Framework for Phenomenological Supergravity Model Building

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Abstract

To explore ways of going beyond the Standard Model (SM) a previous particle scenario based on unbroken supersymmetry is extended to five dimensions as a proposal for unified theory of matter and interactions. The SM particles are composites of the genuinely supersymmetric elementary fields of this scheme, without the SM superpartner issue with experiments. It is proposed that the asymptotically free SM interactions decouple at the fundamental level of particle theory providing a simpler vacuum. With local supersymmetry one arrives at supergravity as a framework for further phenomenological model development.

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1 Introduction

It is commonly stated that science corrects itself. But observations on recent developments in fundamental theory indicate that, for an extensive period of time, old as well as some new schools of thought have been doing well. Except that it has been difficult to go beyond the Standard Model (BSM). To do that here, an alternative, old viewpoint of SM is adopted, which did not originally suppose supersymmetry (SUSY). But it has opened a window, based on the criterion of simplicity rather than more complexity, to find both SUSY and to go BSM. This approach overcomes two major issues in the main stream, namely the lack of experimental evidence for SM superpartners, and the failure of constructing the SM in string theory. The latter may later find a form different from textbooks. It is claimed below that the main stream constructs are unsatisfactory on the fundamental level: the SM internal symmetries are in UV of secondary importance, and, consequently, the elementary constituents are not quarks and leptons.

Within the present framework spacetime has the traditional spacetime symmetries, the Poincaré and supersymmetry. It is assumed that spacetime symmetries cannot be compromised, therefore also supersymmetry must be unbroken. On classical level the construction starts from the five dimensional Einstein equation, the Kaluza-Klein (KK) theory, which provides the bosonic sector, including the electromagnetic theory. Secondly, the fermionic sector is added to the model by requiring supersymmetry. The elementary particles, including the superpartners, are fields which belong to a single representation of global supersymmetry with fields having spin values $0, \frac{1}{2}, 1, \frac{3}{2}$ and 2. The 5D approach is minimal in terms of number of interactions. As will be shown, it is just what is needed for the present scenario with minimal number of supersymmetric fields. The point is that going indeed beyond the SM some quantum leap must be taken rather than making use of effective field theories.

The implementation of the scenario leads to introduction of preons. The preon matter fields turn out to be light spin $\frac{1}{2}$, charge $\frac{1}{3}$ and 0 fields. Quarks and leptons are represented as three preon composite states. The number of elementary fermion fields is $N_F = 2$, whereas in the minimal supersymmetric standard model $N_F = 16$ (2 quarks in 3 colors, 2 leptons and their superpartners, for the first generation in both models). On the other hand, the physics on preon level is largely open. It is contemplated that local supersymmetry will pave the way towards quantum gravity which would provide the interaction which keeps the preons together and explain the heavier two generations as excitations of preon bound states. Such theories have long history in atomic and nuclear systems.

At present, an indirect case of comparing supersymmetric models with available experimental data is given by the CMB data of Planck 2018. The CMB measurements open a window to energies well above any accelerator energy and only a few decades below Planck scale, where supersymmetry is expected to be important. The agreement between the gravity driven inflationary model and data is good. The connection of the leading inflationary model to supersymmetry is elucidated.

The message of this preliminary note is that global supersymmetry has been defined in a meaningful manner as an exact symmetry of nature providing matter-gauge (geometry) unification. Introducing local supersymmetry transforms the task of model construction into the problem of solving supergravity, which is found in the current literature, without a real breakthrough so far. From supergravity, it is hoped by many, one may go towards a UV finite, consistent theory of quantum gravity within superstring or M-theory. The group theory within the present model is Abelian. Therefore this approach simpler and more constrained than the standard model related superstring theory. The validity of the scheme must be analyzed, proven or disproven, by constructing explicit models for supergravity, which is beyond the scope of this brief note.

The article is organized as follows. In section 2 the Kaluza-Klein theory is introduced, providing general relativity and electromagnetism in five dimensions. The basic supermultiplets of the fundamental fields are presented in section 3. With these preliminaries the preon model is defined and the standard model is heuristically constructed in section 4. In section 5 two supersymmetric (or equivalent) models of inflation are compared with the CMB data of Planck 2018. Conclusions are given in section 6. The presentation is kept on elementary level for easy readability to non-experts (including the author).

