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Progress Report

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Preface

This progress report includes three tasks—one theoretical for which Dicus and Sudarshan are the principal investigators, and two other experimental for which Ritchie and Lang are the principal investigators. Accordingly it consists of three separate and complete parts, labeled at the top of each page as Task A, Task B or Task C.

Progress Report

of

Task A

Theoretical

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1 Introduction

This progress report of the Center for Particle Physics of the University of Texas at Austin reviews the work done over the past year and is part of the renewal proposal for the period from January 1, 1994 through December 31, 1994.

The senior academic staff of the Center for Particle Physics (Chiu, Dicus, Ne'eman and Sudarshan) has remained the same. Professor Gleeson, Professor Biedenharn and Professor Bohm are also members of the Center but were not part of this grant and all of their support came from other sources. The contribution to the contract research of Bohm and Gleeson is a contribution by the University and is not reviewed here. Professor Ne'eman was in residence for the Spring semester. The Center also has five members who are experimentalists; Jack Ritchie and Karol Lang, whose progress reports form another part of this document, Peter Riley and Jerry Hoffmann who have separate funding, and Roy Schwitters who is on leave as Director of the SSC. The research associate has been Dr. Palash B. Pal. Some of the work reviewed here was by graduate students. Of these, David Bowser-Chao (Dicus) completed his dissertation. Professor G. Bhamathi of Madras University spent the entire academic year visiting the Center as did Dr. P. Morley of QED Research, Inc. Visitors for shorter periods of time (weeks rather than months) were Scott Willenbrock (Brookhaven), S. Nandi (Oklahoma State), X. Tata (Hawaii), Chung Kao (Florida State), Tom Imbo (U. of Illinois at Chicago), Howie Baer (Florida State), Roberto Vega (SLAC), and Vic Teplitz (SMU). All the visitors collaborated with members of the Center and many wrote papers while here which are reviewed in this report. The staff supported by this grant have also benefited from collaborations with many people outside the University as indicated in the following report.

2 Research Report

2.1 Quantum Gravity and Mathematical Physics

2.1.1 QCD

QCD confines color. Forces between hadrons can only be mediated by the exchange of color-neutral systems, quark-antiquark (mesons) or glueballs. All of these, however, represent massive particles and develop Yukawa potentials with ranges of 1-10 fm. For massless color-neutral quanta to exist, there would have to be a gauge symmetry to protect them. The only such protected colorless system is a two-gluon combination forming a “composite” Riemannian metric—in the infrared limit of QCD. It automatically gauges “artificial” diffeomorphisms. This is Ne’eman’s Pseudo-Gravity, renamed “Chromogravity”. Ne’eman was able to sharpen the proof of the existence of this gauge as a corollary of $SU(3)_{color}$. There is no other approach or approximation to QCD which reproduces Regge sequences. In a calculation (DOE-289) of the invariants of the Affine group $SA(4, R)$ and its $SA(3 < R)$ and $SA(2, R)$ subgroups (appearing as Stability subgroups for the Hilbert Space of Hadron states) Ne’eman, Lernke and Pecina-Cruz classified the representations and proved that $SA(4, R)$ *etc. do not impose kinematical constraints (such as the famous “angular condition” in local current algebra), so that the Regge relation $J \sim M^2$ is free to emerge (as it does) from the dynamics.* Ne’eman reviewed and developed the Nuclear Physics applications in DOE-292 and DOE-316.

2.1.2 $SU(2/1)$

Ne’eman has reviewed the predictions of his $SU(2/1)$ theory (DOE-319). The ever rising lower bound for the “top” quark mass, in addition to the same happening to the Higgs mass, fit with the $SU(2/1)$ picture (which predicts a mass of 170 GeV for the Higgs). The Higgs coupling is a gauge and universal coupling, so that it will provide similar masses in its couplings, including Yukawa-type couplings to fermions. Presumably, this is the case for the top quark. The structure has to be studied within the internal superGUT $SU(7/1)$.

2.1.3 Affine Quantum Gravity

In a study with F.W. Hehl, E.W. Mielke, R. Hecht (Cologne) and J.D. McCrea (Dublin) (DOE-315), Ne’eman developed the entire machinery of Noether and Bianchi identities for Affine spacetime. They also developed the formalism for conformal symmetry; with both

Affine and Conformal symmetries acting, the manifold becomes invariant under their closure, namely the Ogievetsky (infinite) algebra, the four-dimensional analog of the Virasoro algebra. This formalism lays the foundations for a future study of Conformal Field Theory in four dimensions (DOE-320).

