Task B and T Proposal for HEP Research Program at the University of Colorado

S. de Alwis, T. DeGrand, O. DeWolfe, A. Hasenfratz, R. Hoffmann, Z. Liu, K. T. Mahanthappa

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1 Overview

The Colorado research group includes five faculty (Mahanthappa, DeGrand, de Alwis, DeWolfe and Hasenfratz), one post-doc (Hoffman) and two graduate students (Liu and Brown). The group's major research areas at present are string theory and quantum gravity (DeAlwis and DeWolfe), lattice QCD with an emphasis on issues associated with chiral symmetry (DeGrand and Hasenfratz), and beyond-standard model phenomenology and the origin of fermion masses (Mahanthappa). Oliver DeWolfe joined us in January 2006. Ben Shlear will join us as a postdoc in the fall, supported partially by DeWolfe's startup. In past years we have been funded for 1.5 post-docs. We would like to increase that to two post-docs, an increase we feel is justified by the size and activity of the group.

Liu will finish this summer and is going as a postdoc to the University of Paris. Our two postdocs from the first two years of the grant were Stephan Schaefer, now a postdoc at DESY-Zeuthen, and Ivonne Zavala, now at Durham. Two of our recent graduates have just taken faculty positions: Matt Wingate will be a Lecturer at Cambridge University, and Mu-Chun Chen will be an Assistant Professor at the University of California-Irvine.

2 Research of T. DeGrand

Colorado has a small and active group of lattice gauge theorists (DeGrand, Hasenfratz, Liu, Hoffman). The goals of lattice calculations are to understand the non-perturbative properties of the strong interactions (confinement and chiral symmetry breaking) and to compute strong interaction matrix elements relevant to tests of the Standard Model and beyond. The Colorado researchers work on a wide variety of problems.

My work is focused on the study of overlap fermions and their application to problems of physical interest. Overlap fermions are a discretization of QCD which preserves exact chiral symmetry at finite lattice spacing. They have many remarkable properties, which make the theoretical interpretation of results from overlap fermions relatively straightforward. The down side, compared to conventional lattice discretiations, is that they are computationally expensive.

Most of the lattice community prefers to work with cheaper algorithms which lack complete chiral symmetry, and to correct for lattice artifacts during the analysis phase of a project. This can be difficult, particularly if one is working in a small group. (For example, fits to chiral staggered perturbation theory formulas involve about a dozen parameters.) I do not know if this make what I am doing avant-gard or merely irrelevant. Nevertheless, I am at a point now where my collaborators and I are producing interesting physics results, and we have a list of projects which are feasible with present resources.

2.1 Quenched B_K

In the summer of 2003 I was finishing up a calculation[15] of B_K

$$\frac{8}{3}(m_K f_K)^2 B_K = \langle \bar{K} | \bar{s}\gamma_\mu(1-\gamma_5)d\bar{s}\gamma_\mu(1-\gamma_5)d|K\rangle, \tag{1}$$

in quenched approximation. The calculation involved data from two lattice spacings, a fairly sophisticated lattice Dirac operator, and perturbative matching coefficients.

The number I got ($B_K = 0.56(2)$ and $0.55(3)$ at the two lattice spacings, continuum extrapolation $0.55(7)$) compared quite well with a recent world summary of quenched results by Dawson [a], $B_K = 0.58(3)$.

However, this is a quenched result, and quenching systematics are impossible to quantify. To continue doing lattice QCD phenomenology it is necessary to include the effects of virtual quark-antiquark pairs.

[a] C. Dawson, PoS **LAT2005**, 007 (2005).

2.2 Algorithm development for overlap fermions

In Spring 2004 Stefan Schaefer and I began writing a program for simulating full QCD with dynamical overlap fermions. We adopted the basic algorithm of Fodor, et al [a] and added a number of improvements [6, 4, 2]. The most important extensions (of many) were

- Stout links: These are a particular kind of gauge connection invented by Peardon and Morningstar [b] which is both differentiable (necessary for the algorithm) and smooths the gauge field at short distances. After our paper the two other groups doing dynamical overlap adopted this trick.

- Simulations with any number of flavors[1]: "Exact" algorithms for dynamical fermions like Hybrid Monte Carlo are usually constrained to an even number of degenerate flavors, or of multiples of four for staggered fermions. Of course, in the real world there are two light non-degenerate flavors and a third heavier one, and the usual way that $N_f = 2+1$ simulations are done is with an algorithm like refreshed Molecular Dynamics (the "R-algorithm"), which has integration step size systematic errors which must be monitored carefully. Regularities in the spectrum of overlap fermions allowed Schaefer and me to avoid this constraint Our algorithm is based on earlier work by Bode, et al [c]. It is special to overlap fermions. The new ingredient (which they did not describe) is a technical one: how to set up the chiral pseudofermion fields. We regard being able to simulate any N_f as a significant advancement of principle. It also happens that the trick improves critical slowing down at small quark mass, or in sectors of nonzero topological charge, which is a practical advantage.

The present code is probably about 100 times faster than the original Fodor et al algorithm. This year alone we picked up a factor of 2.5 to 3. To run dynamical overlap simulations comfortably, we need another factor of 3 or so in speed. So a big part of the research menu for the next several years will be algorithm development. We can see three areas for improvement:

- dirty coding tricks.
- a better fat link – smoother ones are used in quenched studies, like A. Hasenfratz's HYP link. They speed up the overlap algorithm more than a stout link, but dynamical simulations need a differentiable link, which HYP is not.
- a better algorithm. Separately, Schaefer and Hasenfratz have been experimenting with doing the simulations with an algorithm with inexact chiral symmetry, and then reweighting to produce an ensemble of gauge fields with exact chiral symmetry. Of course, this is real research: we don't know if anything will work.

[a] Z. Food, S. D. Katz and K. K. Szabo, JHEP **0408**, 003 (2004) [arXiv:hep-lat/0311010].
[b] C. Morningstar and M. J. Peardon, Phys. Rev. D **69**, 054501 (2004) [arXiv:hep-lat/0311018].
[c] A. Bode, U. M. Heller, R. G. Edwards and R. Narayanan, arXiv:hep-lat/9912043.

2.3 Physics projects

The physics projects most accessible to simulations with dynamical overlap fermions involve aspects of chiral symmetry breaking.

Schaefer and I have been computing the chiral condensate Σ with $N_f = 1$ and 2 flavors of quarks. We did a pilot study of $N_f = 2$ last year and are hoping to write up a better result by June. The calculations are identical: we perform simulations in sectors of fixed topological charge and record the probability distribution of the eigenmodes of the Dirac operator. Random matrix theory predicts the shape and magnitude of these distributions in terms of the scaling variable $\zeta = \lambda\Sigma V$ for eigenvalue λ, condensate Σ, and volume V. The shape depends on the quark mass through the combination $m_q\Sigma V$ (and N_f, of course). This gives Σ, one of the two parameters of the low energy chiral effective Lagrangian.

To convert from a lattice-regulated number we need a matching factor. We use the so-called Regularization-Independent method, which compares

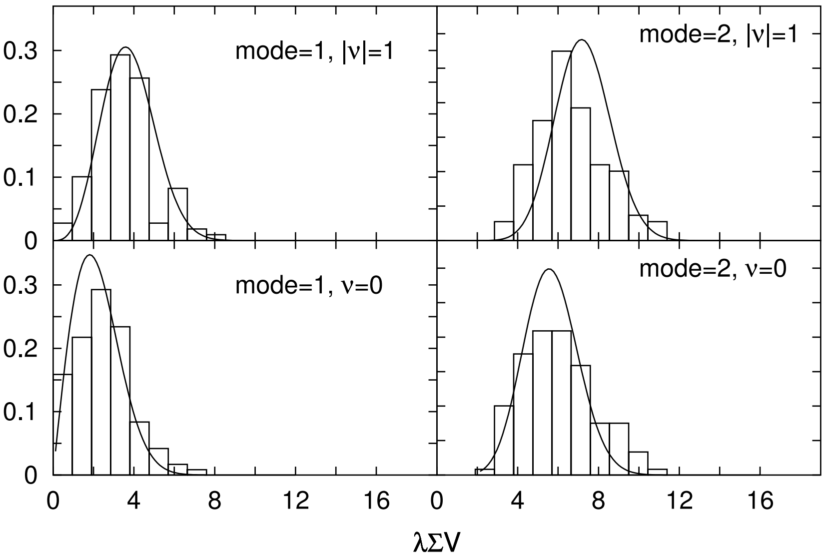

Figure 1: The distribution of the lowest two eigenmodes of the Dirac operator in $N_f = 1$ QCD for our ensemble for the sector of trivial topology and $\nu = \pm 1$. The lines are the result of fits of the random matrix theory prediction to the data for the two lowest modes.

average propagators and vertices computed on the lattice in Landau gauge to perturbative expectations. (This calculation is big part of my student Liu's thesis[3]; he has published a paper doing this in quenched approximation.) The matching factor turns out to be different from what one would find in a direct perturbative calculation. This is important for the final result.

