symmetry.

(11) Local gauge theory exposes an intimate relationship between internal symmetry and space-time. Null zones, including the ancient dipole result, show another face of this relationship, leading to more equations involving the internal variables (e.g., charge) and space-time (e.g., masses and angles).

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[1]We mean by this that the couplings involve no derivatives of Dirac fields and at most single derivatives of scalar and vector fields. Products of single derivatives of distinct scalar fields are allowed. All vector derivative couplings must be of the Yang-Mills trilinear variety or products thereof. Such couplings include all renormalizable theories of current physical interest as well as an infinite class of nonrenormalizable theories corresponding to unrestricted numbers of fields.

[2]Attachments are made onto all charged lines and onto vertices with derivative couplings (seagulls).

[3]A much more detailed discussion will be presented elsewhere: R. W. Brown, K. L. Kowalski, and S. J. Brodsky, to be published.

[4]Apart from the $(p\cdot q)^{-1}$ factors the convection terms are of order q^0 while in the usual cases the spin and contact terms are linear in q. When Dirac or vector particles encounter a derivative coupling involving their own field, quadratic terms appear and generally these violate the theorem. An important exception occurs for the Yang-Mills vertex, where a cancellation occurs due to the cyclic nature of the gauge coupling.

[5]The appearance of the current differences is easy to understand by a complementary version of the theorem. Namely, suppose that all of the $j_i/p_i\cdot q$ factors were equal, then $M_\gamma(V_G)$ vanishes by charge conservation, if we define all particles as outgoing.

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Locally Supersymmetric Grand Unification

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A locally supersymmetric grand unification program is proposed which couples the $N=1$ supergravity multiplet to an arbitrary grand unified gauge group with any number of left-handed chiral multiplets and a gauge vector multiplet. A specific model is discussed where it is shown that not only do the gravitational interactions eliminate the degeneracy of the vacuum state encountered in global supersymmetry, but simultaneously they can break both supersymmetry and SU(2)⊗U(1) down to a residual SU(3)^c⊗U(1) symmetry at ~300 GeV.

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Recently much interest has been devoted to supersymmetric grand unified theories.[1-5] All existing supersymmetric grand unified models are based on *global* supersymmetry. In such theories it is generally easy to break spontaneously the internal, e.g., SU(5), symmetry, but more difficult to break supersymmetry itself. In this paper we propose a new type of supersymmetric grand unified model based on *local* supersymmetry. We consider here $N=1$ supergravity[6] coupled to left-handed chiral scalar[7] and gauge multiplets.[8] We will see that the supergravity couplings automatically produce a spontaneous breaking which removes the degeneracy of the different gauge vacua.[9] We will consider two models in this paper. In a preliminary model the vacuum degeneracy is removed but supersymmetry and SU(2)$\otimes$U(1) symmetry are maintained. In the second model, *the supergravity interactions cause spontaneous breaking of both supersymmetry and* SU(2)$\otimes$U(1). Thus sypersymmetry breaking occurs at the same scale as the SU(2) $\otimes$U(1) breaking, i.e., $m_s \sim 300$ GeV. The model is "realistic" in the sense that the mass hierarchy separating heavy and light particles can be maintained, and the low-energy phenomenology is correctly included. In addition, a variety of new physics is predicted at the teraelectronvolt range. As far as we know, this is the only model where electroweak spontaneous breaking is a consequence of gravitational interactions.

We begin by reviewing briefly the globally supersymmetric theories. For a given grand unified group G one introduces a set of chiral left-handed $N=1$ supermultiplets which form an arbitrary reducible representation of the group G. We shall denote these chiral multiplets collectively by $\Sigma^a=(z^a, \chi_L{}^a, h'^a)$ where

$$z^a = A^a + iB^a, \quad h'^a = F'^a + iG'^a,$$
$$\chi_L{}^a = \tfrac{1}{2}(1-\gamma_5)\chi^a. \tag{1}$$

One also introduces an $N=1$ vector supermultiplet (V_μ, λ, D) which belongs to the adjoint representation of G. The Lagrangian is most easily constructed in the superfield notation and after elimination of the auxiliary fields (the D term of the vector multiplet and the F term of the chiral multiplets) the scalar potential takes the form[10]

$$V(z^a, z^{a\dagger}) = \tfrac{1}{2}|\partial g/\partial z^a|^2 + \tfrac{1}{2}\{g_e(z^{a\dagger}, (T^\alpha z)_a)\}^2, \tag{2}$$

where T^α are the gauge group generators and e_α the corresponding coupling constants while g is the superpotential which is at most cubic in the z^a for renormalizable theories. As is well known, gauge symmetry is broken while supersymmetry is maintained if the equations minimizing V, i.e., $(z^{a\dagger}, T^\alpha z^a)=0$ and $\partial g/\partial z^a = 0$, have a simultaneous solution.