In quantum models of gravity, it is surmized that configurations with degenerate coframes could occur during topology change of the underlying spacetime structure. Ne'eman and his collaborators have researched this difficulty and found that it can be corrected through a change of transformation properties for the coframe, which does not fulfill in the usual formalism the role of a Yang-Mills type gauge field of the translations, since it lacks the inhomogeneous gradient term under gauge transformations. By explicitly restoring this "hidden" piece within the framework of the affine gauge approach to gravity, Ne'eman and collaborators have shown that one can avoid the metric or coframe degeneracy—which would otherwise interfere with the integrations within the path integral. This is an important advantage for quantization.

2.2 Phenomenology

2.2.1 High Energy Phenomenology

The need to unravel the mechanism for the spontaneous breakdown of electroweak symmetry is one of main reasons for exploring the TeV energy scale at, for instance, hadron supercolliders such as the Superconducting Supercollider (SSC) in the United States and the Large Hadron Collider (LHC) in Europe. In the Standard Model (SM) the breaking of electroweak symmetry is realized by introducing a doublet of spin zero fields which acquires a non-zero value in the ground state. A scalar particle, the Higgs boson is a relic of this method of breaking the symmetry, and can be searched for at colliding beam facilities. The non-observation of a signal for Higgs bosons produced via $Z \rightarrow Z^* + H_{SM}$ in the experiments at LEP has been translated to a lower bound, $m_{H_{SM}} > 57\text{GeV}$ on the mass of the SM Higgs boson, where H_{SM} is the physical Higgs boson of the SM.

Unlike as in the SM, the Higgs sector of any supersymmetric theory contains at least two $SU(2)$ doublets. Within the minimal supersymmetric model (MSSM) the Higgs sector is completely specified by just two doublets h and h' that couple to the $T_3 = \frac{1}{2}$ and $T_3 = -\frac{1}{2}$ fermions, respectively. The physical particles, therefore, consist of two neutral scalars, H_t and $H_b(m_{H_t} < m_{H_b})$, one pseudoscalar (H_p), and a pair of charged bosons ($H^\pm$). At tree level, the masses and couplings of all these particles are completely determined by $\tan \beta = \frac{v}{v'}$

and the mass of any one of the bosons, which we take to be m_{H_p} .

In DOE-302, Dicus, together with H. Baer and Chung Kao of Florida State University and M. Bisset and X. Tata of Hawaii, has made a detailed study of the detectability of Higgs bosons of MSSM, including the case where Higgs decays to charginos and neutralinos are allowed. First, they mapped out regions of MSSM parameter space already constrained by precision data from LEP on Z decays and found that LEP, and even LEP 200, will not be able to cover the whole MSSM parameter space in the search for Higgs bosons.

Hadron supercolliders such as the SSC and LHC will be able to cover most of the remaining parameter space via the conventional search for $\gamma\gamma$, $l\gamma\gamma$, and $4l$ events assuming (along with many other authors) that supersymmetric decay modes of Higgs bosons are not allowed. In many of the regions of parameter space, it is possible that more than one Higgs boson can be discovered, although there are also regions where only one Higgs may be visible. However, a "hole" in the parameter space was found, where none of the Higgs bosons yields an observable signal.

When working within the framework of the MSSM, it is not a realistic assumption to neglect the possibility of supersymmetric decay modes of Higgs bosons. They show that the branching fractions for the heavier Higgs bosons (H_p , H_h and $H^\pm$) into charginos and neutralinos can not only be substantial, but even dominant, for a wide range of MSSM parameters. This necessitates a re-analysis of the case where SUSY decay modes are allowed. It is found that when SUSY decay modes of Higgs bosons are allowed, the regions of parameter space where more than one Higgs boson may be visible are decreased. The "hole" where no Higgs boson is visible also expands, due to the decrease of Higgs boson branching fractions into SM modes. The region where $t \rightarrow bH^+ \rightarrow b\tau\nu$ is potentially visible decreases as well.