The $N_f = 2$ result is relevant to the real world (it is $SU(2) \times SU(2)$ chiral symmetry). As of this moment we don't have a final number, but $\Sigma \sim (250\text{MeV})^3$, the phenomenological result, is close to what we will find.

$N_f = 1$ is interesting. Very few analytic techniques are available to study nonperturbative properties of QCD. Of these, the most prominent are large-N_c expansions. Recently, Armoni, Shifman, and Veneziano [a] suggested a new large-N_c expansion with some remarkable features. In contrast to the 't Hooft large-N_c limit ($N_c \to \infty$, $g^2 N_c$ and N_f fixed, with quarks in the fundamental representation of $SU(N_c)$), quarks are placed in the two-index antisymmetric representation of $SU(N_c)$. Now in the $N_c \to \infty$, $g^2 N_c$ and N_f fixed limit of QCD, quark effects are not decoupled, because there are as many quark degrees of freedom as gluonic ones, $O(N_c^2)$ in either case. Armoni, Shifman and Veneziano have argued that a bosonic sector of $\mathcal{N} = 1$ super-Yang-Mills theory is equivalent to this theory in the large-N_c limit. The large-N_c QCD-like theory is called "orientifold QCD."

For $N_c = 3$, orientifold QCD is equivalent to QCD with a single flavor of fundamental representation quark. In a recent paper [b], Armoni, Shifman and Veneziano estimate the quark condensate in one-flavor QCD from the value of the gluino condensate in SUSY Yang-Mills. They find

$$\Sigma = \{0.014,\ 0.021,\ 0.028\}\ GeV^3 \tag{2}$$

We can check this. Right now our number is bang on their central value! The paper should be out in a few weeks.

[a] A. Armoni, M. Shifman and G. Veneziano, Phys. Rev. Lett. **91**, 191601 (2003); Nucl. Phys. B **667**, 170 (2003) [arXiv:hep-th/0307097].

[b] A. Armoni, M. Shifman and G. Veneziano, Phys. Lett. B **579**, 384 (2004) [arXiv:hep-th/0309013].

There are many directions open for future research:

- The quark condensate for $N_f = 3$: this would be pretty straightforward given our experience with $N_f = 1$ and 2: I am guessing it would take 6 months on a few processors of the Colorado Beowulf cluster. It's believed that $SU(3) \times SU(3)$ is more realistic chiral symmetry than $SU(2) \times SU(2)$, so the number would be more physical than what we have done so far. I am amazed that big groups have not done this already.

- $N_f = 1$ QCD looks wide open to us. The problem is that most physics questions involve "disconnected diagrams" (OZI suppressed graphs). These are really hard to compute. Hopefully the orientifold people will notice our paper and suggest other things to try. Apparently, there are consequences for LHC phenomenology [a] (!) (I'm sorry to be vague, but this is a new area of physics for me.)

- "Deconfinement physics:" I am currently doing simulations across the confinement - deconfinement or chiral restoration line. I am collecting eigenmodes and looking at how their properties change as chiral symmetry is restored. The spectrum changes pretty dramatically. There is a small literature on the global properties of the low eigenmodes and whether it changes across the transition (do the eigenmodes delocalize?) which I can test.

- More conventional things: The commonest lattice simulations are done on lattices which are long in one direction, and measure correlators which extend across the lattice. Their outputs include spectroscopy and hadronic matrix elements used in Standard Model tests. Right now we can generate about one trajectory per day per processor for $10^3 \times 20$ lattice at a small quark mass at a lattice spacing of 0.15 fm. A real simulation needs several hundred trajectories at several masses. We have the computer power to do this, but I am hesitant to try until we speed up the algorithm a bit more. The obvious target of such simulations is the so-called "epsilon-regime," where the combination $m_\pi L \ll 1$ (L is the box size) while $m_H L > 1$ for the other hadrons. Measurements of correlation functions in sectors of fixed topology can allow calculations of pseudoscalar decay constants and other parameters of the chiral effective Lagrangian.

[a] M. J. Strassler and K. M. Zurek, arXiv:hep-ph/0604261.

2.4 A book

C. Detar of the University of Utah and I are finishing a book, "Lattice Methods for Quantum Chromodynamics," to be published by World Scientific this fall. From the advertising blurb: "This book provides a thorough introduction to the specialized techniques needed to carry out numerical simulations of QCD: a description of lattice discretizations of fermions and gauge fields, methods for actually doing a simulation, descriptions of common strategies to connect simulation results to predictions of physical quantities, and a discussion of uncertainties in lattice simulations. More importantly, while lattice QCD is a well defined field in its own right, it has many connections to continuum field theory and elementary particle physics phenomenology. The authors make a major effort to elucidate those connections."

The table of contents is:

- Continuum QCD and its phenomenology,
- Path integration,
- Renormalization and the renormalization group,
- Yang Mills theory on the lattice,
- Fermions on the lattice,
- Numerical methods for bosons,
- Numerical methods for fermions,
- Data analysis for lattice simulations,
- Designing lattice actions,
- Spectroscopy,
- Lattice perturbation theory,
- Operators with anomalous dimension,
- Chiral symmetry and lattice simulations,
- Finite volume effects,

- Testing the standard model with lattice calculations,
- QCD at finite temperature and density

3 Research of A. Hasenfratz

3.1 Dynamical Simulations of the Classically Perfect Action

The goal of lattice calculations is to understand the non-perturbative properties of Quantum Field Theories in the continuum limit. The discretization of the action provides the use of numerical methods in this quest but introduces discretization errors or lattice artifacts. The lattice artifacts can be reduced by choosing better lattice actions but there are no miracles: good scaling, good chiral properties, theoretical safety and the expenses are in balance. Short of an algorithmic breakthrough one can expect to see in the future a plethora of full QCD simulations and results obtained with different formulations adapted to the physical problem.

In collaboration with the University of Bern (P. Hasenfratz and F. Niedermayer) our approach has been to avoid any compromise in the lattice action and accept that the numerical algorithm is more complicated and less effective than for more standard calculations. We have developed a full QCD algorithm for 2+1 light flavors with the parametrized fixed point action[21]. The lightest quark mass m_{ud} which can be simulated is set only by the small chiral symmetry breaking caused by the parametrization error, the expenses of a full updating sweep are practically independent of m_{ud}. Our updating procedure has no special problems in connecting different topological sectors nor in suppressing the topological susceptibility. The algorithm is exact and the action certainly describes QCD in the continuum limit. It is a partially global update where the pieces of the determinant are switched on gradually in the order of their expenses. The partially global update implies that this is a volume-squared algorithm which constraints the size of lattices one can cope with in the simulations.

Future directions:

During the last year we have collected a good size (100+ independent) dynamical configurations both on $8^3 \times 24$ and $12^3 \times 24$ lattices at lattice resolution $a \approx 0.15$fm at physical quark mass values. (In the smaller volume we have a set at approximately zero mass as well.) We are in the process of analyzing these configurations: standard low energy hadron spectroscopy, the AWI mass (confirming $m_{ud} \approx 3-5$MeV), the condensate from the eigenmodes of the Dirac opeartor using Random Matrix Theory, etc. In the analysis we use the overlap operator based on the perfect action kernel - a small change but potentially important if we look at chiral properties.

All our runs are in the ϵ regime (or δ regime since the time direction is long), at very small quark masses. Obviously this is the region where our action and method are competitive.

Several students from the University of Bern joined this collaboration in the last 6 months. Next year I will spend my sabbatical in Europe, based in Munich, but I will spend considerable time in Bern. I expect that during that time we will be able to complete the on-going analysis, finish the algorithm development still in progress, and obtain physically meaningful, exciting results.

3.2 4th Root Issues

One of the most controversial and dividing issues the lattice community faces these days is the validity of the 4th root trick used in 2 and 2+1 flavor staggered action dynamical simulations. Staggered fermions describe 4 tastes, there is no 2 or 1 flavor staggered action. The usual trick is to take the 4th root of the fermion determinant in the Boltzman weight thus reducing the effective fermion number of the simulations. The problem is that there is no guarantee that this Boltzman weight corresponds to a local fermion action in the same universality class as continuum QCD.