2 Kaluza-Klein Theory

As a warm-up and of historical interest let us consider the Kaluza-Klein theory briefly. The idea of unifying gravity with electromagnetism was born about one hundred years ago. Nordström [1] in 1914 and Kaluza [2] in 1921 were the first physicists to make this unification (for careful reviews, see [3, 4, 5]). They proposed a theory in five dimensions with variables $(x^0, x^1, ..., x^4)$. An immediate question was why we do not see any fifth dimension in nature? Both physicists avoided this question by assuming that all derivatives with respect to the fifth dimension variable x^4 vanish. The two men obtained successfully the field equations of both gravity and electromagnetism from a five dimensional theory. This success is due to $U(1)$ gauge invariance added onto Einstein's equations in the guise of invariance with respect of coordinate transformations in the x^4 direction. Gauge symmetry is interpreted as geometrical symmetry of spacetime in extra dimensions. Klein [6] showed that the fifth dimension should be handled by the method of compactification. It means that x^4 has circular topology and its scale is very small, like of the order of Planck scale.

Compactification of extra dimensions has been studies actively beyond 5D, up to 10D superstring theory and 11D supergravity. Eleven has been shown to be (i) the maximum number of dimensions with a single graviton and (ii) the minimum number required of a Kaluza-Klein theory to contain the standard model gauge group $SU(3) \times SU(2) \times U(1)$. But unfortunately, these higher dimensional theories do not seem to have satisfactory solutions [7]. Within the present model, however, the condition (ii) can in fact be dropped as explained in the first paragraph of section 4. Therefore, I take this situation as pronounced evidence for the approach of this article.

The Einstein equation in an empty 5D space, i.e. without any 5D energy-momentum tensor of matter, reads

$$\hat{R}_{AB} - \frac{1}{2}\hat{R}g_{AB} = 0 \tag{2.1}$$

where $\hat{R}_{AB}$ is the Ricci tensor. The capital Latin indices A, B, ... have values 0, 1, 2, 3, 4. Five dimensional quantities are denoted by a hat on top of them. The corresponding 5D action is

$$S = -\frac{1}{16\pi\hat{G}}\int \sqrt{-\hat{g}}\; d^4x dy \hat{R} \tag{2.2}$$

where $y = x^4$ is the fifth coordinate and $\hat{G}$ is the 5D gravitational constant.

The missing matter source terms in (2.1) and (2.2) indicate Kaluza's key point that the universe in dimensions $D > 4$ is empty. Matter in 4D would be a manifestation of geometry in higher dimensions. If matter has to be introduced by hand in higher dimensional fields, the ideal would be lost. I take the humble phenomenological attitude of introducing electromagnetism from the fifth dimension and organizing the matter and interactions within the compactified supersymmetric model as defined in section 3.

The five dimensional Ricci tensor and Christoffel symbols are defined in terms of the metric as in 4D

$$\begin{aligned} \hat{R}_{AB} &= \partial_C \hat{\Gamma}^C_{AB} - \partial_B \hat{\Gamma}^C_{AC} + \hat{\Gamma}^C_{AB}\hat{\Gamma}^D_{CD} - \hat{\Gamma}^C_{AD}\hat{\Gamma}^D_{BC} \\ \hat{\Gamma}^C_{AB} &= \frac{1}{2}\hat{g}^{CD}(\partial_A \hat{g}_{DB} + \partial_B \hat{g}_{DA} - \partial_D \hat{g}_{AB}) \end{aligned} \tag{2.3}$$

Everything in (2.3) is like in general relativity, except indices running up to 4, not 3.

Now a form for the five dimensional metric has to be chosen. The four dimensional part $\alpha\beta$ is as before. The lower right corner contains the scalar field ϕ and the four potential takes the remaining two vacant corners. A useful realization is the following

$$\hat{g}_{AB} = \begin{pmatrix} g_{\alpha\beta} + \kappa^2\phi^2 A_\alpha A_\beta & \kappa\phi^2 A_\alpha \\ \kappa\phi^2 A_\beta & \phi^2 \end{pmatrix} \tag{2.4}$$

where the vector potential is scaled by constant κ for later purposes (a good choice turns out to be $\kappa = 4\sqrt{\pi G}$). The signature is (+ - - -).

