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THEORETICAL HIGH ENERGY PHYSICS RESEARCH AT
THE UNIVERSITY OF CHICAGO

Progress Report
for period October 1, 1992 - April 30, 1993

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TECHNICAL PROGRESS REPORT
Theoretical High Energy Physics Research
at the University of Chicago

I. INTRODUCTION

The present contract supported work by **Jonathan L. Rosner** (principal investigator), **Emil J. Martinec** (co-investigator) **Robert G. Sachs** (co-investigator), Research Associates **Peter Bowcock** and **Glenn Boyd**, and graduate students in elementary particle physics at the University of Chicago.

The present report deals with work performed during the last eight months of Calendar Year 1992 and the first four months of Calendar Year 1993. For earlier work, see previous Technical Progress Reports.

Prof. **Mark Wise** of the California Institute of Technology visited the Theory Group during July of 1992. His visit was supported in part by the Enrico Fermi Institute.

Dr. **Nikolai Uraltsev** of the Petersburg Institute of Nuclear Physics (Gatchina) visited the Theory Group at Chicago for the month of April, 1993.

He discussed his work and other topics of mutual interest with members of the theoretical and experimental high energy physics groups.

II. RESEARCH ACTIVITIES

A. J. ROSNER, COLLABORATORS, AND STUDENTS

J. Rosner has been invited to prepare a brief history of elementary particle physics for a book, *Twentieth Century Physics*, to be edited by L. M. Brown, A. Pais, and B. Pippard (IOP/AIP, 1994). He is collaborating with Val Fitch of Princeton University on the project. He visited The Technion in October and November of 1992, under the auspices of the U. S.-Israel Binational Science Foundation, with brief visits to CERN, Tel Aviv University, and the Weizmann Institute. During this time he collaborated with Michael Gronau (Technion) and Alex Nippe (CERN) on a method for identifying the flavor of neutral B mesons (see below). He has been supervising the work of graduate students James F. Amundson, Aaron Grant, Gerard Jungman, Emmin Shung, and Mihir Worah.

1. CP violation, Cabibbo-Kobayashi-Maskawa matrix, and B physics.

A review of the CKM matrix has now been published in a book on B decays.¹

Investigations regarding possible quark mass matrices leading to the observed form of the CKM matrix, performed in collaboration with **Mihir Worah**, a graduate student at Chicago, have now been published.² Mr. Worah presented this work at the Division of Particles and Fields Meeting at Fermilab in November of 1992.³

The review of Ref. 1, adapted for the special case of b quark physics and presented at a workshop in Edinburgh in December, 1991, has now

been published,⁴ as has work done at that workshop in collaboration with **Paul Harrison** concerning the information about the structure of the CKM matrix.⁵

In collaboration with **James F. Amundson**, **Mihir Worah**, and **Mark Wise**, a means was devised for testing a suggestion⁶ that b quark decays proceed through a right-handed current. It was proposed that one examine the spectra of leptons emitted in the decays of Λ_b baryons produced at LEP.⁷ The spectrum is softer in the Gronau-Wakaizumi model ($V + A$ couplings at both vertices) than in the standard model ($V - A$ couplings at both vertices). This result was presented at the 1992 DPF Meeting.⁸

Heavy meson decay constants (particularly those of B mesons) enter critically into discussions of CP violation and CKM parameters. In collaboration with **James F. Amundson** and several members of the CLEO Collaboration, a method was proposed⁹ for obtaining these quantities from isospin splittings of D mesons (recently measured with great precision¹⁰) and B mesons (using an extrapolation from K mesons based on the quark model). A suggestion for measuring the decay $D \rightarrow \mu\nu$ using the associated π^0 in $D^{*+} \rightarrow D^+\pi^0$ was made.¹¹ This body of work was described at the 1992 DPF Meeting.¹²

In collaboration with **Michael Gronau** (The Technion) and **Alex Nippe** (CERN), a method was proposed for identifying the flavor of neutral B mesons decaying to CP eigenstates, using the charges of pions produced nearby in phase space.¹³ Discussions were held with experimentalists regarding this method at a workshop on B physics at Fermilab following the 1992 DPF Meeting.