A year ago the general expectation of staggered practitioners and their fellow travelers were that even though the rooted staggered action is nonlocal, there nevertheless exists a local action which determinant is identical to the rooted determinant, up to local gauge loops. Looking back to this expectation now, it seems very naive. There are several obvious examples that show the rooted staggered action cannot be local at the massless limit and likely not even at the small mass region[a]. I found one last year [22]: If the staggered 4-taste action were identical to a flavor symmetric fermion action plus local gauge terms, the determinant could be written as

$$\det(\mathrm{D_{st}}(\mathrm{m_{st}})) = \det(\mathrm{D_{symm}}(\mathrm{m}))\det(\mathrm{T}), \qquad (3)$$

where $D_{st}(m_{st})$ is the massive staggered action, $D_{symm}(m)$ is the massive flavor symmetric action and T represents the pure gauge terms. On a topologically non-trivial configurations $\mathrm{det}(\mathrm{D}_{\mathrm{symm}}(\mathrm{m}=0))$ vanishes, while $\det(D_{st}(m_{st}))$ is always finite. det(T) of a local pure gauge action cannot change that, Eq. 3 cannot be correct in the massless limit, or for light masses either. In ref. [22] I argued that the controversy could be resolved if $m_{st}=0$ did not imply $m=0$, i.e. the matching fermion masses between the staggered and overlap actions are offset. As it turned out this does not "solve" the problem, Eq. 3 is simply invalid [a], nevertheless the idea of fermion matching and mass offset seems to be valid. Also, the non-locality of the rooted staggered action does not mean that the rooted theory is in the wrong universality class.

In a recent paper with R. Hoffmann we have explored the above ideas[23]. Our basic question was if the value of the staggered determinant could be matched with an overlap determinant plus arbitrary local gauge terms on typical dynamical configurations. Any residue of this matching signals non-local gauge terms. While we cannot not tell if these non-local gauge terms correspond to local or non-local fermionic terms, we could show that they scale away in the continuum limit with a high power of the lattice spacing, i.e. they do not influence the continuum limit. We also found that the best matching occurs when the staggered and overlap masses are offset by some $O(a^2)$ value. While this offset is only a lattice artifact and vanishes in the continuum limit, at a finite lattice spacing it can make a large difference. Our results imply that configurations generated by the rooted staggered action are, up to lattice artifacts, identical to overlap configurations, but care must be taken in approaching the continuum limit with small quark masses. Figure 2 illustrates the power of the matching. It shows the topological susceptibility on staggered and overlap configurations as the function of the quark mass. The raw staggered data shows large lattice artifacts but most if it disappears if the data are replotted as the function of the matching overlap mass. Note that $m_{st}=0$ corresponds to a finite matched overlap mass, and the mass offset and the quality of the matching is quite independent of the number of flavors.

Future directions

The results of Ref. [23] are encouraging but there are many other open questions about the validity of the rooted approach.

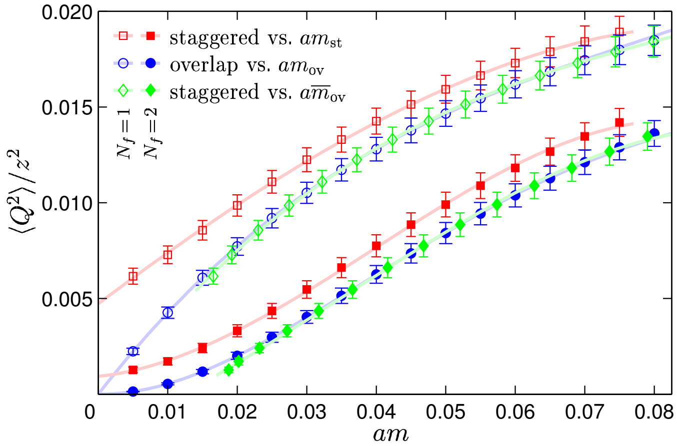

Figure 2: The topological susceptibility of the 2 dimensional Schwinger model on staggered and overlap configurations as the function of the quark mass. The raw staggered data shows large lattice artifacts but most if it disappears if replotted as the function of the matching overlap mass.

In a nearly complete work with R. Hoffmann we push forward with the Schwinger model. We consider the scalar condensate, a quantity that has very different behavior with staggered and overlap fermions: for $N_f = 1$ it is finite in the chiral limit with the latter while vanishes with the former action [b]. We found that with our mass offset the scalar condensate on the staggered background, if measured with the overlap operator, reproduces the overlap results, again supporting the idea that the staggered configuration set is correct. We also investigate the pion spectrum on the two backgrounds and see if they match with the mass offset predicted by our earlier work. This checks that the configurations can be matched not only in determinant values but in their spatial correlations as well giving a much more stringent test.

The Schwinger model is an excellent testing ground, but it is still only a toy model. An obvious next step is to see if the 4 dimensional staggered action could be matched with an overlap one and study the scaling of the residue there. We are trying to develop methods to do the matching without actually calculating the determinant as that is very expensive in 4 dimensions, even if one does the calculation stochastically.

[a] C.Bernard, M.Golterman and Y.Shamir, arXiv:hep-lat/0604017.

[b] S.Durr and C.Hoelbling, Phys. Rev. D **72**, 071501 (2005)

3.3 Mixed Action Calculations

Mixed action calculations, calculations where the dynamical sea quark action is different from the valence quark action are increasingly common. The cost of dynamical simulations justifies the use of simpler, non-chiral actions for the sea quarks but for many measurements one needs exact chiral symmetry. Several groups now use staggered or Wilson dynamical configurations with overlap or domain wall valence quarks.

The chiral condensate on staggered background with overlap valence quarks

This project is at an advanced stage. It is as much a test of the validity of the 4th root trick as a study of fermion matching, and we do expect to get a physical prediction for the condensate as well.

The Random Matrix Model predicts the eigenspectrum of the continuum Dirac operators from basic symmetries. Its applicability and validity has been checked in several quenched calculations. In particular in [a] it has been shown that on lattices as small as $L \approx 1.5$fm linear size the eigenvalue ratios match the RMT predictions to high accuracy in the $Q = 0,\ 1$ and 2 sectors, up to 3-4 eigenmodes.

We plan to do a similar test using staggered configurations of $L \approx 1.5$fm size and measuring the eigenmode spectrum of an overlap operator. Since the RMT prediction uses massless overlap, we don't have to worry about the quark mass in the measurement. However the RMT predicted value does depend on the quark mass so in the analysis we have to introduce an overlap quark mass value that physically corresponds to the original staggered quark. The idea is that the measured overlap eigenmodes will agree with the RMT prediction only at one mass value that will signal the matching overlap quark mass. At that value then we can proceed and determine the bare scalar condensate. To obtain the condensate in the $\overline{MS}$ scheme at 2GeV one needs the renormalization factor, but that is the overlap renormalization factor and can be obtained just like in [3]. Preliminary results indicate that the matching is possible and the scalar condensate is consistent with expectations.

The scalar condensate in principle can be obtained from a single quark mass, finite volume run, but because there are issues about matching and we are at the same time testing the 4th root trick as well, we will repeat the calculation at larger volumes at different quark masses as well.

[a] L. Giusti, M. Luscher, P. Weisz and H. Wittig, JHEP **0311**, 023 (2003)

Mixed action dynamical simulation

The ratio of the fermionic determinants on two different configurations are usually large, but most of it comes from the UV modes. Using the reduced determinant can reduce it by 80-90%. The remaining difference is well approximated by the low lying fermionic eigenmodes. These two observations are at the heart of the perfect action simulations of [21]. We also observed that the low eigenmodes are close to the overlap eigenmodes on most configurations suggesting that it is quite feasible to reweight our perfect action ensemble to an overlap perfect action ensemble.

The perfect action is still complicated to simulate, but similar “closeness” is expected if we consider a simpler improved kernel action (for example obtained by expanding the overlap operator to a finite, fixed order). Simulating such an improved action should be much easier than the overlap action, and since the overlap square root is replaced by a smooth function it should have no (or less) problem with changing topology. These configurations can be reweighted to an exactly chiral overlap one. Whether one should reweight a dynamical configuration at every trajectory or only on independent configurations should be considered.

4 Research of S. de Alwis

String theory is the only framework for going beyond standard model physics, that a) contains at least the basic ingredients of the standard model and b) is unified with gravity and is ultra-violet complete. There is simply no alternative at this point. In addition it has had remarkable theoretical successes such as the AdS/CFT correspondence.

This work is focused on attempts to relate string theory to particle phenomenology and cosmology. This has become feasible in the past few years due to the discovery of methods for generating a potential that stabilizes the so-called moduli of string theory. These are related to the size and shape of the six-dimensional internal manifold on which the theory is "compactified" in order to get a four dimensional theory. In addition the coupling constant in string theory is a field - the "dilaton" which also gets stabilized by these potentials. This takes care of a long standing problem in string phenomenology by eliminating unwanted Brans-Dicke scalars and violations of the equivalence principle and it would seem that this opens up the possibility of doing calculations that can be compared with data. Given that there is now a wealth of cosmological data and that in the coming years there will be a lot data coming out of the LHC, it is extremely important to focus on what the theory says about our world.