Using the metric (2.4) and the definitions (2.3) together with the cylinder condition in (2.2) one gets three terms after pulling out the y-integral

$$S = -\int d^4x\sqrt{-g}\phi\Big(\frac{R}{16\pi G} + \frac{1}{4}\phi^2 F_{\alpha\beta}F^{\alpha\beta} + \frac{2}{3\kappa^2}\frac{\partial^\alpha\phi\partial_\alpha\phi}{\phi^2}\Big) \tag{2.5}$$

where G is defined as $G \equiv \hat{G}/\int dy$.

The boson sector of the KK world consists now of the graviton, photon and a massless scalar, having spins j=2, 1, 0, respectively, and charge 0. These are associated with representations of the Lorentz group. But we have one more spacetime symmetry available for model building in the next section 3.

3 Supersymmetry

Supersymmetry transforms bosons to fermions, and vice versa [8, 9]. An operator Q which generates such transformations is an anti-commuting spinor

$$Q|\text{boson}\rangle = |\text{fermion}\rangle, \quad \text{Q}|\text{fermion}\rangle = |\text{boson}\rangle \tag{3.1}$$

and its hermitian conjugate $Q^\dagger$ carrying spin $\frac{1}{2}$. Therefore supersymmetry must be a spacetime symmetry. The generators Q and $Q^\dagger$ satisfy the algebra

$$\begin{aligned} \{Q, Q^\dagger\} &= P^\mu \\ \{Q, Q\} &= \{Q^\dagger, Q^\dagger\} = 0 \\ [P^\mu, Q] &= [P^\mu, Q^\dagger] = 0 \end{aligned} \tag{3.2}$$

where P^μ is the four momentum generator of space-time translations.

In the N=1 supersymmetric model there is the graviton G and its spin $\frac{3}{2}$ superpartner gravitino $\tilde{G}$

$$G = \begin{pmatrix} \rightarrow \\ \leftarrow \end{pmatrix} \quad \text{and} \quad \tilde{\text{G}} = \begin{pmatrix} \rightarrow \\ \leftarrow \end{pmatrix} \tag{3.3}$$

This the graviton supermultiplet.

Secondly, as introduced in [10], there are the massless fields the photon γ and its neutral spin $\frac{1}{2}$ superpartner, the photino $\tilde{\gamma}$, denoted $\tilde{m}^0$ in the notation of the next section 4. They form the vector supermultiplet

$$\gamma = \begin{pmatrix} \rightarrow \\ \leftarrow \end{pmatrix} \quad \text{and} \quad \tilde{\text{m}}^0 = \begin{pmatrix} \uparrow \\ \downarrow \end{pmatrix}, \tag{3.4}$$

The third superpair is the spin $\frac{1}{2}$ fermion m and scalar superpartners $\tilde{s}$ (in section 4 notation). Here one has to introduce charge for the superpair since we have in (2.5) the electromagnetic vector potential A_μ. This chiral supermultiplet therefore is m^+ and its scalar superpartner $\tilde{s}^+_{1,2}$

$$m^+ = \begin{pmatrix} \uparrow \\ \downarrow \end{pmatrix} \quad \text{and} \quad \tilde{\text{s}}^+_{1,2} \tag{3.5}$$

In the next section 4 it turns out that the charge needed in (3.5) is $\frac{1}{3}$ of electron charge.[1] In (3.3) – (3.5) the horizontal and vertical arrows refer to helicity and

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[1] By simplicity, the charge $\frac{1}{3}$ is more natural in a relativistic theory than traditional the quark charges $\frac{2}{3}$ and $-\frac{1}{3}$

spin, respectively, and + and 0 refer to charge in units of $\frac{1}{3}$ electron charge. The $\tilde{m}^0$ is a Majorana fermion. The R-parity for fields is simply $P_R = (-1)^{2(spin)}$. The m^+ and $\tilde{m}^0$ are assumed to have zero, or light mass of the order of the first generation quark and lepton mass scale.

