\rangle$-condensate. FGN estimate that the scale M_s^2 of super-symmetry-breakdown is given by:

$$M_s^2 \sim (\sigma\mu^3/4M_p) \quad , \tag{4}$$

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*) The extension of these considerations to non-abelian gauge symmetries is straightforward.

while the gravitino-mass is given by

$$m_{3/2} \approx \sigma\mu^3/(4\sqrt{3}\, M_p^2) \quad . \tag{5}$$

For $m_{3/2} \sim 300$ GeV and $\sigma \sim (1/10)$, one would obtain $M_s \sim 10^{10} - 10^{11}$ GeV, and $m_\lambda \sim 10^{14}$ GeV. This last corresponds numerically to the conventional grand unification scale. In this scenario then, we can have the picture of flavour and colour getting defined for energies below $m_\lambda \sim 10^{14}$ GeV, while supersymmetry breaks around 10^{11} GeV and $m_{3/2} \sim 300$ GeV.

2. To be realistic, for the minimal flavon-chromon model, we showed in Ref.1 that one needs four chiral superfields, to compose one quark-lepton family:

$$\Phi_{1+} = \begin{pmatrix} u_L \\ r \end{pmatrix}^i \ , \ \Phi_{2+} = \begin{pmatrix} d_L \\ y \end{pmatrix}^i \ , \ \Phi_{3-} = \begin{pmatrix} u_R \\ b \end{pmatrix}^i \ , \ \Phi_{4-} = \begin{pmatrix} d_R \\ \ell \end{pmatrix}^i \ .$$

Here r,y,b and ℓ stand for the red, yellow, blue and lilac chromons, while the index i signifies the charge of these multiplets if the preonic gauge symmetry G_p is U(1). More generally index i signifies the label for the fundamental representation $\underset{\sim}{n}$ for the preonic gauge symmetry $G_p = SU(n)$. The fields Φ_{3-} and Φ_{4-} may equivalently be replaced by

$$\Phi_{3+} = \begin{pmatrix} u_L^c \\ b^* \end{pmatrix}^{i*} \quad \text{and} \quad \Phi_{4+} = \begin{pmatrix} d_L^c \\ \ell^* \end{pmatrix}^{i*} \quad ;$$

where i* denotes the complex conjugate representation of i.

Note that in the supersymmetric limit, the model possesses a global $SU(2)_I \times SU(2)_{II}$ symmetry, where for the $SU_I(2)$, (u_L^i, d_L^i) <u>and</u> (r^i, y^i) are doublets; likewise (u_R^i, d_R^i) and (b^i, ℓ^i) are doublets of the second $SU_{II}(2)$. $SU_I(2)$ is the diagonal sum of what we shall eventually identify with $(SU(2)_L)_{flavour}$ and $SU(2)^{(r,y)}_{colour}$; while $SU_{II}(2)$ is the diagonal sum of $(SU(2)_R)_{flavour}$ and $SU(2)^{(b,\ell)}_{colour}$ *).

In other words, in the supersymmetric limit of the minimal model sketched above, flavour and colour do not have independent meaning. Once supersymmetry, and in particular R-invariance, breaks and gauginos λ acquire a mass m_λ exceeding 3×10^5 GeV, colour and flavour do acquire their independent meaning. Recall that the gaugino couplings are of the form $\bar{\lambda}(u r + \dots)$. These terms do not admit of flavour and colour as commuting (independent) symmetries. Once λ is superheavy, we can however essentially discard these terms. The rest of the preonic Lagrangian permits flavour and colour to be defined as commuting symmetries. Since quarks and leptons exhibiting flavour and colour have inverse sizes exceeding 1 TeV, m_λ must be in excess of 1 TeV. Further, if we desire for $SU(4)^{colour}$ to emerge as a good effective gauge symmetry – at least up to 3×10^5 GeV, from limits on $K_L \to \mu e$, it follows that m_λ should exceed this larger scale (3×10^5 GeV). Thus for the regime of energies below (the smaller of) the masses m_λ and M_s, the diagonal sum symmetry enlarges into

$$G_{flavour} \times G_{colour} = [SU(2)_L \times SU(2)_R]_{flavour} \times SU(4)_{colour},$$

where $SU(2)_{L,R}$ act on the fermions $(u,d)_{L,R}$ and $SU(4)_{colour}$ on the bosons (r,y,b,ℓ) only. It is amusing that with supersymmetry breaking the internal symmetry becomes larger and not smaller.