They also investigated whether the SUSY decays of Higgs bosons can lead to new modes for detection. It was found to be very difficult to detect H_p or H_h via $2l + \cancel{E}_T$ final states due to large backgrounds from direct WW and $\tilde{W}_1\tilde{W}_1$ production. The most promising case for detecting H_p and H_h via SUSY decays is when $H_{p,h} \rightarrow \tilde{Z}_2\tilde{Z}_2 \rightarrow 4l + \tilde{Z}_1\tilde{Z}_1$, an analogue of the "gold-plated" $H_{SM} \rightarrow ZZ \rightarrow 4l$ mode. Over some substantial regions of parameter space, the $4l + \cancel{E}_T$ mode leads to observable rates if detectors can detect relatively soft isolated leptons. The most dangerous background is direct production of neutralino pairs; however, when the $H_{p,h} \rightarrow 4l + \cancel{E}_T$ signal is large, this background typically occurs at a much smaller rate. The $4l + \cancel{E}_T$ signal can sometimes fill part of the "hole" referred to above, but this is not true in general. An interesting ramification of the $4l + \cancel{E}_T$ mode is that it may allow a mass measurement of the $\tilde{Z}_2$ and $\tilde{Z}_1$ particles, if the decaying Higgs particle mass is

already measured via its $\gamma\gamma$ or $ZZ \rightarrow 4l$ mode; such mass measurements are difficult even in the environment of an e^+e^- supercollider. Finally, it is found that if $t \rightarrow bH^+$ decays are allowed, there exist regions of parameter space where a rare decay of

$$t \rightarrow bH^+ \rightarrow \widetilde{W}_1 \widetilde{Z}_2 \rightarrow b + 3l + E_T$$

may be observable, again, if there exists sufficient detection capability for low p_T leptons ($p_T \sim 2 - 10$ GeV). This would signal the decay of charged Higgs to SUSY particles, and could conceivably allow an m_{H^+} mass measurement, if one already knows $m_{\widetilde{Z}_1}$.

The most direct probe of the electroweak-symmetry-breaking mechanism is longitudinal-vector-boson scattering. The LHC/SSC will provide the first opportunity to study longitudinal-vector-boson scattering. There are other sources of longitudinal-vector-boson pairs at these machines, and one might ask if we could study longitudinal-vector-boson scattering indirectly via the final-state interaction (rescattering) of the vector bosons.

One difficulty with posing such a question is how to separate the effects of the final-state interaction from direct effects. For example, in the process $gg \rightarrow V_L V_L$ ($V = W, Z$; L denotes longitudinal polarization), which proceeds via a top-quark loop, the standard-model Higgs boson couples directly to the top quark as an s -channel resonance. This direct effect is much larger than any effect due to a final-state interaction.

In DOE-305, Dicus, Basdevant (Orsay), Berger (Argonne), Kao (Florida State) and Willenbrock (Fermilab) study a model in which the Higgs boson which appears as a resonance in longitudinal-vector-boson scattering does not couple directly to the top quark, so we can study its effect on $gg \rightarrow V_L V_L$ via a final-state interaction. For simplicity they actually study the process $t\bar{t} \rightarrow V_L V_L$ ($t = \text{top quark}$), which one may regard as a subprocess of $gg \rightarrow V_L V_L$.

The process $gg \rightarrow V_L V_L$ was chosen because it is a large source of longitudinal vector bosons at the LHC/SSC. The process $q\bar{q} \rightarrow V_L V_L$ is also a copious source of longitudinal vector bosons (except for $Z_L Z_L$), but almost entirely in the $J = 1$ partial wave. The model they study has only $J = 0$ resonances, so it does not produce large effects in the latter process. The process $V_T V_{T,L} \rightarrow V_L V_L$ (T denotes transverse polarization) has been shown not to be a large source of longitudinal vector bosons.

One may regard the standard Higgs model as economical, in that it generates both vector-boson and fermion masses via the same mechanism. However, we have no guarantee that nature has chosen this model, so we should keep an open mind regarding the possible manifestations of the vector-boson and fermion mass-generating mechanisms. These two mechanisms could be quite distinct and have very different experimental signatures. This point has recently been emphasized.

Possibly the simplest model in which the vector-boson and fermion masses are generated by separate mechanisms is a two-Higgs-doublet model. One may introduce a discrete symmetry to ensure that only one doublet couples to fermions. If this doublet has a small vacuum-expectation value, it couples only weakly to vector bosons, but with correspondingly enhanced strength to fermions. The neutral scalar boson associated with this doublet unitarizes $t\bar{t} \rightarrow V_L V_L$, but it contributes very little to the unitarization of $V_L V_L \rightarrow V_L V_L$, which is unitarized almost entirely by the neutral scalar boson associated with the other doublet. This model has been considered previously with a rather different motivation. We do not regard this model as a candidate for a fundamental theory, but as the simplest model which embodies the philosophy described above, and useful for suggesting signatures for the vector-boson and fermion mass-generating mechanisms.