A specific example of the above is furnished by the globally supersymmetric grand unified model of Dimopoulos and Georgi[3] and Sakai.[4] In this SU(5) model, one has the following left-handed multiplets: a $\Sigma_y{}^x$ in the adjoint representation $\underline{24}$ of SU(5), two Higgs multiplets H^x and H_x' in the $\underline{5}$ and $\underline{5}^*$ representations, and the matter multiplets $\overline{M}_j{}^{xy}$ and M_{jx}' in the $\underline{10}$ and $\underline{5}^*$ representations (j is a generation index). The superpotential is[11]

$$g_1 = \lambda_1(\tfrac{1}{3}\mathrm{Tr}\Sigma^3 + \tfrac{1}{2}M\ \mathrm{Tr}\Sigma^2) + \lambda_2 H_x'(\Sigma_y{}^x + 3M'\delta_y{}^x)H^y + \lambda_3 U H_x' H^x + \epsilon_{uv\omega xy}H^u M^{v\omega} m_1 M^{xy} + H_x' M^{xy} m_2 M_y', \tag{3}$$

where m_1 and m_2 are matrices in the generation space.

The potential for Eq. (3) has a minimum when the vacuum expectation values for H^x, H_x', U, M^{xy}, and M_x' vanish and when one of the following three solutions for the vacuum expectation value of Σ holds:

$$\text{(i)}\ \Sigma_y{}^x = 0,$$
$$\text{(ii)}\ \Sigma_y{}^x = \tfrac{1}{3}M[\delta_y{}^x - 5\delta_5{}^x\delta_y{}^5], \tag{4}$$
$$\text{(iii)}\ \Sigma_y{}^x = M[2\delta_y{}^x - 5(\delta_5{}^x\delta_y{}^5 + \delta_4{}^x\delta_y{}^4)].$$

Solution (i) corresponds to no symmetry breaking, (ii) breaks SU(5) into SU(4)$\otimes$U(1), while (iii) breaks SU(5) into SU(3)$\otimes$SU(2)$\otimes$U(1). The three solutions are all degenerate and there is no way to lift the degeneracy within global supersymmetry. If one picks solution (iii), the masses of the Higgs doublets $H^{4,5}$ and $H_{4,5}'$ can be made zero by setting $M'=M$.

We consider now our preliminary model of a local, supersymmetric, grand unified theory obtained by promoting the global supersymmetry to a local one by the introduction of the $N=1$ supergravity multiplet. With use of the techniques of tensor calculus the most general Lagrangian for the coupling of supergravity to a single chiral multiplet (excluding higher derivatives) has been worked out by Cremmer *et al.*[7] We generalize their result to an arbitrary number of left-handed chiral multiplets as well as including the vector gauge multiplet[8] in our analysis.

The most general form of the Bose part of the coupling of supergravity with matter after Weyl scalings is

$$L_B = -(e/2\kappa^2)R(e,\omega) + (e/\kappa^2)\mathcal{G}_{,a\bar{b}}[\partial_\mu z^{b\dagger} + \tfrac{1}{2}ig_e(z^\dagger V_\mu)^b][\partial^\mu z^a - \tfrac{1}{2}ig_e(V^\mu z)^a]$$
$$+ (e/\kappa^4)\exp(-\mathcal{G})[3 + (\mathcal{G}^{-1})^{\bar{b}a}\mathcal{G}_{,a}\mathcal{G}_{,\bar{b}}] - \tfrac{1}{4}e\,\mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) - 2e(3/k^2\varphi)^2[e_\alpha(\varphi_{,a}, (T^\alpha Z)_a)]^2, \tag{5}$$

where $G=\kappa^2/8\pi$ is the gravitational constant, $R(e,\omega)$ is the curvature scalar, $F_{\mu\nu}$ are the Yang-Mills field strengths, and $\mathcal{G}$ is given in terms of φ which is a general function of z^a and $z^{a\dagger}$:

$$\mathcal{G}=3\ln[-(\tfrac{1}{3}\kappa^2)\varphi]-\ln(\tfrac{1}{4}\kappa^6|g|^2). \tag{6}$$