2. *Radiative corrections and electroweak observables*

A review of the impact of various measurements for specification of regions in the (m_t, M_W) plane, prepared for the new section ("Colloquia") of Reviews of Modern Physics, has now been published.¹⁴ Periodic updates of this review have been performed for conference reports at the 1992 DPF Meeting at Fermilab¹⁵ and for a conference on neutral currents at Santa Monica, California, in February of 1993.¹⁶

3. *Heavy quark symmetry*

Work performed in collaboration with **J. Amundson**, a graduate student at Chicago, regarding patterns of deviations from heavy quark symmetry in charmed particle decays, has now been published.¹⁷ This work was described by Mr. Amundson at the 1992 DPF Meeting.¹⁸

A study of mass splittings in mesons containing a single heavy quark (c or b) was performed in collaboration with **Mark Wise**. It was shown that the photons emitted in the decays $B_s^* \rightarrow B_s \gamma$ and $B^{*0} \rightarrow B^0 \gamma$ are expected to have the same energies to better than 1 MeV.¹⁹ This work was described briefly at the 1992 DPF Meeting.¹²

In collaboration with **James F. Amundson**, **Glenn Boyd**, **Mark Wise**, and authors at other institutions, the radiative decays of D^* mesons were examined within the framework of heavy quark and chiral symmetry.²⁰ Experimental data on these decays were analyzed to provide constraints on the $D^* D \pi$ coupling.

4. *Heavy meson spectroscopy*

In collaboration with **Aaron Grant** and **Eric Rynes** (formerly a senior thesis student at Chicago), a study was performed of the optimum power-law potential $V = \lambda r^\alpha$ which can describe both $c\bar{c}$ and $b\bar{b}$ systems.²¹ A small

negative power was found to provide the best fit to the data. This work was described by Mr. Grant at the 1992 DPF Meeting.²²

Work with **Aaron Grant** on the relative strengths of electric dipole transitions with $\Delta L = 1$ between states with various numbers of nodes in the radial wave function was published.²³ The suppression of the decay $\Upsilon(3S) \rightarrow \chi_b(1P)$ was found to be an example of much more general behavior. Mr. Grant reported on this work at the 1992 DPF Meeting.²²

5. *Composite models of quarks and leptons*

A study of a composite model of quarks and its implications for the CKM matrix, mentioned in last year's Technical Progress Report, has been published.²⁴ In this work, quarks and leptons were taken as composites of spin-1/2 fermions F with charges $\pm 1/2$ and spinless bosons S with charges $-1/6$ and $+1/2$, Higgs bosons were proposed to be composed of $F\bar{F}$, and additional spin-1 $F\bar{F}$ states with isospins $I = 0$ and 1 were predicted to lie in the TeV region.

In a further examination of the model, the lightest families of quarks and leptons were identified as linear combinations of $F\bar{S}$, $FSSS$, and $FSS\bar{S}\bar{S}$, bound into singlet of a superstrong SU(4) gauge group. Exotic quarks with charges $Q = (-4/3, -1/3, 2/3, 5/3)$ and leptons with charges $Q = (-2, -1, 0, 1)$ were predicted to have TeV-scale masses.²⁵

6. *Supersymmetric quantum mechanics, inverse scattering, and the vertex operator*

In collaboration with *Aaron Grant*, the connection between two methods for adding a soliton to multi-soliton solutions of the Korteweg-de Vries (KdV) and related equations was studied. One method relies upon a transformation of supersymmetric quantum mechanics; the other makes use of the vertex

operator, which arises in a number of contexts in the theory of integrable systems and in string theory. This work has been submitted for publication.²⁶

7. *Pedagogical efforts*

An article mentioned in last year's Technical Progress Report regarding the connection between quantum mechanics and the Smith Chart, a graph used for antenna impedance matching, was published in the American Journal of Physics.²⁷ In the course of receiving a Referee's Report on this work it was learned that such connections had been noted in the context of microwave research during the 1940's, both in the U. S. and Japan.

In collaboration with **Aaron Grant**, an article has been submitted²⁸ to the American Journal of Physics on classical orbits in power-law potentials, illustrating the relation $(\alpha + 2)(\beta + 2) = 4$ between pairs of potentials behaving as r^α and r^β . Apparently Newton knew of several special cases of this relation; a historical and pedagogical review is given.