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*) For the special case of the gauge symmetry $G_p = SU(2)$, since $\underset{\sim}{2}$ and $\underset{\sim}{2}^*$ are equivalent, the four superfields Φ_{1+}, Φ_{2+}, Φ_{3+} and Φ_{4+} may be considered as a $\underset{\sim}{4}$-plet of a global $SU(4)$ which contains the above $SU(2)_I \times SU(2)_{II}$. This global $SU(4)$ is once again the diagonal sum of a flavour $SU(4)$ and a corresponding colour $SU(4)$.

We further assume that for momenta $\ll m_\lambda$, the symmetry $G_{flavour} \times G_{colour} = [SU(2)_L \times SU(2)_R] \times SU(4)_{colour}$ emerges not just as a global symmetry but also as an effective local (gauge) symmetry where the gauge bosons are preonic composites, e.g.

$$\vec{W}_{L,R} \sim \sum_i \bar{f}^i_{L,R} \gamma_\mu \vec{\tau} f^i_{L,R} \quad \text{and} \quad (\vec{V}_\mu) \text{ gluons} \sim \sum_i C^{i\dagger} \vec{\lambda} \overleftrightarrow{\partial}_\mu C^i,$$

$$\left(f^i_{L,R} = (u^i, d^i)_{L,R} \quad \text{and} \quad C^i = (r,y,b,\ell)^i \right) .$$

In this picture not only $W^\pm$ and Z, but also the gluons and even the photon are "born" only for a scale of momenta below m_λ. Some of these acquire masses $< m_\lambda$ spontaneously through VEV of spin-zero Higgs-fields, which are also composites [1] of the type $\bar{f}f$, C^*C, ffC^*C^* etc. Simultaneous with the formation of spin-1 (W,Z, gluons, X's) and spin-0 ($\phi, \dots$) composites, the spin 1/2 quarks and leptons are born as fC^* composites.

There is one characteristic feature of this minimal $N = 1$ flavon-chromon supergravity model which clearly distinguishes it from non-preonic $N = 1$ supergravity models. Here, we do not expect to see analogues of the Winos $\tilde{W}^\pm$, Zinos $\tilde{Z}^0$ and gluinos, which are the hall-marks of the non-preonic models. This is due to the fact that flavons and chromons are super-symmetric partners of each other in this minimal model. In a sense, the supersymmetric partners of composite spin-1 W's $\sim \bar{f}f$ and gluons $\sim C^\dagger \partial_\mu C$ would have been the spin-1/2 composites $\bar{f}C$; these objects however are precisely the composite quarks and leptons. In other words, the price one pays (if it is a price) by adhering to the minimal flavon-chromon model *), is the absence of the "standard" Winos, Zinos, gluinos and photinos. Likewise, we would not expect to see the familiar squarks and sleptons; the analogues of these in the minimal model are in a sense the Higgs, which are spin-0 $\bar{f}f$, C^*C, ffC^*C^*-like composites.

Note further that:

(i) If there are n colours (i.e. n spin-0 chromons including leptonic chromons), and if masslessness of spin-1/2-composites (quarks and leptons) is to be attributed to an effective global chiral symmetry **), then the 't Hooft requirement that the associated anomaly at the preon-level should match the corresponding anomaly at the composite level is automatically satisfied, if the binding gauge symmetry G_p is SU(n). Thus for four colours, we would need G_p = SU(4). (Anomaly-matching is relatively trivial[7] because quark-lepton composites are made up of spin 1/2 flavons and spin-0 chromons.)***)

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*) For the "maximal" supersymmetric flavon-chromon preonic models discussed in Ref.1 and independently by R. Barbieri (Ref.6), in which flavons and chromons correspond to distinct chiral super-fields, and for which one can define flavour and colour even in the limit of exact supersymmetry, one will of course expect to see composite Winos, Zinos, gluinos, photinos, squarks and sleptons. The supersymmetry breaking mechanism of this paper can be used for this maximal model in a straightforward manner.

**) For the flavon-chromon model, with 2 flavons, this global symmetry is $SU(2)_L \times SU(2)_R \times U(1)_f$, where $U(1)_f$ is the vectorial flavon-number symmetry. Since $U(1)_f$ is not traceless, $SU(2)_L \times U(1)_f$ and also $SU(2)_R \times U(1)_f$ exhibit anomalies at the preon as well as the quark-lepton level.

***) The idea that quarks and leptons are made of spin-1/2 flavons and spin-0 chromons sharing the same flavons, but differing from each other in respect of their chromon ingredient, was suggested by the authors in Ref.8. The set of ideas behind the model has been used subsequently by a number of authors (Ref.9).

(ii) The scale of the gaugino mass m_λ which in the dynamical model discussed here, may lie around 10^{14} GeV is numerically close to the scale of grand unification-mass. This may or may not have anything to do with grand unification at the quark-lepton level. But in any case, a scale of this sort could play a role in the phase-transitions in the early universe including perhaps the transition associated with inflation.

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