The major problem that one is confronted with is that there appears to be a plethora of classical four dimensional solutions to string theory (called the landscape) with all moduli stabilized. Of course it was known from the mid eighties that there were a large number of possible compactifications, each of which gave a different four dimensional theory. However these models had no potential for the moduli, and the hope was that once we learn how to stabilize them, we would get - if not a unique four dimensional theory - at least just a few, so that there was still some predictive power. The landscape seems to have eliminated this possibility since even with certain observational restrictions such as the requirement of a cosmological constant at the $10^{-3}eV$ scale, there may be 10^{100} or more candidate models. One might put further restrictions such as demanding that there are just three generations with the standard model gauge group (or perhaps just the minimally supersymmetric standard model (MSSM)). While to this date no one has found such a model (with all moduli stabilized) they have come close, and it is likely that the landscape contains a very large number of such candidate models.

Given this situation one has the following options for making progress.

- Try to extract qualitative predictions that may apply to generic classes of models in the landscape. For instance does a string theoretic cosmology necessarily lead to a particular type of inflationary scenario? Do string theory models of particle physics lead to particular patterns of masses for super-partners of the standard model particles?

- Investigate theoretical issues in the landscape such as the possibility of transitions between the different vacua - in short the dynamics of the landscape. One could also apply ideas from quantum cosmology to discuss the possibility of a selection mechanism that picks one, or more likely a class, of models on the landscape.

- The landscape is a set of solutions to low energy classical string theory.

> Perhaps the full quantum theory does not allow all these solutions. One could implement the duality symmetries (S -duality which is a strong weak coupling duality and T- duality which is a large small volume duality) of string theory to cut down the number of solutions. It is even possible that these symmetries pick a unique solution.

As detailed below de Alwis' work has covered various aspects of these three items.

4.1 Compactification with fluxes and warped solutions

There has been much activity following the observation of Giddings, Kachru and Polchinski [24] (GKP) that the so-called complex structure moduli and the dilaton can be stabilized in effective low energy type IIB string string theory, when certain fluxes are turned on in a compact six-dimensional internal space. The resulting four dimensional theory is expected to be $\mathcal{N}=1$ supergravity with a potential for some of the moduli. de Alwis investigated the derivation of this potential in [25] and has also investigated [26] a toy five-dimensional brane world theory with a view to clarifying some of the issues raised by the warped compactification solutions of GKP. It was shown that there was a clear conflict between the equations of motion derived directly from the higher dimensional action and the equations derived from the effective four dimensional theory derived from naive truncation using the factorized metric ansatz of [24], in the presence of non-trivial warping. In other words there appears to be no clear way of separating the moduli fluctuations from the Kaluza-Klein fluctuations in such a warped background. This problem is being investigated further.

4.2 Potentials for light moduli

In GKP the problem of stabilizing the so-called Kaehler moduli was not addressed. This was discussed subsequently by Kachru et al. [27] (KKLT). They added non-perturbative corrections to the flux superpotential derived in GKP and showed that Kaehler moduli could also be stabilized. However the minimum of the potential was negative and the solution was in fact supersymmetric. In order to get a positive (deSItter) minimum they added a contribution from a Dbar brane. At the four dimensional effective supergravity level this is an explicit breaking of supersymmetry and it is not entirely clear how to get a low energy supergravity broken at some low or intermediate scale from this argument. An alternative way of getting deSitter minima is discussed by Brustein and de Alwis in [28]. It was found that with one light modulus there is no stable critical point with zero or positive cosmological constant but there is one with two light moduli. Also in this paper the first attempt at stabilizing moduli using fluxes and gaugino condensation, in the context of the heterotic string, by Dine et al [29], was reexamined. It was found that contrary to what had been widely believed, this mechanism does actually work and a stabilization of all moduli in the heterotic string can also be achieved though the degree of fine tuning needed is much greater than in the IIB case. This fine-tuning may be considerably reduced if α' effects are included. This is being investigated currently.

4.3 Cosmological issues

This is work with Ramy Brustein and a student (Paul Martens). There has been a long standing problem in string cosmology known as the overshoot [30]. This relates to the fact that with generic initial conditions string moduli tend to overshoot the barrier in their potential (which is typically parametrically smaller than the string scale) and the theory tends to end up in the decompactification or zero coupling region. The recent attempts at string cosmology inspired by KKLT also suffers from this problem. In the work of de Alwis et al. a minimal KKLT type scenario with radiation (or matter) in the initial state was investigated. It was found that there is a window of initial conditions which make the moduli bound.

The most economical cosmological models in the context of string theory are ones in which one or a combination of the closed string moduli (describing the size and shape of the internal manifold) or the dilaton, plays the role of the inflaton. These models are however fine-tuned (as are the models involving brane-antibrane annihilation). This is a generic feature of supergravity potentials and therefore is a problem for all string theoretic potentials considered so far. The question of how much fine-tuning is needed and how the degree of fine tuning varies with the different flux compactifications that are used, is also currently being investigated.

4.4 Potentials for light moduli

In KKLT it was assumed that flux configurations could be chosen such that all the complex structure moduli as well as the dilaton-axion were heavy, and could be integrated out, yielding a potential for the light moduli after the inclusion of non-perturbative term(s). However this was done in two stages. In the first stage the superpotential just had flux terms as in GKP. The complex structure and dilaton which are assumed heavy are integrated out with this potential. This gives a constant superpotential and generically it is non-zero and supersymmetry is broken. At the next stage the non-perturbative terms were added and a potential for the Kaehler modulus was generated. The question of whether this two stage procedure was valid was investigated by de Alwis in [32]. It was found that there is no approximation in which this could be justified. In fact an approximate evaluation of the potential after including the non-perturbative terms *ab initio* actually showed that one can get positive (i.e. deSitter minima which of course break supersymmetry) without the need for the uplifting (Dbar) terms of KKLT.

As a corollary of this project de Alwis has also investigated [33] the conditions under which heavy fields can be integrated out in supersymmetric theories. It was found that even in globally supersymmetric theories the usual condition used in the literature is in general too strong. A weaker condition was derived in both N=1 global and local supersymmetry and the restrictions implied by the stronger condition are discussed. In fact in supergravity it was shown that the imposition of the usual condition that the Kaehler derivative of the heavy fields vanish was in fact too strong. However it was argued that this condition may still be used just for the purpose of getting the scalar potential for light moduli.

4.5 Quantum Cosmology and the Landscape

Quantum cosmology is usually discussed as a method for evaluating probabilities for tunneling from nothing to a closed universe with some value of the cosmological constant - the latter being viewed as an integration constant that can take different values. In the landscape of string theory the potential for the moduli depends on a set of integration constants - the (quantized) values of the fluxes which are turned on through some cycles in the internal space. The minimum of the potential is of course the cosmological constant which is now determined in terms of those fluxes (and some other parameters). Thus it is possible to use these old ideas in a new context. However there are two issues that need to be dealt with. Firstly we are dealing with string theory and not just General Relativity coupled to some scalar field as in the old discussions. Secondly we need to take into account the fact that there is some non-trivial potential for the moduli. Clearly an effective four dimensional mini-superspace description (which is the only case for which calculations can be done given current technology) cannot be valid in string theory all the way from a nothing state. We therefore take for our starting point a primordial thermal state at just below the Hagedorn (string scale) temperature. We then ask for the probabilities for tunneling to different points of the landscape, assuming that the end point is a closed universe. As in the old Hartle-Hawking, Linde and Vilenkin discussions, there is a classical barrier and one can compute the quantum tunneling probability. In contrast to those discussions however we use an initial state coming from the decay of string states which is modeled as a thermal state with a temperature just below the Hagedorn (string scale) temperature.

Our results [34] are quite interesting. They tell us that the probability is maximized for tunneling to a point on the moduli potential that is sufficiently flat to allow for accelerated expansion and is close as possible to the central region of moduli space (where the moduli are close to being $O(1)$. In particular the tails of potentials (which lead to decompactification and zero coupling) appear to be strongly disfavored. In addition there are constraints on the values of the parameters of the potential, but these are much more difficult to analyze. Of course we do not expect that such an analysis would determine the potential uniquely or solve the cosmological constant problem. But it is interesting that there is a possibility of getting some dynamical selection criteria in the space of string vacua using these ideas.