4 Preon Model

In the standard model the unification energy of gauge interactions is of the order $\Lambda_{cr} = 10^{16}$ GeV. It is also the unified theory proton decay mediating X-boson mass lower limit, corresponding to a proton lifetime of 10^{32} years. To build the current model, the non-Abelian gauge interactions must operate below Λ_{cr} as usually in the SM providing the luxury of nuclear physics and chemistry, but above Λ_{cr} they do not contribute. This condition stems in fact from asymptotic freedom of the SM. This requirement can be made stronger by relegating the color and weak charges in favor of a combinatorial system [11] in which the quarks and leptons are composite states of three preons.

The present model is physically equivalent to the models of Harari [12], Shupe [13] and Finkelstein [14, 15] as to SM interactions and fermion structure. The models of these three authors were in turn shown to produce the properties of the SM.

Above Λ_{cr} the quarks and leptons inonize, or make a phase transition to unbound phase. Such model for quark and lepton structure was defined in [10, 16, 17].[2] Below Λ_{cr} a binding mechanism must operate. I presume that this model may show a direction towards quantum gravity, which will organize the preons in bound states in three generations [16]. Alternatively, there may be a new very strong gauge interaction between the preons, like e.g. in [18, 12, 13, 19].[3] It may be noted that in those cases introducing supersymmetry as indicated above fails.

Assuming a generic attractive interaction, or potential, three preons combine freely without extra assumptions into standard model fermion composite states. They form a combinatorial system modulo three [11]. For the same charge preons fermionic permutation antisymmetry factor ϵ_{ijk} must be included. These arguments lead heuristically to four bound states made of preons, which form the first generation quarks and leptons (dropping the tildes)

$$\begin{aligned} u_k &= \epsilon_{ijk} m_i^+ m_j^+ m^0 \\ \bar{d}_k &= \epsilon_{ijk} m^+ m_i^0 m_j^0 \\ e &= \epsilon_{ijk} m_i^- m_j^- m_k^- \\ \bar{\nu} &= \epsilon_{ijk} \bar{m}_i^0 \bar{m}_j^0 \bar{m}_k^0 \end{aligned} \tag{4.1}$$

The strong and weak interactions are built to operate between the three preon

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[2] Supersymmetry was anticipated in passing in [16].

[3] A different kind of supersymmetric preon model has been presented in [20, 21].

bound states in (4.1) as gauge boson mediated transitions between them. More details are given in [10, 11] and references therein.

Bound states of scalar constituents do not make a spectrum like fermions. A neutral, very light two body bound state is expected to exist

$$a_i^0 = \tilde{s}_i^+ \ \tilde{s}_i^- , \quad i = 1, 2 \tag{4.2}$$

Scalar bound states can also be formed from the fermions

$$\begin{aligned} b^0 &= m^+ m^- \\ c^0 &= m^0 m^0 \\ h^\pm &= m^\pm m^0 \end{aligned} \tag{4.3}$$

The states (4.2) and (4.3) (and other possible states including mixtures) are candidates for the Higgs, axion and the like, which are important in spontaneously broken symmetries of the standard model. Finally, the model allows an unbound scalar charge $\frac{1}{3}$ field.

5 Cosmological Inflation

Several models of inflation have been proposed in the literature and experimental results from the sky have become more and more accurate. It was noted in [22, 23] that quantum corrections to general relativity are important in the early universe. They lead to R^2, with R being the curvature of spacetime, corrections in the Einstein-Hilbert action. In situations where curvature is large these corrections lead to an effective cosmological constant causing an inflationary de Sitter era. In addition, predictions for corrections to the microwave background were obtained in detailed calculations. The simplest Starobinsky action is

$$S_{Staro} = \frac{M_{\rm Pl}^2}{2} \int \rm d^4x \sqrt{-g} \Big(R + \frac{R^2}{6m^2} \Big) \tag{5.1}$$

where m ($\sim 3 \cdot 10^{13}$ GeV) is the inflaton mass as the only parameter. Note that it is entirely based on gravitational interactions but it is non-renormalizable. Starobinsky inflation is equivalent to Higgs inflation in supergravity because both models lead to indistinguishable predictions. The potential of the Starobinsky inflation in terms of the canonical inflaton field ϕ

$$V(\phi) = \frac{3}{4} M_{\rm Pl}^2 m^2 \Big[1 - \exp\big(- \sqrt{2/3}\ \phi / M_{\rm Pl} \big) \Big]^2 \tag{5.2}$$