At the invitation of L. M. Brown, an article is being written in collaboration with Val Fitch of Princeton University on elementary particle physics in the second half of the twentieth century. This will form a chapter of a book to be published jointly by the Institute of Physics (U. K.) and the American Institute of Physics (U. S.).²⁹

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JIM AMUNDSON

Our work this past year has focused on phenomenological implications of heavy quark symmetry. In one project, we applied heavy quark symmetry to the semileptonic decays of D mesons. This approach, which involves treating the strange quark as heavy, allowed us to extract estimates of the subleading (*i.e.*, $1/m$ suppressed) effects in the heavy quark theory directly from experimental data. We have also used heavy quark symmetry to get estimates of pseudoscalar decay constants and to propose an experimental test of a theory of right-handed b decays. Finally, we used the theory of combined heavy quark and chiral symmetry in conjunction with measured D^* decay rates to place limits on the $D^*D\pi$ coupling.

GLENN BOYD

Most recently, I have examined various existing prescriptions for computing the finite temperature effective potential of a theory. The combinatorics of different resummation methods was analyzed in a toy scalar model, some methods were shown to overcount graphs, and a favored method was presented.

In "Radiative D^* Decay...", (see Ref. 20 on p. 8 and first reference on p. 25) the implications of chiral and heavy quark symmetry for various radiative decays of the D meson were discussed. $SU(3)$ violating corrections were computed, and experimental data was used to constrain the $D^*D\pi$ coupling.

In "Corrections to...", (see p. 27) an infinite class of infrared divergent diagrams contributing to the electroweak effective action was summed. Some derivative corrections were also considered. The phase transition was found to be weakened as a result of these corrections.

AARON GRANT

During the past year I have worked on quantum mechanical potential models of heavy mesons, on classical orbits in power law potentials, and on the relationship between supersymmetric quantum mechanics and certain equations of the Korteweg-de Vries type. In the work on heavy mesons, we used power law potentials to describe the masses, leptonic widths, and electric dipole transition rates of quarkonium systems and other systems containing heavy quarks. We found that many properties of these systems can be described quantitatively or qualitatively using non-relativistic quantum mechanics. In the work on classical orbits, we studied certain transformations that convert orbits in one type of potential into corresponding orbits in a potential of a different type. We used some results obtained here to improve a semi-classical expression for the energy levels in a power law potential. In our work on supersymmetric quantum mechanics, we studied the connection between supersymmetry transformations that add a bound state to a potential, and Bäcklund transformations that add a soliton to a solution of the Korteweg-de Vries equation.

GERARD JUNGMAN

In the past year I have, with T. Gherghetta, finished the analysis of the cosmological constraints on lepton-number violation in $SO(10)$ models with the minimal fermion mass prescription. This work extends, and effectively completes, some earlier work on fermion masses in $SO(10)$. Our improved quantitative understanding of the cosmological constraint has narrowed the window of viability for minimal $SO(10)$ grand unification to effectively one scenario. Note that the survival of the minimal model is slightly surprising, considering earlier work which estimated that the cosmological constraint

was quite severe. The surviving scenario does not give rise to interesting neutrino phenomenology at low energies. Predictive non-minimal models, possessing certain discrete family symmetries, have qualitatively different behaviour, and we are considering the possibilities for such models at present. Preliminary work seems to indicate that there are strong constraints, though of a different nature.

Work with M. Booth has led to interesting constraints on CP-violating dimension eight Weinberg operators, which have received some attention recently. The operators we studied are actually mixed electromagnetic-gluonic operators which are expected to occur on equal footing with the purely gluonic operators which lead to effects such as the electric dipole moment of the neutron. The mixed electromagnetic-gluonic operators can give rise to CP-violating mixing of atomic states due to effective long-range electron-nucleon interactions, and are thus constrained.

EMMIN SHUNG

In the past seven months I have been concerned with techniques for calculating QCD corrections to the decay constants and hyperfine splittings of mesons containing a heavy quark (quarkonia or heavy-light mesons). In particular I have been interested in the portability of techniques used in the study of the QED analogues: positronium and muonium. These include Bethe-Salpeter methods, and non-relativistic QED. The principal concerns are that the QCD binding, unlike the QED binding, is not well approximated by a single scalar quantum exchange; and that at least in heavy-light mesons, the motion of the light meson is relativistic. My work has been to assess the degree to which these obstructions may be overcome.