4.6 Transitions in the Landscape

A given choice of a compactification manifold (such as a Calabi-Yau threefold) a set of (integer) fluxes through its cycles, an orientifold projection (in IIB or IIA cases) and an associated set of D-branes, defines a classical string background and hence a point on the landscape with no more than N=1 supersymmetry (so that we have a chance of getting chiral fermions). The four dimensional fluctuations around such a background would form supergravity (SUGRA) multiplets and in particular one expects the moduli to be chiral scalar fields with the standard SUGRA potential. This potential may have many minima (for instance if we have more than one condensing gauge group giving several non-perturbative terms) each of which gives a meta-stable vacuum. This may be called a mini-landscape. The usual discussion of eternal inflation (in the context of string theory) is really within this mini-landscape. Within this however there is still a classical dynamic (for instance if as one might expect - the field starts off at a high point close to the central region) that will result in the system ending up in the lowest vacuum and one might regard this as the true cosmological constant of the mini-landscape. But this is not what is relevant for the discussion of Brown and Teitelboim [35] and Bousso and Polchinski [36] (BTBP) where brane nucleation will change the fluxes etc/ and hence all the parameters of the mini-landscape. In the context of the string theory landscape these cause transitions between different points of the landscape in contrast to tunneling between different minima of a given classical potential (i.e. mini-landscape).

This process has not really been investigated in detail within a framework in which the moduli are stabilized. de Alwis has been pursuing two related projects in this area. In one the question of whether an action which describes these processes exists in the supergravity approximation is addressed. The different configurations of branes which interpolate between different points of the landscape are discussed in detail. However while the classical configurations appear to exist, it does not seem possible to construct an action which describes this. In type IIB this is of course related to the well-known difficulty of writing down an action for the self-dual five form. In IIA on the other hand while it is possible to write down an action in the absence of zero form flux (i.e a ten dimensional cosmological constant) when this is turned on gauge invariance appears to break down. Since the transition is quantum mechanical and takes one from one background to another (with different values of the CC) it is imperative that a proper action which is background independent (and hence Lorentz invariant) which only propagates the physical degrees of freedom exists. At least at the level of supergravity this appears not to be the case. Of course this does not mean that transitions cannot take place. But the description may be essentially stringy.

A related investigation is of the scales involved in such transitions. Elementary transitions (resulting from the nucleation of one brane) generically cause a change in the CC of the order of the string scale. Generically this means that a world with a tiny cosmological constant would have arisen from the nucleation of a brane in a world with a string scale CC! Obviously it does not make sense to describe this process in low energy effective supergravity. Thus a proper discussion would seem to require the yet to be discovered background independent formulation of string theory such as a possible string field theory.

4.7 String Phenomenology

A necessary condition to get phenomenologically relevant information from string theory is to derive a four dimensional SUGRA model that has all the moduli stabilized. With the recent discovery of flux compactified string theory we now have such models, even though as pointed out earlier we still do not have one which is just the standard model (or rather the minimal supersymmetric standard model (MSSM)). However suppose we do find a model that is exactly the MSSM (or some viable extension of it). There have been many calculations of the MSSM parameters (such as the soft mass terms) under this assumption. These calculations start with the classical potential computed from flux compactified string theory with non-perturbative terms and uplifting terms (to get a small positive CC in agreement with observation) as in KKLT [27]. Then these parameters (soft masses etc.) are run down to the weak scale using the RG equation. However they invariably ignore the running of the CC! A consistent calculation needs to take into account the quantum corrections to the CC as one goes from just below the string scale (or rather the Kaluza-Klein (KK) scale which is lower) to the weak scale. In particular for generic SUGRA models the leading corrections to the CC are quadratic in the cutoff! In special circumstances (such as no-scale models) they can be logarithmic. In any case clearly what is required at the classical string theory level is not a model with the observed CC but one which can become the latter when the quantum corrections are taken into account. This makes the whole question of how to get phenomenology out of these calculations much more intricate since the initial conditions for the RG running of the soft masses etc. are dependent on the fluxes etc. which in turn have to be determined by the initial value of the CC - not its currently observed value. A meaningful calculation may be possible only in the case of exponentially large internal volumes with correspondingly large Planck to string scale. de Alwis is currently preparing a detailed discussion of these issues.

4.8 String Theory Dualities and the Landscape

This is work done in collaboration with Ramy Brustein. As discussed earlier string theory has various duality symmetries such as strong-weak coupling (S-duality) and large radius-small radius duality (T-duality). In the late eighties and early nineties several groups imposed these dualities on the effective potential for the moduli and the dilaton in the context of heterotic string theory. In particular [37] derives a class of S-duality invariant potentials for the dilaton, which in the weak coupling limit become equal to the so-called race-track models obtained from including non-perturbative effects in the low energy four dimensional effective action. These authors argue that in string theory the dilaton (and the moduli) should be restricted to the fundamental domain of the corresponding duality group. Other authors have similarly constructed T-duality invariant potentials for heterotic strings compactified on orbifolds.

Today it is known that S-duality takes a heterotic theory to a type one or M-theory. So the argument of [37] would be valid in some sense in a meta-theory (containing the two string theories which are related by S-duality). It is not quite clear how to implement this at the current stage of development of the theory. On the other hand type IIB theory is supposed to be S-dual. Thus these arguments may be reconsidered in that context where (unlike in the heterotic case) there are already classical potentials which stabilize the dilaton. Some preliminary work has been done on how this works out. The hope is that S-duality will impose some restrictions on the landscape.

4.9 Supersymmetry breaking and warped compactification

This is work being done in collaboration with Cliff Burgess, Fernando Quevedo and Kerim Suruliz. String compactifications with fluxes and branes introduces non-trivial warping so that the six dimensional internal geometry has throat-like regions where as one goes down the throat the effective four dimensional scale is exponentially reduced compared to that in the bulk. Consider now the theory far down this throat - for instance on a D3 brane living down there. All scales for modes localized far down this throat are exponentially suppressed compared to the typical scale in the bulk as in [38]. Standard estimates of the supersymmetry breaking scale however appear to give unwarped scales. This would seem to mean that there is no effective 4D SUGRA way down the throat since the warped KK scale is lower than the splitting between supermultiplets. We propose to do a systematic reevaluation of the calculations of supersymmetry breaking in these warped metrics in order to identify precisely what type of four dimensional theory is obtained down the throat. Preliminary investigations appear to show that the standard calculations need to be modified in the presence of non-trivial warping. This is in accord with the arguments of [25].

5 Research of O. DeWolfe

5.1 Background

Theoretical particle physics is now in an era of data-driven challenges from multiple directions. Accelerator experiments have confirmed the effectiveness of the Standard Model over a wide energy range, but essential questions have remained: issues such as the mechanism of electroweak symmetry breaking and the stability of the hierarchy between the electroweak and Planck scales will be probed by the Large Hadron Collider at CERN in the coming years, as a vital new energy scale opens up. But no less important have been the questions raised by observational cosmology: the existence of dark matter, of dark energy, and the suggestion that the early Universe underwent a period of exponential expansion are all exciting and crucial challenges for theory to understand.

String theory is at its roots a proposal for a quantum mechanical theory of gravity. Making sense of how gravity is reconciled with quantum mechanics is a longstanding and essential problem, and string theory (or M-theory, as its nonperturbative completion is sometimes called) represents an outstanding candidate for such a reconciliation. It is not, however, only concerned with gravitation: part of its appeal is the the way in which it naturally includes most of the ideas of contemporary particle physics and quantum field theory in its scope, such as Yang-Mills gauge theories, chiral fermions and supersymmetry. This ambitious program thus can reasonably be expected to have valuable things to say about the observed phenomenology and cosmology of the Universe, as well as about the fundamental nature of gravity and spacetime.

It is thus only natural to ask: what can such a theory tell us about the observed world? The primary focus of my current work is attempting to address this question. The most promising avenues lie in the direction of so-called *flux compactifications.* These backgrounds for string theory combine the original string phenomenological idea of a compact, curved spacetime with the additional ingredients of generalized electromagnetic fields (fluxes) and branes, whose central role in the theory has more recently become apparent. In so doing, they constitute essentially *generic* backgrounds for string theory, in that they include all of the theory's phenomena in the background. Flux compactifications have the promise to resolve the long-standing problem of moduli stabilization, and allow phenomenological and cosmological questions to be addressed.

5.2 Summary of Previous Work

Quantum consistency requires that the superstring propagate with a fixed number of degrees of freedom; the simplest allocation of these degrees of freedom is for the string to exist in ten flat spacetime dimensions. From the outset, phenomenological applications of string theory have focused on replacing some of these dimensions with a compact spacetime of small size, leaving the observed four dimensions of spacetime large. The effect of these "compactified" dimensions does not vanish from the theory: rather, the various vibrations of the string in the compact directions lead to a rich spectrum of particles in four dimensions, with desirable properties such as non-Abelian gauge groups and chiral fermions. Compactifications on so-called "Calabi-Yau" spaces lead to minimal supersymmetry in four dimensions as well.

