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RESEARCH IN PARTICLE PHYSICS BEYOND THE STANDARD MODEL

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Progress Report

This report summarizes the work accomplished during the last year. This research was supported in part by the United States Department of Energy. The first part discusses work in string theory; the second part describes the research on bosonic technicolor.

A. String Physics

In *Gauge-Invariant Modification of Witten's Open Superstring*, Phys. Lett. **B213** (1988) 431, Olaf Lechtenfeld and I found a way of modifying the Witten superstring field theory so as to render it gauge-invariant by using both left- and right-moving operators and by modifying the free part of the theory. A computation of the four-vector amplitude in this new theory revealed that it was finite and agreed on-shell with the standard superstring theory.

There were, however, two undesirable features of our modified theory: (a) Unlike the bosonic case, it could not be cast in terms of a Chern-Simons form and (b) Picture-changing collisions occurred in the gauge transformations when two successive gauge transformations were performed, thus making it unclear if the gauge algebra closes. In *On the Modified Superstring Field Theory*, Nucl. Phys. **B338** (1990) 38, Robert Bluhm and I explored the higher-point tree amplitudes. We found that if a particular regularization scheme was used that there was agreement on-shell with the first-quantized theory. However, we found infinities in the off-shell amplitudes involving five or more bosons. Finally, C. R. Preitschopf, C. Thorn and S. Yost changed the picture of the bosonic string field and incorporated our ideas of using both left- and right-moving picture-changing operators to arrive at a theory which is finite on- and off-shell at tree level.

Having found an off-shell Veneziano formula in *Off-Shell Covariant String Amplitudes*, Nucl. Phys. **B308** (1988) 285, it was natural to try to obtain off-shell amplitudes for the higher-point tree-level cases. Working with Robert Bluhm at Indiana University during the past year, we achieved this. In *The Off-Shell Koba-Nielsen Formula*, Nucl. Phys. **B323** (1989) 337, the off-shell Koba-Nielsen formula as determined from the Witten string field theory was presented. Proving that it agreed on-shell with the dual-resonance was highly non-trivial and involved the N-point generalization of the ghost-jacobi identity found by S. Giddings for the four-point case.

We then went on to solve the one-loop case *Off-Shell Conformal Field Theory at the One-Loop Level*, Nucl. Phys. **B325** (1989) 275. The map taking the half-annulus onto the string field theory configuration was determined. Using it, the off-shell one-loop amplitudes were calculated. It was explicitly verified that the Feynman graphs appropriately cover moduli space. After finding the one-loop ghost-jacobi identity, on-shell agreement with the first-quantized theory was established. The two-point non-planar computation had first been carried out by D. Freedman, S. Giddings, J. Shapiro and C. Thorn. They discovered an unusual off-shell pole structure

whose ramifications are still not fully understood. When we restricted our results to the $N=2$ case, we found exact agreement with these authors.

In *Solving the Open Bosonic String in Perturbation Theory*, Nucl. Phys. **B241** (1990) 513, I constructed the map from a canonical domain, given by the uniformization theorem, to the L -loop N -point configuration of the Witten open bosonic string field theory. With this, off-shell computations beyond one-loop were carried out. A crucial step was deriving the higher-loop ghost-jacobi identity. On-shell and off-shell conformal field theory were used as well as many topics in Riemann surface theory such as the uniformization theorem, normal polygons, the Riemann-Roch theorem, Poincaré series, q -differentials, Θ -functions and the Riemann vanishing theorem. Particular emphasize was given to make sure that each step of the calculation was computable in the sense that numbers could be obtained using numerical methods. An algorithm for obtaining moduli space of the open string configurations was achieved. The work *Solving the Open Bosonic String in Perturbation Theory* represents a complete solution in perturbation theory for the open bosonic string.