MIHIR WORAH

Observationally, the possibility that neutrinos are massive is implied by the solar neutrino data, and by the “dark” matter in the universe. I have worked on the implications of neutrino mass on the phenomenology and structure of the Standard Model. I have also studied the possibility that compositeness of quarks and leptons could be an explanation for the observed mass spectrum, family structure, and CP violation in the standard Model.

B. E. MARTINEC, COLLABORATORS, AND STUDENTS

My research in the past year has focussed on three major areas:

1) Models of Black Hole Evaporation

Callan *et.al.* pointed out that a class of scalar+gravity models in 1+1 dimensions shares important features with four-dimensional general relativity: in particular, there is a Schwarzschild-like solution with a horizon hidden behind a classical singularity. Since gravity is renormalizable in 1+1 dimensions, one can attempt to follow the Hawking evaporation process to the point where quantum gravity effects become important, and see whether it is possible to maintain a unitary description of black holes in quantum mechanics. So far no convincing models have arisen from this study; the main difficulty turns out to be that the information stored in conformally coupled matter waves is irretrievable. In addition in some models the evaporation process does not terminate, leading to an instability toward negative gravitational mass solutions. Verlinde and Verlinde proposed an ad hoc modification of the model that reflects the information back into the asymptotic region. Sumit Das and Martinec have studied the semiclassical limit of this model and found that their prescription appears to require a kind of analytic continuation of the dynamics through complex values of the fields, whose interpretation is

unclear.

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2) The Light Cone in String Theory

In quantum field theory, causality is guaranteed by the vanishing of the field commutator at spacelike separation together with the locality of interactions. In string theory, the interaction is not strictly local according to the string center of mass, and the commutator of two string fields had never been examined. Martinec examined the commutator of two string fields in light-front quantization, making a natural ansatz for the corresponding object in covariant quantization. It turned out that the region where the commutator vanishes is not the union of the spacelike regions of the points along the string, but rather a kind of average along the string of the separation interval determines the outcome. This appears to be a major surprise, as it says that the two strings do not have to be entirely in causal contact (as determined by the underlying point manifold light cone structure) in order for the string fields evaluated at those two strings to interfere.

3) Surfaces in the 3D Ising Model

The strong-coupling expansion of gauge theories in four dimensions and spin models in three dimensions is naturally expressed as a theory of fluctuating surfaces, leading to the hope that there might be a dual formulation of these theories in terms of surface dynamics. It has been difficult to find a continuum surface theory that would describe the simplest example, the three-dimensional Ising model. In order to help guide such a search, Martinec, in collaboration with V. Dotsenko, G. Harris, E. Marinari, M. Picco,

and P. Windey, embarked on a numerical study of the properties of the self-avoiding surfaces in the 3d Ising model defined by the phase boundaries between up and down spins. They found two characteristic transitions (well-known in the statistical mechanics community): the standard Ising magnetization transition, characterized by the vanishing of the surface tension; and a percolation transition at a temperature below the Curie point, characterized by the appearance of infinitely large surfaces that dominate the free energy. New information added by the study includes a measurement of the topology of these surfaces (to see if either of these transitions could be understood perturbatively in string theory), as well as a qualitative description of the phase diagram in terms of known properties of string dynamics.

JADWIGA BIENKOWSKA

In the last year I pursued different aspects of $N=2$ SUSY theories, specifically the non-critical $N=2$ superstrings. Due to the momentum freezing effect, these theories can live in a space with $(1,2m)$ Minkowski type signature. The $N=2$ non-critical strings have an infinite number of negative norm states; however, we can truncate the spectrum of the states of the theory to the subset with positive norm and zero $U(1)$ charge ("tachyons"). For example, this truncation is natural in the model with one spatial dimension of the target space compactified on a circle with a given radius. I have calculated the tree level scattering amplitudes of the zero charge ("tachyon") states in the $N=2$ noncritical strings model and found that the propagating states are also "tachyons" as expected from charge conservation.

I have also studied 2D gravity and particularly the Liouville model. I have quantized the Liouville model, defined on the affine Minkowski space in light-cone coordinates. The quantum theory can be fully expressed in terms

of the operators of a free pseudo-scalar field and is consistent with conformal algebra properties. The light-cone formulation greatly simplifies the analysis of the Liouville model. This approach can be readily applied to quantize the Callan, Giddings, Harvey and Strominger (CGHS) model of evaporation of a two-dimensional black hole. Recently Bilal and Callan and also de Alwis have shown the equivalence of the CGHS model to the Liouville-like model.