These compactifications, however, are not without their difficulties. The most significant longstanding problem has been that of *unfixed moduli*: the low-energy theory is plagued with massless scalars coupling with gravitational strength. These moduli fields represent continuous choices in the possible compactifications, and lead to unacceptable consequences, both for particle physics and large-scale gravity.

However, in recent years it has become apparent that such geometric compactifications represent an exceptional case in the set of all string backgrounds. There are other essential elements of string theory – "fluxes" of generalized electromagnetic fields as well as dynamical "branes" (and related objects, the orientifolds) – which in general are present, opening up a large new set of possibilities for string compactification. Unlike simpler, geometric-only compactifications, the flux compactifications generically freeze many of the moduli. Each of the corresponding vacua sits at an isolated point on what used to be moduli space; hence unlike the continuous families of simple geometric compactifications, flux compactifications occur in discrete sets.

Because the moduli problem may be overcome, flux compactifications represent the state of the art for connecting string theory with phenomenology and cosmology. It is thus extremely interesting to understand their properties: what choices exist and what properties the different vacua have, as well as what kind of dynamics can occur in the various backgrounds.

In early work with S. Giddings [39] I investigated the energy scales of various modes arising in IIB flux compactifications, calculating the gravitino mass, moduli masses and scales of supersymmetry breaking. The IIB flux compactifications were the first ones to be well-understood, and this work provided the values of phenomenologically interesting quantities in typical such backgrounds. This analysis required a careful reduction of the ten-dimensional IIB action to four-dimensions, including a proper treatment of the subtle self-dual five-form flux.

We additionally recognized the coupling between Kähler moduli and brane fluctuations that was induced by the "no-scale structure" of these backgrounds. It had not been fully appreciated previously how the geometric moduli of the compactification space interact in a subtle fashion with the coordinates determining the positions of embedded branes. This interplay would turn out later [**?**] to be an important obstacle to realizations of brane inflation, a manifestation in the IIB context of the so called "η-problem".

With A. Giryavets, S. Kachru and W. Taylor [40] and alone [41], I investigated the existence and distributions of vacua with enhanced discrete symmetries and unbroken supersymmetry, two properties that are very useful for model-building and cosmology, again in IIB flux compactifications. Unbroken supersymmetry (at tree level) was associated with the vanishing of the superpotential, which could occur only for particular choices of the background fluxes. Although supersymmetry is broken in the real world (if it exists), it is difficult to break it without the scale of the breaking being too high: such vanishing-superpotential models are promising candidates for circumventing this difficulty. Furthermore, enhanced discrete symmetries can also arise for particular choices of fluxes, sometimes associated with vanishing of the superpotential, sometimes not. Such symmetries (or R-symmetries) can be very useful for forbidding dangerous operators in the low-energy theory.

Besides finding that such enhanced symmetry vacua existed, we also investigated how common they are as a fraction of all flux vacua, as well as finding their distribution on (what used to be) moduli space. Such a statistical approach is one promising direction for dealing with the large number of potential flux vacua. We found that techniques of *number theory* came into play as the appropriate mathematical language for the calculations, and exploited a few number theoretic techniques, though far greater sophistication is surely possible. Symmetric vacua were found to be surprisingly common in many models.

Also with A. Giryavets, S. Kachru and W. Taylor [42] we studied flux compactifications in a different regime of string theory, type IIA. The more traditional, more well-studied IIB models have some advantages, but suffer from a technical problem: fluxes only provide stabilization for half the geometric moduli, the so-called "complex structure" moduli, but not the "Kähler moduli". Although mechanisms for stabilizing the remaining moduli are believed to exist, they involve non-perturbative phenomena that are much harder to get under theoretical control, and much harder to calculate with.

Clearly therefore providing a type of flux compactification where *all* moduli are stabilized by the fluxes directly is useful and desirable. We demonstrated that the type IIA flux vacua do exactly that. This represents a significant step forward in the study of flux compactifications, and opened up a new, potentially more calculable set of string backgrounds for examination. These type IIA compactifications are thus very promising for the future. We showed that in general all geometrical moduli are stabilized, and also examined a particular compactification to demonstrate this in detail.

In a cosmological direction, with S. Kachru and H. Verlinde [43], I developed an alternate scenario for inflation in warped compactifications avoiding the η-problem alluded to previously. This scenario involved the unwrapping and annihilation of anti-branes against background fluxes [44], and represented a mechanism intimately connected to the more intricate features of brane/flux physics, while still proceeding from reasonable initial conditions. The scenario, however, could only realize slow-roll at the edge of theoretical control.

Finally, I will mention one result from the last few years not in the area of flux compactifications, but instead gauge/gravity correspondence.

Knowledge of nonperturbative string theory has led to a number of advances in understanding non-gravitational quantum field theory. The culmination of these advances is gauge/gravity duality, where string theory in a certain background is directly dual to a quantum field theory without gravity in a lower dimension, a manifestation of the holographic principle. The regime where one description is useful is associated to a regime in the dual that is hard to calculate – for example, weak curvatures on the gravity side are mapped to strong coupling in the gauge theory. Gauge/gravity duality is extremely powerful, and has by now passed many nontrivial checks.

I had previously studied the introduction of fundamental matter into the gauge/gravity correspondence, which is essential for any hope of using the duality to understand real QCD. On the gravity side of the duality, fundamental matter is associated with D-branes. With D. Z. Freedman and H. Ooguri [45], we had precisely characterized a novel field theory dual to the introduction of such a brane: this theory contained fundamental matter confined to a *defect* and was inspired by [46]. This defect field theory retains the exact superconformal properties of its parent, and we characterized the spectrum of operators and the dual open string excitations. This work inspired further work on the holographic realization of fundamental matter in [47].

A more recent development in gauge/gravity correspondence has been the appreciation that both sides in some cases represent *integrable* systems, and that this integrability could be a crucial tool towards understanding the behavior of gauge theories if it persists to more general theories. With graduate student N. Mann [49], now a postdoc at the University of Chicago, I studied the question of whether the integrability survives the introduction of fundamental matter, as described above. We found that indeed an integrable structure persists in the scalar sector, corresponding to solutions of the boundary Yang-Baxter equation. Hence integrable structures do indeed persist into more complex theories with realistic matter, reinforcing the hope they may be applied to an analytic understanding of QCD. N. Mann has studied this further in [50].

5.3 Future research directions

Thanks to the ability to resolve the problem of unfixed moduli, flux compactifications have cleared an important obstacle to the contact of phenomenology and cosmology with string theory. The immediate issue that now confronts us concerning flux compactifications is their *variety* – although not continuously infinite as were traditional Calabi-Yau compactifications, they still apparently occur in great numbers, each vacuum possessing different microscopic properties and correspondingly distinct low-energy physics. The inevitable next problem in string phenomenology is confronting the diversity of these vacua. Two distinct but valuable approaches are on the one hand studying *individual compactifications* and their precise properties, and on the other hand studying properties of *sets of ensembles* of vacua.

The study of specific compactifications is quite valuable despite the plethora of possibilities, for the ability to identify whether a given construction or mechanism can be realized at all in a string background, and furthermore to be able to examine carefully how the details work. I am concentrating primarily on the less-well explored but more theoretically tractable type IIA models. With the absence of nonperturbative stabilization for geometric moduli, brane inflation models with D6-branes may be able to avoid the η-problem discussed earlier, with the lesson of the IIB models being that brane modes and bulk fields couple in a subtle fashion, and the type IIA analog of this must be carefully understood.

The type IIA string theory is also a good scenario to investigate dark energy, entailing the development of nonsupersymmetric and de Sitter vacua. Natural paths to pursue include adding a nonsupersymmetric D6-brane, analogously to the D3-brane in type IIB [27], or by looking directly for vacua not associated with stationary points of the superpotential. More intriguing still is the possibility of a uniquely IIA mechanism with no easy translation to the more familiar type IIB side.

Finally, the appearance of Standard Model gauge groups or unified generalizations in type IIA flux compactifications must be further studied. It is natural for D6-branes to be present in the geometry, and their intersection can lead to chiral charged fermions; some work in this direction has already been done for simple orientifolds. The problem of generalizing this work to generic geometries remains, and the charge conservation constraints placed on the branes by the fluxes are stringent. A goal for the next few years is to find a single IIA model with all moduli stabilized, a realistic gauge and matter sector, and a positive vacuum energy; demonstrating the existence of such a background is within current reach, and would represent a concrete and promising step forward.