In DOE-305 the authors calculate the zeroth partial wave of $t\bar{t} \rightarrow Z_L Z_L$, with the t and $\bar{t}$ of the same helicity. The H_2 resonance, which couples directly to the top quark, produces the expected peak. The H_1 , which does not couple directly to the top quark, produces a dip. Such dips are generic for a final-state interaction which proceeds via a resonance, and are known in hadronic physics. A simple understanding of this phenomenon is gained by noting that the absorptive part of the loop diagrams, obtained via the Cutkosky rules by putting the Goldstone-boson propagators on mass shell, is proportional to the product of the tree amplitude $t\bar{t} \rightarrow V_L V_L$, the vector-boson-scattering amplitude $V_L V_L \rightarrow V_L V_L$ (using the equivalence of the Goldstone bosons and V_L in the limit $g \rightarrow 0$), and a phase-space factor $\beta = (1 - 4M_V^2/s)^{1/2}$. Denoting the tree amplitude by a_B (B = "Born") and writing the vector-boson-scattering amplitude in a unitary phase-shift representation, $\frac{1}{\beta} e^{i\delta} \sin \delta$, we obtain for the full amplitude

$$\begin{aligned} a &= a_B + i\beta a_B \frac{1}{\beta} e^{i\delta} \sin \delta \\ &= a_B e^{i\delta} \cos \delta \end{aligned}$$

Thus the amplitude vanishes at the resonance position, $\delta = \pi/2$. The real part of the loop integral shifts the position of the zero.

A dip in the $V_L V_L$ invariant mass spectrum will be very difficult to observe at the LHC/SSC. There is a large continuum background from $q\bar{q} \rightarrow V_T V_T$ and $gg \rightarrow V_T V_T$ which is typically an order of magnitude larger than the $gg \rightarrow V_L V_L$ continuum. At the H_2 resonance, $gg \rightarrow V_L V_L$ is enhanced such that the signal is comparable to or greater than the background. However, a dip in the $gg \rightarrow V_L V_L$ process near the H_1 mass will be

difficult to distinguish on the large continuum background. Furthermore, the H_1 will appear as a resonance in longitudinal-vector-boson scattering, so one would have to separate this process from $gg \rightarrow V_L V_L$ in order to have any chance of observing the dip in the latter. Such a separation may be possible by tagging the forward jets associated with longitudinal-vector-boson scattering, but it is not one-hundred percent efficient. While the $t\bar{t} \rightarrow V_L V_L$ (via $gg \rightarrow V_L V_L$ at the LHC/SSC) is likely to tell us about the mass-generating mechanism for the top quark, it is unlikely to reveal information on the mass-generating mechanism for the vector bosons via the final-state interaction of the longitudinal vector bosons.

The possibility of producing high-luminosity photon beams by backscattering laser beams from high-energy polarized electrons has prompted theoretical investigations suggesting that the photon fusion processes

$$\gamma\gamma \rightarrow W_L^+ W_L^-, Z_L^0 Z_L^0,$$

can be used to probe the Higgs sector of the standard model. It has also been shown that the photon fusion processes above can be used in the search for ultraheavy fermions at high energy hadron colliders. In either case, the $W_L^+ W_L^-$ and $Z_L^0 Z_L^0$ signals receive large contributions from one-loop diagrams containing $W_L^\pm$, Z_L^0 and Higgs bosons, H .

In DOE-307, Dicus, together with a student, David Bowser-Chao, A. Abbasabadi of Ferris State University, and W. W. Repko of Michigan State University, examine the effect of a strongly interacting Higgs sector on the photon fusion by unitarizing the s -wave amplitudes for $W_L^+ W_L^-$, $Z_L^0 Z_L^0$ and $\gamma\gamma$ scattering using the K -matrix formalism. It is then possible to increase the longitudinal coupling strength $\lambda = g^2 m_H^2 / 8m_W^2$ by varying m_H . Additionally, the Higgs width is introduced in a manner which preserves the Goldstone-boson equivalence theorem.

They find that unitarity corrections to the cross sections for $\gamma\gamma \rightarrow Z_L^0 Z_L^0$ and $\gamma\gamma \rightarrow W_L^+ W_L^-$ are large for $m_H \gtrsim 5$ TeV. Nevertheless, in the large m_H limit there is still a cross section on the order of several femtobarns for either of these processes. This implies that searches for ultraheavy fermions which make use of photon fusion must take into account these sources of gauge boson pairs.