PETER BOWCOCK

My research has centered on studying the symmetries of two-dimensional conformal field theories. Following work on a Lie algebraic characterisation of extended conformal algebras, I applied these ideas to classify extensions of the Virasoro algebra by fields of spin-1 and spin-3/2. The study revealed a number of new superconformal algebras which were constructed explicitly. In order to understand to what extent one could rigorously define conformal field theories we extended the work of Bauer, Itzykson and Zuber who explained how one used null vectors of the Virasoro algebra to solve explicitly for the operator product expansion and null vectors associated to Virasoro primary fields. Our work explained how to proceed analogously for more general W -algebras, although for simplicity we concentrated on the specific algebra W_3 . At present I am completing a work on the representation theory of W -algebras obtained from generalised Hamiltonian reductions. This is a very general class of algebras and a proper understanding of the representation theory is crucial for constructing the appropriate conformal field theories.

ALBION LAWRENCE

The subject of Lawrence's research has been string quantization in a black hole spacetime background. The object of study is the linearized ap-

proximation of a single string “attached” to a Schwarzschild black hole in an arbitrary space-time dimension. The first issue that was addressed was stability: One finds that the solutions to the equations of motion for the small fluctuations around a long, straight radial string are stable to small perturbations. Currently the program is continuing with the Becchi-Rouet-Stora-Tyutin (BRST) quantization procedure in conformal gauge.

C. R. SACHS, COLLABORATORS, AND STUDENTS

1. *A resolution of the strong CP problem (R.G.S.)*

The strong CP violation (sCPv) associated with QCD raises a number of questions concerning the physical interpretation of the theory. As reported over a period of several years I have made an attempt to resolve the principal question of the meaning of sCPv but have found that what I thought was a resolution of the problem has simply raised new issues of interpretation. I summarize below the essential issues and my resolution of them that has now been resubmitted to Phys. Rev. D. [1]

The sCPv is associated with a parameter θ which characterizes the topological properties of the gauge fields and is usually referred to as a “new physical constant.” The parameter is one of those specifying the eigenstates $|\theta, q\rangle$ of the unitary gauge transformations which serve as basis states of the functional Hilbert space of the quantum field theory. In general all of the basis states and associated matrix elements can be constructed by applying the field operators to the vacuum states $|\theta, vac\rangle$.

The first question of principle arises at this point. The axioms of quantum field theory on which this construction of states is based include the requirement that the vacuum state be non-degenerate. But the state $|\theta, vac\rangle$ is well-known to be degenerate with the state $|- \theta, vac\rangle$. This problem is

resolved by invoking the superselection rule associated with the gauge invariance: All matrix elements of gauge invariant operators between states associated with different values of θ must vanish. Therefore the sector of the Hilbert space associated with one value of θ is kinematically and dynamically isolated from all other sectors. The usual assumption is that there exists just one such sector in the Universe, the one associated with the value of “the new physical constant,” θ . This, then, is an assumed boundary condition selecting one sector from among all possible sectors representing mathematical solutions of the problem.

This assumption overcomes the degeneracy problem by asserting that, although the state $|\theta, vac\rangle$ is a perfectly good mathematical solution of the equations of QCD, it has no physical existence. Because of the superselection rule it is possible to establish the fundamental cluster decomposition theorem and the associated properties that justify treating any one θ -sector as a complete Hilbert space of a quantum field theory.

The next fundamental question concerns the meaning of parity. “Strong CP violation” really means P and T violation since the theory shows that it leads to an electric dipole moment proportional to $\sin \theta$. Since P is violated the question arises: Is the remarkable success of parity selection rules for hadron transitions (e.g. isomeric transitions of nuclei) evidence that θ is a very small number?

The answer is in the negative because selection rules relate to the parity *difference* between states and the strong P violation is a property of the vacuum state which cannot change in the transitions because of the superselection rule. The usual selection rules are independent of the properties of the vacuum.