Complementary to searching for particular precise setups with desirable properties, one may consider the set of all flux compactifications and attempt to find dynamics that are generic or common to many. Attempts have been made to perform a statistical analysis of sets of flux vacua [51]. Such studies are difficult but potentially valuable if they lead to insight as to how common or uncommon various properties of the vacua are. However, it is clear at this point that flux compactifications do *not* exhaust all the string backgrounds of their type: in particular, the set of flux compactifications is not closed under dualities. Instead, dualities map flux backgrounds to compactifications with geometrical torsion. An ambitious outstanding problem in which I have great interest is to classify all vacua in this larger set that includes geometric torsions. Without such a generalization, studying sets of flux vacua constitutes looking only at a particular “slice" through the set of all compactifications. Torsions are, unfortunately, less easy to understand than geometric fluxes. However, I have begun studying via duality local models of the twisted cycles associated to torsions. It is clear that certain torsions are actually non-geometric, involving a patching together of geometry using stringy dualities. Understanding in detail these “quanta" of torsion is essential to classifying all possible string compactifications with some supersymmetry, and the question represents an essential problem before all possible string backgrounds are known.

Finally, once the breadth of string compactifications is understood, one must confront the question of how a single vacuum is selected from all these. Ultimately, one must find that either there is a dynamical principle that favors a vacuum resembling our Universe from the set of all vacua that do not, or that the world we observe is randomly selected. Understanding this problem is deep and difficult because it moves beyond merely a classification of vacua into understanding not merely dynamics, but also initial conditions. This is the direction in which my research is headed over a span of years.

6 Research of K.T. Mahantappa

6.1 Fermion Masses, Mixing and CP Violation

At present, there is still lack of a fundamental understanding of the origin of fermion mass hierarchy, flavor mixing and CP violation. A less ambitious aim is to reduce the number of parameters that parametrize the Yukawa sector. I have been working on this problem, in collaboration with Mu-Chun Chen (FNAL), in the framework of grand unification and have successfully constructed models that achieve this goal with additional symmetries. In the next few years, I would like to look at the fermion mass problem in a more model-independent way. This may shed light on the fundamental origin of the mass hierarchy, flavor mixing and CP violation.

6.1.1 Fermion Masses, Lepton Flavor violation and Soft Leptogenesis in SUSY SO(10)

SUSY SO(10) is an attractive framework in view of small neutrino masses. We have constructed a SUSY $SO(10) \times SU(2)_F$ model in which a set of symmetric mass matrices with five texture zeros (having 12 parameters) leads to 22 measurable fermion masses, mixing angles and CP phases, all in agreement with experiments within 1 sigma [52, 53, 54]. In addition, because the Majorana mass term for the right-handed neutrinos is generated by the $\overline{126}$ dimenional Higgs, R-parity is preserved at all energy scales. The LMA solution for solar neutrinos is obtained and the prediction for $\sin\theta_{13}$ is $\sim \sqrt{\Delta m^2_{\odot}/\Delta m^2_{atm}}$, which is within the reach of the next generation of reactor experiments. The ordering among the three light neutrino masses exhibits normal hierarchy, leading to a much suppressed value for the matrix element of the neutrinoless double beta decay. We have also investigated several lepton flavor violating charged lepton decays, such as $\mu \to e\gamma$, $\mu \to 3e$ and $\mu - e$ conversion [55]. Unlike models with lop-sided textures which give rise to a dangerously large decay rate for $\mu \to e + \gamma$, the decay rate in our model is much suppressed and yet it is large enough to be accessible to the next generation of experiments. In addition, we have investigated the possibility of baryogenesis resulting from soft leptogenesis. We find that, with soft SUSY masses assuming their natural values of the order of a TeV, the observed baryon asymmetry in the Universe can be accommodated in our model. Our work has resulted in an invited review paper [56] as well as several invited talks, including a plenary talk at the 10th International Symposium on Particles, Strings and Cosmology (PASCOS 04, Boston, Massachusetts, 16-22 Aug 2004) [57], a plenary review talk at the 2003 KAIST-KIAS Workshop in South Korea, the 5th International Workshop on Neutrino Factories and Superbeams (NuFact 03, New York, New York, 5-11 Jun 2003) [58], the 2004 Aspen Summer Workshop, the Tenth Marcel Grossmann Meeting on General Relativity (MG X MMIII, Rio de Janeiro, Brazil, 20-26 Jul 2003) [59] and at the 8th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2003, New York, New York, 19-24 May 2003) [60], DPF 2004 [61] and EPS-HEP 05 [62]. It has also resulted in many invited seminars and has been presented at SUSY 2004 [63] and SUSY 2005.

6.1.2 Spontaneous CP Violation and Leptogenesis

The evidence of non-zero neutrino masses opens up the possibility that the leptonic CP violation might be responsible, through leptogenesis, for the observed asymmetry between matter and anti-matter in the Universe. However, due to the presence of extra phases and mixing angles in the right-handed neutrino sector, it is generally difficult to make connection between leptogenesis and CP-violating processes at low energies. We found that [64], in the minimal left-right symmetric model, there are only two intrinsic CP violating phases to account for all CP violation in both the quark and lepton sectors, if CP is broken spontaneously by the complex phases in the VEV's of the scalar fields. In addition, the left- and right-handed Majorana mass terms for the neutrinos are proportional to each other due to the parity in the model. This is thus a very constrained framework, making the existence of correlations among the CP violation in leptogenesis, neutrino oscillation and neutrinoless double beta decay possible. We find that, the leptonic Jarlskog invariant $J_{CP}^{\ell} > 10^{-5}$ has to be satisfied to yield a sufficient amount of baryonic asymmetry. In these models, CP violation in the leptonic sector and CP violation in the quark sector are also related. We find, nevertheless, that such connection is rather weak due to the large hierarchy in the bi-doublet VEV's required in order to satisfy the constraints from flavor-changing-neutral currents in the quark sector. We are currently investigating the possibility of observable electric dipole moment of the electron and neutron-anti-neutron oscillation in this model. Utilizing double seesaw mechanism to generate neutrino masses, the breaking scale of $SU(2)_R \times U(1)_{B-L}$ can be as low as a few TeV. This thus greatly enhances the electron EDM as well as the rate of neutron-anti-neutron oscillation. And as the left-right parity forbids the QCD θ -term above the B-L breaking scale, the strong CP problem is solved. This model thus provides a unified solution to both the strong and weak CP problem, and it is highly predictive because leptogenesis, neutrino oscillation, electron EDM and neutron-anti-neutron oscillation are all closely connected.

6.1.3 Quark-Lepton Complementarity

Precise measurements in neutrino oscillation parameters have revealed an interesting relation that the deviation of the solar mixing angle from the maximal is of the size of the Cabibbo angle, $\theta_{sun} + \theta_c = \pi/4$, to a high accuracy. This relation, if true, suggests a deeper structure in which the quark and lepton mixing angles are closely related. One of the difficulties in constructing a natural model with quark-lepton complementarity in the framework of Grand Unified Theories is that the conventional way to obtain the Georgi-Jarlskog relations at the GUT scale often leads to the relation that the (12)-mixing angle in the charged lepton sector is one third that of the Cabibbo angle, thus spoiling the quark-lepton complementarity relation. We are currently investigating the possibility of quark-lepton complementarity in an $SO(10)$ model without such difficulty utilizing a new way to get the Georgi-Jarlskog relations. The radiative corrections can be large when certain conditions are met [65]. These corrections could thus potentially destabilize such relation. We will investigate if such relation can be protected against the radiative corrections by some symmetries.

6.1.4 Fermion Mass and Mixing in Extra Dimensions and String Compactification Models

In models with extra dimensions, there exist novel ways to generate flavor mixing among the fermions, including the neutrinos, from the geometry. We plan study neutrino mass generation and flavor physics in general in some classes of string compactification models, such as the intersecting D-brane models and models derived from heterotic string theory. It has been shown that in many of the string-derived models, it is difficult to obtain the Majorana type masses for the neutrinos. This aspect could be model-dependent, and we are investigating if there are new ways of generating Majorana neutrino masses in this framework.

6.1.5 Geometrical Origin of CP Violation

The conventional wisdom in four dimensions is that CP violation is generated either explicitly by having complex phases in the coupling constants or spontaneously by having relative complex phases among the vacuum expectation values of scalar fields that are responsible for the generation of fermion masses. For models in extra dimensions, additional sources of CP violation, such as those coming from compactification, could exist. One example of this is the Hosotani phase resulting from the compactification utilizing the Hosotani mechanism. The Hosotani mechanism can break both the gauge symmetry and supersymmetry. In the former case, the quadratic radiative corrections to the scalar masses are absent, thus providing a non-SUSY alternative to solve the gauge hierarchy problem. We plan to investigate whether a viable flavor sector can be produced incorporating the CP violation from the Hosotani phase. Existence of such a mechanism will the implications for Baryogenesis.