$(\mathcal{G}^{-1})^{\bar{b}a}$ appearing in Eq. (5) is the inverse of the metric $\mathcal{G}_{,a\bar{b}}$. In the following we shall limit ourselves to the case where the kinetic energy of the scalar field is normalized so that $\mathcal{G}_{,a\bar{b}}=-\frac{1}{2}\kappa^2\delta_{a\bar{b}}$. This choice corresponds to

$$\varphi(z,z^+)=-(3/\kappa^2)\exp[-(\tfrac{1}{6}\kappa^2)z^{a\dagger}z^a] \tag{7}$$

and the scalar potential takes the form

$$V=\frac{e}{2}\exp\left(\frac{\kappa^2}{2}z^{a\dagger}z^a\right)\left[\left|\frac{\partial g}{\partial z^a}+\frac{\kappa^2}{2}z^{a\dagger}g\right|^2-\frac{3}{2}\kappa^2|g|^2\right]+\frac{e}{2}[e_\alpha(Z_a{}^+,T^\alpha Z_a)]^2. \tag{8}$$

The minimization of the potential requires now

$$\partial g/\partial z^a+\tfrac{1}{2}\kappa^2 z^{a\dagger}g=0. \tag{9}$$

Use of Eqs. (9) in Eq. (8) gives us the value of the potential at the set of solutions $z_0{}^a$. One finds

$$V_{\min}(z_0{}^a,z_0{}^{a\dagger})=-\tfrac{3}{4}\kappa^2|g(z_0{}^a)|^2\exp(\tfrac{1}{4}\kappa^2 z_0{}^{a\dagger}z_0{}^a). \tag{10}$$

It is now clear that the degeneracy of the vacuum solutions encountered in the global supersymmetry case would be lifted due to $O(\kappa^2)$ corrections to the vacuum energy.[9] These corrections are proportional to $g(z_0{}^a)$ which takes on three different values for the superpotential of Eq. (3). With neglect of $O(\kappa^2M^2)$ corrections to the solution of Eq. (9), the three solutions for $g_1(z)$ of Eq. (3) are

$$g_1(z_0{}^a)=(0,\tfrac{10}{27}\lambda_1M^3,5\lambda_1M^3). \tag{11}$$

The last solution which corresponds to the SU(5) breaking into SU(3) ⊗ SU(2) ⊗ U(1) is the one with the lowest energy according to Eq. (10). The solution is plagued, however, with a large cosmological constant. We may arrange this solution to have a vanishing cosmological term by the addition of a constant to $g_1(z)$. When this is done the other two solutions would then clearly correspond to states of lower vacuum energies. Weinberg,[9] however, has argued that the flat vacuum would actually be stable for any finite-size perturbations even though it does not have the lowest energy. We shall adopt the Weinberg stability argument for the remaining analysis of this paper.[12]

While the analysis presented above resolves the problem of the vacuum degeneracy encountered in global supersymmetry, the theory still possesses an exact local supersymmetry and an exact SU(2) ⊗ U(1) local gauge invariance.

To break supersymmetry we examine first a form of $g(z)$ first discussed by Polony[7,13] which uses a singlet super-Higgs field Z so that the superpotential has the form $g_2(Z)=m^2(Z+B_0)$, where B_0 and m are constants of dimensions of mass. The potential in this case is

$$V_2=\tfrac{1}{2}e\exp(\tfrac{1}{2}\kappa^2|Z|^2)m^4(|1+\tfrac{1}{2}\kappa^2|Z|^2+\tfrac{1}{2}\kappa^2B_0Z^+-\tfrac{3}{2}\kappa^2|Z+B_0|^2. \tag{12}$$

The solution to $\partial V/\partial Z=0$ at the minimum Z_0 and the requirements for the vanishing of the vacuum energy $V(Z_0)=0$ yield

$$Z_0=(\sqrt{2}a+\sqrt{6}b)/\kappa;\quad B_0=-(2\sqrt{2}a+\sqrt{6}b)/\kappa;\quad a^2=1=b^2, \tag{13}$$

where a and b take on values ±1 such that $ab=-1$, producing two solutions. Though *a priori* g_2 is independent of κ, the supergravity interactions make the vacuum expectation value of the singlet field Z to be of the order of the Planck mass. Its fermionic partner is then absorbed by the gravitino making it massive and indicating that the super-Higgs phenomena are occurring. The mass of the gravitino is given by $\sqrt{2}m_s\exp(2+ab\sqrt{3})$ where $m_s=\kappa m^2$. Thus if we want to break supersymmetry in the range of 300 GeV to 1 TeV, one must choose $m\sim10^{11}-10^{12}$ GeV.