The characteristic features of this scalar potential are: it is bounded from below, it has an absolute minimum at $\phi = 0$ and it has a plateau which leads to slow roll inflaton in the inflationary period. The inflaton potential drives the inflation and its quantum fluctuations generate deviations from flatness, isotropy and homogeneity.

The Starobinsky model predicts for spectral tilt n_s and tensor-scalar ratio the values $n_s = 1 - 2/N$ and $r = 12/N^2$, where N is the number e-folds. The 2018 CMB data from the Planck satellite [24] give r < 0.064 (95 percent confidence) and $n_s = 0.9649 \pm 0.0042$ (68 percent confidence level; $n_s = 1$ means scale independent power sectrum).

Starting from the early model of supersymmetry, the Wess-Zumino model [8], one is interested to know whether the CMB data can be tried on it. The data disfavor simple models of inflation with monomial potential ϕ^n. Instead potentials with concave regions like $\phi^2(v-\phi)^2$ may provide reasonable inflation if $v >> M_{\rm Pl}$ and $\phi_0 \sim v/4$. This form can be interpreted as coming from the minimal Wess-Zumino model with superpotential W and scalar potential V as follows for real fields Φ [25, 26]

$$W = \frac{1}{2}\mu\Phi^2 - \frac{1}{3}\lambda\Phi^3, \quad V = |\frac{\partial W}{\partial \Phi}|^2 \tag{5.3}$$

The W-Z model field Φ is complex, and it can be written as modulus and phase $\Phi = \frac{1}{\sqrt{2}}\phi \ \exp(i\theta)$. The scalar potential becomes now

$$V = A\big(\phi^4 - 2\cos(\theta)v\phi^3 + v^2\phi^2\big) \tag{5.4}$$

This reduces to hilltop form when $\theta = 0$: $V = A(\phi^2(v-\phi)^2$. For the phenomenological analysis a two field form of $\Phi = (\psi + i\sigma)/\sqrt{2}$ is used. The parameters n_s and r were calculated using perturbation theory, quantum field theory techniques and numerically integrating two-point scalar field perturbations in Fourier space. The model gives for $N = 50$ foldings and $v = (5-10)M_{\rm Pl}$ with initial conditions near $\sigma = 0$ axis results, which are very close to what the Starobinsky model gave.

The cosmological composition in the scenario is that dark energy is due to the cosmological constant and dark matter consists of the gravitino and to some extend of primordial black holes. Such a model is described in [27] but the treatment is, in my opinion, contrived perhaps due to different chiral supermultiplet (3.5).

6 Conclusions

The present supersymmetric preon model is based on the proposal that the physical domain of supersymmetry is the preon level instead of quark and lepton level. Consequently, all the fundamental fields and their superpartners must be in the basic supermultiplets (3.3), (3.4) and (3.5).

From global supersymmetry the next intermediate step is to study supergravity [28, 29, 30]. It can be defined in dimensions $4 \leq D \leq 11$. It is hoped that this model would increase interest in superstring theory in 5D, which may be the unified, consistent quantum theory of gravity and electromagnetism. This article is intended to serve as conceptual study of a research proposition, which is hoped to receive community response.[4]

What would this model change? With unbroken supersymmetry and Abelian interactions of the elementary fermions there is less freedom, fewer parameters and a simpler vacuum for new model building. The real test of the model is the success, or lack of success, of constructing new, consistent phenomenological models for supergravity. A feature of the model are gravitational couplings of like charge quarks and leptons of different generations. These couplings are, however, smaller than weak couplings even near Λ_{cr}. Within the present knowledge, it is difficult to observe experimentally the graviton and the gravitino, which due to spontaneous breaking of local supersymmetry has non-zero mass and long lifetime [29]. The spin $\frac{1}{2}$ fermions are supposed to be observable only above Λ_{cr}.

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