6.1.6 Dynamical Generation of Fermion Mixing

It was realized in the early 70's that the Cabibbo angle can be generated dynamically in a two-flavor approximation by imposing a set of consistency conditions, the so-called Bootstrap Equations, for the breaking of the flavor symmetry [66]. We will generalize this idea to the case with three famlies to obtain the CKM matrix. We will also search for a similar dynamical origin for large neutrino mixings.

6.2 New Scenarios for Electroweak Symmetry Breaking

The successes of the Standard Model have been tested experimentally to very high accuracy. The only missing link, however, is the non-observation of the Higgs boson which is needed to break the electroweak symmetry and to generate fermion masses. With the operation of LHC, the existence of a SM- or MSSM-like light Higgs will soon be confirmed or refuted. It is therefore important to search for alternative mechanisms for electroweak symmetry breaking and new solutions to the gauge hierarchy problem. Projects along this line that I have been investigating are described below.

Higgsless Model in Warped Extra Dimension. A new way to achieve electroweak symmetry breaking without a Higgs boson has been proposed very recently, where the symmetry is broken by boundary conditions associated with an extra dimension. In order to satisfy the electroweak precision constraints, it has been shown that the extra dimension has to be warped. One of the main problems with the idea of symmetry breaking without a Higgs in warped extra dimension is the violation of perturbative unitarity in the scattering of the W-boson. This is due to the incomplete cancellation among terms that grows as the square of the center of mass energy in the scattering amplitude. The ony existing proposal to restore the unitarity is by adding kinetic terms on the IR brane. However, the agreements with the SM electroweak precision measurements are worsened in this case. We are developing a new mechanism to restore the unitarity by extending the gauge group in the bulk to be $G_1 \times G_2$ and by choosing the boundary conditions in such a way that the gauge symmetry $G_1 \times G_2$ is broken down on the Planck brane to its diagonal subgroup which is then identified as the SM gauge group and the massless W and Z gauge bosons of the SM are thus orthogonal linear combinations to the massive gauge bosons W' and Z' of the broken gauge symmetry. As long as there is an enhanced global symmetry on the Planck brane, it is possible that the tri-linear coupling constants among the massive gauge bosons and those among the SM gauge bosons can have equal magnitudes but opposite signs. As a result, additional cancellations among terms growing as the square of the center of mass energy which arise from the exchange of the neutral gauge bosons in the SM and their KK states and those of the broken gauge symmetry may occur. This enhanced global symmetry may act as a custodial symmetry. If that is the case, the agreements with the electroweak measurements can be preserved. We will also investigate the implications to the unification of the gauge coupling constants in this model. In addition, we will search for possible mechanisms that generate fermion masses. The subtleties associated with anomaly cancellation in this framework will also be examined.

7 Computing Resources Request

Lattice gauge theorists use computers for two kinds of projects. The first is to perform large-scale high-statistics simulations using well-studied methodology, in order to produce refined predictions for comparison with experiment. These projects are best done on remote supercomputers. We do the second kind of projects, which include "everything else"–algorithm development, proof-of-principle simulations, and novel calculations. It is difficult to do this kind of work on remote supercomputers because the work involves the ability to make rapid changes in the code and to collect data rapidly for small tests. It is also hard to make the time and resource estimates necessary to obtain cycles at remote machines. But without "second-type" projects, supercomputer simulations would never progress.

We have had a very successful program of QCD studies with small computers. In 2001 we constructed a 32-node Beowulf cluster. Over the last three years it has been upgraded to a system of 20 P4E processors, and with the third year of computing support is will grow to 24-28 processors. Using these local computing resources, we have written over 35 research papers and conference proceedings.

Very likely, simulations with dynamical overlap fermions will use a major fraction of our available resources. If we were to freeze algorithm development now, a full scale $N_f = 2$ QCD calculation in the ϵ regime would probably use two years' worth of local resources. We have outlined a mix of other projects which are potentially more interesting and would compete with it.

At present, the most efficient use of computing for overlap is not parallel supercomputing, it is one job per processor, like experimental computing. The cost of the present system of P4E processors is just under $1000 per processor. It is hard to know precisely what will give us the best price/performance ratio would be in the next several years, but we imagine that it will be similar to what we are spending now. Adding 10 processors per year (for $10K in computer resources per year) would certainly sustain our healthy research program.

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Theoretical Advanced Study Institute (TASI) in Elementary Particle Physics-Task T

K. T. Mahanthappa is the general director of TASI.

The theme of TASI-2006 is "Exploring New Frontiers Using Colliders and Neutrinos" and the program has been arranged in cooperation with Dr. Sally Dawson of BNL Professor Rabindra Mohapatra of University of Maryland. Dawson is well known for her work on precision measurements of electroweak interactions with theoretical implications for various aspects of beyond the Standard Model. Mohapatra has made significant contributions to various aspects of neutrino physics and grand unified theories. Mahanthappa has been active in both formal and phenomenological aspects of particle theory, and astro-particle physics, and is currently working on supersymmetric grand unified theories and CP violation, connections between lepton violating decays and leptogenesis as described in Task B. TASI-2006 will have 63 students and 74 lectures by 21 lecturers. (The duration of each lecture is 75 minutes so that the students can ask questions during the lecture instead of having a separate question-hour.) There are 15 mini-courses each with three/five lectures on sub-fields.

The plans for TASI 2007 are still being discussed. It is very likely it will emphasize formal and phenomenological aspects of string theory and will cover experimental and theoretical aspects of TeV and neutrino physics.

The local organizing committee includes S. P. (Shanta) de Alwis, Thomas DeGrand, Oliver DeWolfe, Anna Hasenfratz and K.T. Mahanthappa. TASI Scientific Advisory Board of 2006 consists of J. Bagger (Chair), G. Feldman, J. Lykken, A. Nelson, N. Seiberg, J. Womersley and K.T. Mahanthappa.

Some of the important goals of TASI are:

(i) Introduce advanced graduate students in particle theory to a much broader range of topics than they normally experience at their home institutions while working on their dissertation topics and

(ii) Provide an atmosphere which facilitates intense interaction between students and lecturers, and among students themselves. For example, in addition to lectures, there are student-organized seminars in the evening. The interaction between students and lecturers is enhanced by the majority of lecturers staying in the student housing. [In the past there have been quite a few cases of student interaction at TASI leading to collaborative publications.] TASI has been very highly successful in fulfilling these goals as evinced by the comments of past TASI participants and by the excellent reviews of Mahanthappa's five-year (2003-2007) proposal approved by NSF, and it also had strong support by reviewers of past three-year DoE proposals. TASI has become an asset in training younger generation of theoretical particle physicists. It has come to be known as one of the best, if not the best, summer schools in the World in the field.

World Scientific of Singapore is the publisher of our proceedings.

A list of names of the lecturers and topics for TASI-06 is given below. We expect the proceedings to come out in late Spring of 2006.

LECTURERS AND COURSE TITLES

- K.Agashe (Syracuse) - Extra Dimensions
- K.Babu (Oklahoma State) - Supersymmetric Models
- M.Battaglia (LBL) - International Linear Collider
- J.Beacom (Ohio State) - Astrophysical Aspects of Neutrinos
- Z.Bern (UCLA) - QCD
- M.-C.Chen (FNAL) - Leptogenesis
- J.Conrad (Columbia) - Experimental Aspects of Neutrinos
- J.Conway (UC Davis) - Experiments at LHC
- S.Dawson (BNL) - Introduction to the Standard Model
- K Dienes (Arizona) - Strings
- S.Dodelson (FNAL) - Cosmology
- K.Ellis (FNAL) - Collider Physics
- G.Fuller (UCSD) - Neutrino Astrophysics
- B.Kayser (FNAL) - CP Violation and Neutrinos
- M.Lindner (Munich) - Long Base Line Neutrino Experiments
- R.Mohapatra (Maryland) - Neutrino Theory
- M.Peskin (SLAC) - Introduction to Supersymmetry
- D.Rainwater (Rochester) - Searching for the Higgs Boson
- T.Rizzo (SLAC) - Extra Z Bosons
- A.Smirnov (ICTP) - Neutrino Phenomenology
- P.Vogel (CalTech) - Neutrinoless Double Beta Decay

Budget

TASI has been supported by NSF and DoE on almost fifty-fifty basis since 1989. For TASI 2006 year the respective shares were \$58,000 (NSF) and \$57,000 (DoE). For TASI 2007 we request \$59,000 from DoE; with inflation of 3% the requested amounts for 2008 and 2009 are \$61,000 and \$63,000 respectively. Please note that the most of the cost is to support travel and local expenses of lecturers and local expenses of participants. The costs have gone up, and inadequate budget would affect the quality of the Institute.