We now arrive at our basic locally supersymmetric grand unified model defined by the superpotential which is the sum of Eqs. (3) and the super-Higgs term $g_2(Z)=m^2(Z+B_0)$,

$$g(z^a,Z)=g_1(z^a)+g_2(Z). \tag{14}$$

Introducing the notation $z^A=(z^a,Z)$, one finds that the scalar potential $V(z^A,z^{A+})$ in this case is given by Eq. (8) with z^a replaced by z^A, etc. We search for solutions $\partial V/\partial z^A=0$ for this combined potential. In the full analysis of this problem the g_2 term acts as a driving term in the Higgs sector and one finds that the Higgs field H^α ($\alpha=4,5$) develops nonvanishing vacuum values.

Since the cross terms between g_1 and g_2 in Eq. (8) are order $\kappa m^2 \equiv m_s$ (or higher) structures, it should be possible to solve for the conditions for minimizing V in a perturbation analysis starting with Eqs. (4) and (13) as the zeroth-order solution. Introducing the notation

$$(\Sigma_y{}^x)_{\rm diag} = M(1+\epsilon_1)(2,2,2,-3+\epsilon_2,-3-\epsilon_2), \quad (15)$$

$$U = -\kappa m^2 xa/\sqrt{2}\lambda_3, \qquad H^x = H_x{}' = y\kappa m^2/\sqrt{2}\lambda_3\delta_5{}^x, \quad (16)$$

we find to lowest order

$$\epsilon_1 = -\kappa m^2 a/\sqrt{2}\lambda_1 M; \qquad \epsilon_2 = -\kappa^2 m^4 y^2 \lambda_2/20\lambda_1\lambda_3{}^2 M. \quad (17)$$

x and y obey the algebraic equations

$$x^2 + x(3+ab\sqrt{3}-6\lambda) + y^2 + (1-3\lambda)^2 = 0, \qquad y^2(3+ab\sqrt{3}-6\lambda) + 2xy^2 + x = 0, \quad (18)$$

where $\lambda \equiv \lambda_2/\lambda_1$. One may show that there exists a range of values of λ for which Eqs. (18) possess real roots for x and y implying nonvanishing vacuum expection values of U, H^x, and $H_x{}'$. *It is important to note that this breaking of SU(2) ⊗ U(1) and supersymmetry produced by supergravity is* $O(\kappa m^2)$ *and hence "semigravitational." (Recall that the Newtonian gravitational constant is* $\sim\kappa^2$*.) From Eq. (16), then,* $\kappa m^2 \sim 300$ *GeV to account correctly for the W and Z mass.*

Unlike the global supersymmetry case, there are no light scalar bosons in this theory.[10] Those scalar bosons that do not become superheavy gain a common mass $\sim m_s$ from the supersymmetry breaking. The boson partners of quarks, however, have a cancellation of this $m_s{}^2$ in mass differences, so that these boson mass-squared differences are the order of the corresponding quark mass-squared differences. This leads to a suppression of the flavor-changing neutral currents as in the corresponding globally supersymmetric theory,[3] though note that here the supersymmetry breaking and corresponding boson mass-difference formulas are a *consequence* of the supergravity model and not put in by hand.[14]

The theory predicts a gravitino mass of $\sim 10^3$–10^4 GeV, which is consistent with the recent analysis of Weinberg[15] regarding cosmological constraints on the scale of supersymmetry breaking. The fermionic partners of the Higgs bosons also grow masses $\sim m_s$, indicating a rich array of phenomena in the teraelectronvolt region. The fermionic partners of the W and Z mesons grow masses at the tree level. The only light particles in the theory at the tree level are the fermionic partners of the gluons and the photon.

As is well known, supergravity coupled with matter is not a renormalizable theory in the conventional sense. An approach such as that of "asymptotic safety,"[16] however, could possibly make the quantum theory meaningful.

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Quasifree $(e,e'p)$ Reaction on ^{3}He

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The proton momentum distribution of ^{3}He has been determined up to momenta of 310 MeV/c by use of the reaction ^{3}He$(e,e'p)$. The experimental missing-energy resolution, $\delta E_m = 1.2$ MeV, was sufficient to separate the two- and three-body breakup channels. Results for the three-body disintegration have been obtained up to missing-energy values of 80 MeV. The resulting spectral function is compared to the predictions of Faddeev and variational calculations.

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The theoretical progress made in the last decade in the field of nucleon-nucleon interactions and in the calculation of properties of the three-nucleon system with realistic NN forces[1,2] has motivated detailed experimental investigations of such systems. Proton knockout coincidence experiments induced by electrons, performed in the region of quasifree kinematics, allow a direct determination of the proton momentum distribution[3] and can therefore serve as a particularly stringent test of NN interaction models.

In the plane-wave impulse approximation (PWIA) the quasifree scattering process is described as follows: An incident electron is scattered elastically from a moving bound target proton with momentum $\vec{p}$, which is ejected and propagates