That sCPv is a property of the vacuum state has been shown by con-

structing the unitary operator function of field operators $\mathcal{P}$ which generates the transformation P on the field operators. It turns out that $\mathcal{P}|\theta, vac\rangle = |-\theta, vac\rangle$ so that this operator transforms the physical vacuum into a non-physical vacuum. This shows that $\mathcal{P}$ is not a physical operator. In fact $\mathcal{P}$ cannot be gauge invariant because it violates the superselection rule. The result is consistent with the fact that the parity of the vacuum is not measurable. Only relative parity can be determined but $\mathcal{P}$ cannot be used to determine relative parity because it transforms every physical state into an unphysical state. Nevertheless the origin of sCPv is associated with this unphysical property of $\mathcal{P}$.

In order to define the relative parity of physical states I define an “intrinsic parity” operation as in ordinary quantum mechanics, $P_i|\theta, q\rangle = |\theta, q'\rangle$, where q' is the parity-transformed set of eigenvalues q . Thus P_i is a mapping of the set q onto itself and $|\theta, q'\rangle = \pm|\theta, q\rangle$ defines the physical (intrinsic) parity eigenstates.

The parity selection rules for the matrix elements of parity even or odd operators $O_{\pm}$ are determined by application of $\mathcal{P}$ to the matrix element, an operation that yields

$$\langle\theta, p|O_{\pm}|\theta, q\rangle = \pm\langle-\theta, p'|O_{\pm}|-\theta, q'\rangle = \pm(\pm)\langle-\theta, p|O_{\pm}|-\theta, q\rangle,$$

where $(\pm)$ refers to the relative intrinsic parity of the states $|p\rangle$ and $|q\rangle$. Thus the only non-vanishing matrix elements are either those that are even functions of θ and satisfy the usual parity selection rules or those that are odd functions of θ and satisfy the converse selection rules.

The result is consistent with the fact that, for $\theta = 0$, there is no sCPv and conventional selection rules apply to hadron operators. Thus, in general, the matrix elements of these operators must be even functions of θ , the

conventional (intrinsic) parity selection rules apply irrespective of the value of θ .

On the other hand the diagonal matrix element of the electric dipole moment operator is an odd function of θ so that it need not vanish as required by the selection rules of electromagnetic interactions. This shows that topological strong CP violation, as represented by the predicted edm, is associated with the properties of the vacuum state.

Since strong CP violation associated with $\theta \neq 0$ has been introduced by the *assumption* of a P and T-violating boundary condition, namely that the vacuum state is $|\theta, vac\rangle$, the question can be raised whether there exists an alternative to that boundary condition.

A boundary condition or initial condition prescribing the conditions under which a measurement is made is, in general, best described in terms of the von Neumann density matrix. Since it is the vacuum state that is to be prescribed in QCD and there are two vacuum states leading to exactly the same spectrum for observables, namely $|\theta, vac\rangle$ and $|- \theta, vac\rangle$, the relevant density matrix is the 2×2 matrix $\rho_{vac} = |\theta\rangle\rho_+ \langle\theta| + |- \theta\rangle\rho_- \langle - \theta|$. This density matrix is in diagonal form because of the superselection rule. Also because of this rule ρ_{vac} is constant in time and cannot be changed by any physical process.

The conventional assumption is that ρ_{vac} describes the pure state $|\theta, vac\rangle$, that is, $\rho_+ = 1$ and $\rho_- = 0$. However I propose the alternative, the ideal mixed state, $\rho_{\pm} = \frac{1}{2}$, which is consistent with all principles of QCD. While the former is transformed into $\rho_+ = 0$ and $\rho_- = 1$ by $\mathcal{P}$ and $\mathcal{T}$, the latter is a multiple of the unit matrix and therefore invariant under these transformations. Thus the ideal mixed state provides a P and T-invariant boundary condition. Under this condition the electric dipole moment associated with

θ vanishes.

There remains one more puzzling aspect of the strong CP problem to be considered. It is generally believed that the process of quark mass generation will produce a chiral rotation of the quark mass term in the QCD Hamiltonian, introducing a dynamical source for P and T violation. This effect, which is measured by a chiral phase χ , can be removed from the Hamiltonian by a change of representation having the effect of replacing θ by $\chi + \theta$. Therefore, with the conventional condition, all strong CP-violating effects are measured by a single topological parameter $\chi + \theta$. The two physically distinct effects, a topological boundary condition and an *ad hoc* chiral rotation of the mass, are indistinguishable.