One of the prime motivations in the studies of string field theory undertaken by myself and others has been to obtain some non-perturbative results. In *Nonperturbative Many-Body Physics in the Open Bosonic String*, Phys. Rev. Letts. **64** (1990) 2238 and *On a Nonperturbative Vacuum for the Open Bosonic String*, Nucl. Phys. **B336** (1990) 263, Alan Kostelecký and I have performed a calculation which produces an approximate static tachyon potential. We found a local minimum about which we studied the physics. This allowed us to do calculations in a non-perturbative vacuum in $D=26$ dimensions. Given that the bosonic string is a model and not phenomenologically relevant, we tried to extract those features of the calculation which pertain to a generic theory. We uncovered several dramatic effects. The spectrum in the non-perturbative vacuum was quite different from the perturbative one. Some states even became non-propagating. Most surprisingly, the original massless vector field obtained a mass term even though the local gauge invariance was unbroken. This is compatible with gauge invariance due to cancellations between an infinite number of interactions of an infinite number of particle states. The lack of long-range propagation of the vector is related to the fact that strings have tree-level asymptotic freedom. The physics is similar, in many respects, to confining non-abelian gauge theories with the exception that bound states are probably not formed.

Our $D=26$ results complement those recently obtained in two dimensions in an effort to understand quantum non-perturbative strings.

B. Bosonic Technicolor

When the low energy group $SU_c(3) \times SU_L(2) \times U_{Y_W}(1)$ is embedded in a grand unified theory, the hierarchy problem arises. It is unnatural for the mass of the Higgs field to be much less than the scale of unification. There have been two proposals to deal with this problem: supersymmetry and technicolor. Both theories have some phenomenological drawbacks. In

technicolor, one must introduce additional gauge interactions, extended technicolor forces, to generate quark and lepton masses. A side effect of this procedure is the introduction of flavor-violating processes above present experimental limits. Technicolor also predicts light techni-meson states in the 5 to 20 GeV range which have not been observed. In supersymmetry, flavor violation also occurs unless squark and slepton masses have a high degree of degeneracy. No supersymmetric particle states have yet been observed experimentally.

In *Bosonic Technicolor*, Nucl. Phys. **B347** (1990) 625, I proposed a theory called bosonic technicolor which uses both supersymmetry and technicolor to address the hierarchy problem. In this theory, a fundamental Higgs field is used to produce quark and lepton masses and a technicolor sector is used to break $SU_c(3) \times SU_L(2) \times U_{Y_W}(1)$ to $SU_c(3) \times U_{EM}(1)$. Although technicolor was proposed to avoid fundamental scalar fields, it may be that nature chooses this system. There are phenomenological reasons why the bosonic technicolor may be relevant to the hierarchy problem.

The phenomenological benefits of bosonic technicolor are as follows. Technicolor mesons are heavier than in ordinary technicolor theories. Furthermore, the supersymmetry breaking scale, m_{ss} , is at least an order of magnitude larger than in the usual supersymmetric standard models. Since $m_{ss} > 1$ TeV, supersymmetric particles are also heavier. Thus the combined system produces heavier masses for the unseen particles that each theory predicts. This may explain why that states have not yet been experimentally detected.

In a subsequent work *Naturalness in Supersymmetry, or Raising the Supersymmetry Breaking Scale*, Phys. Lett. **243B** (1990) 250, Michael Dine, Alex Kagan and I showed that bosonic technicolor alleviates the flavor problem. Because m_{ss} is in the TeV range instead of the 100 GeV range, one does not need severe squark and slepton mass degeneracy to avoid sizeable flavor-violating processes. The most stringent constraints coming from the $K^0 - \bar{K}^0$ mass difference and $\mu \rightarrow e\gamma$ are satisfied. Naturalness, in the sense of 't Hooft, is significantly improved in bosonic technicolor. This theory, which is a specific way of combining supersymmetry and technicolor, produces the good features of supersymmetry and technicolor while avoiding the difficulties that each has separately. It can be used for a model of SSC physics.

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