However, the assumption of the alternative boundary condition separates them in a way that makes θ and χ separately measureable parameters. The reason is that the two states represented by ρ_{vac} are then $|\chi + \theta\rangle$ and $|\chi - \theta\rangle$. For example, the electric dipole moment which is proportional to $\sin(\chi + \theta)$ in the conventional theory is now proportional to $\cos\theta \sin\chi$, showing that the strong CP violation is entirely due to the dynamical effect of the chiral rotation of the quark masses.

2. Alternate phenomenological theory of CP violation (R.G.S.)

There is another question that can be raised about strong CP violation: Can it possibly be used in place of the *ad hoc* KM phase to account for the (weak) CP violation that is observed in neutral K-meson phenomena? In principle it could but, in the conventional interpretation of QCD, there is just the one parameter $\chi + \theta$ measuring CP violation and its magnitude is constrained by the experimental upper limit on the edm of the neutron which requires $|\sin(\chi + \theta)| \leq 10^{-9}$. This is much too small a value to account for

the observed CP violation.

One consequence of the added flexibility in the interpretation of QCD introduced by the alternative boundary condition is that this condition is replaced by $|\cos \theta \sin \chi| \leq 10^{-9}$. Therefore the conditions on θ and χ can be separated. For example, if $|\theta - \frac{\pi}{2}| \leq 10^{-9}$, χ is undetermined. Although the constraint on $\cos \theta \sin \chi$ means that any direct CP-violating effect like ϵ' is extremely small, indirect effects like the parameter ϵ , which is the only one shown by experiments to be non-vanishing, may depend on different combinations of θ and χ which are not small. I have been exploring this possibility [2].

Because the W-quark interaction is a vector and axial vector interaction, a chiral rotation of the quark mass does not lead to P or T-violating effects in tree approximation. In particular the chiral effect on the usual box diagram does not contribute to ϵ . I have explored the possibility that the chirally rotated scalar Higgs coupling could make such a contribution to the Higgs box diagram and it does if it is assumed that there are two Higgs doublets. There are contributions proportional to $\cos 2\theta \sin 2\chi$ which can be of order one. However, on the basis of a rough estimate it appears that the double penguin diagram for the Higgs will lead to a much greater P and T-violating effect than the box diagram.

It was pointed out to me by A. Chakrovorty that when the double penguin diagram is considered for the W it also makes a P and T-violating contribution (it is not a tree diagram). Therefore there is the possibility that the observed value of ϵ can be accounted for without invoking the extra Higgs doublet. This effect does not depend on any new parameter other than χ . Therefore ϵ should be predictable in terms of χ but the effect is a delicate one that requires a very careful analysis of the double penguin diagram.

Chakrovorty and I are in the process of carrying out that analysis.

In addition to the consideration of CP violating effects for neutral K-mesons, the effects predicted by this theory for the B mesons are being considered. Rough estimates were carried out [2] for the case of two Higgs doublets and they indicated a possibility for using the B's to make a definitive comparison of this theory with the standard KM model. A final assessment awaits completion of the analysis of the double penguin for the W's.

[1] R. G. Sachs, The Origin of Strong CP Violation

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[2] R. G. Sachs, A Minimal Phenomenological Theory of CP Violating Weak Interactions

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MICHAEL BOOTH

In this past year I have completed a study of CP violating gluonic operators in the Standard Model. I found that in contrast to most other models of CP violation, there is no dimension-six CP violating gluonic operator — it is eliminated by the GIM mechanism. This operator has been found to enhance the EDM in other models; its absence means that the neutron EDM in the Standard Model remains at the level of $10^{-33}e\text{ cm}$.

With G. Jungman I have explored the consequences for atomic P and T violation of certain dimension-eight gluonic-photonic operators. These operators are expected to occur on an equal footing with the dimension-eight gluonic operators which are believed to give a significant contribution to the neutron EDM. We found that current limits on atomic dipole moments place non-trivial constraints on models of *CP* violation.

Most recently I have shown that, contrary to an earlier claim, there is no electric dipole moment of the W -boson d_W to three loop order in the Standard Model. Four-loop QCD corrections are estimated to give $d_W \approx 8 \cdot 10^{-31} e \text{ cm}$ which in turn induces an electron EDM $d_e \approx 8 \cdot 10^{-41} e \text{ cm}$.

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