As we have been discussing a knowledge of deviations of vector boson scattering from lowest order electroweak perturbation theory predictions is essential for accurate interpretation of future proton-proton collider results for vector boson production. Toward this end, a number of authors have computed corrections for various values of the Higgs mass using various approaches.

In DOE-302, Dicus and Vigdor Teplitz (SMU and SSC lab) use the N/D method to unitarize the amplitude. The defining property of the method is that, given a potential, it produces an amplitude that satisfies a unitarity condition and has the same discontinuity across the left-hand cut as that of the potential. The unitarity condition is that of elastic unitarity in the two coupled channels, $V_L V_L$ and HH where V_L is a longitudinal vector boson. The HH channel is an important one because the potential rises as m_H^4 , although the effect is damped by the $4m_H^2$ increase of the elastic threshold. However, the H lifetime decreases rapidly (m_H^{-5}) with increasing m_H , casting doubt on the validity and interpretation of HH scattering results.

Dicus and Teplitz adopt the viewpoint that while the H lifetime falls with m_H , HH scattering increases and, at the same time, $V_L V_L$ scattering into inelastic channels rises with the HH intermediate state potentially a major contributor. They thus consider inclusion of the HH intermediate state potentially an improvement over consideration of only $V_L V_L$ elastic scattering. To some extent, effects of inelasticity are independent of the details of the inelasticity. Specifically, the opening of inelastic channels provides increased attraction in the lowest threshold channel so that, at the very least, inclusion of the HH intermediate state should provide qualitative insight.

They show that, for an elementary Higgs of mass less than 1 TeV, N/D unitarization predicts very little nonresonant background in VV scattering below 2 TeV. It is essentially independent of the choice made for the potential in s -wave scattering.

For Higgs masses in the region above 1 TeV, the results do depend on the assumptions about the potential. Assuming that the “correct” potential is the full field-theory tree amplitude, their results are that, in spite of the large values of the potential, the unitarized amplitudes for $m_H = 1.5$ and $m_H = 2$ TeV contain a narrowed Higgs bound state.

On the other hand, if the appropriate potential is that obtained from analytic continuation from high J to $J = 0$ (with a CDD pole for the elementary Higgs) then the (narrowed) elementary Higgs is accompanied, for $m_H \lesssim 1.6$ TeV, by increasingly strong scattering just above the VV threshold. For $m_H > 1.6$ TeV, a bound state develops at the VV threshold and for increasing m_H , the bound state moves to smaller s , eventually becoming a tachyon. A VV bound state would be distinguishable from a low-mass elementary Higgs because its residue would be an order of magnitude greater.

A major feature of the results is the narrowing of the elementary Higgs width. The unitary amplitudes generated by the N/D procedure give widths for the peaks in the $I = J = 0$ amplitude far less than the values predicted on the basis of the potentials.

The next generation pp , e^+e^- , and ep colliders will search for the Higgs boson over a wide range of Higgs masses m_H . Detection of a heavy Higgs ($m_H > 2m_Z$) is considered feasible at the Superconducting Super Collider (SSC) or CERN Large Hadron Collider (LHC) through the gold-plated channel, $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$, and also at the Next Linear e^+e^- Colliders (NLC) through the decay of $H \rightarrow WW$, $ZZ \rightarrow (jj)(jj)$. Beyond the discovery of the Higgs boson and the determination of its mass, the measurement of its coupling to photons is desirable for the information afforded on the Yukawa coupling of the Higgs to the top quark and the existence of ultraheavy new particles. For a heavy Higgs, however, the branching ratio for $H \rightarrow \gamma\gamma$ is too small for accurate experimental measurement of the $H\gamma\gamma$ coupling at the SSC, LHC or NLC.

Proposed $\gamma\gamma$ colliders, based on the underlying next-generation linear e^+e^- colliders, provide both a means of detecting the Higgs boson as well as obtaining information on the $H\gamma\gamma$ coupling, through direct Higgs production via photon-photon fusion. Hard $\gamma\gamma$ collisions at e^+e^- machines can be produced by directing a low energy (a few eV) laser beam at a very small angle α_0 , almost head to head, to the incident electron beam. Through Compton scattering, there are abundant, hard back-scattered photons in the same direction as the incident electron, which carry a substantial fraction of the energy of the incident electron. Similarly, another laser beam can be directed onto the positron beam, and the resulting γ beams effectively make a $\gamma\gamma$ collider.

The heavy Higgs boson may be detected through $\gamma\gamma \rightarrow H \rightarrow ZZ$, W^+W^- , $t\bar{t}$, and $b\bar{b}$. The $b\bar{b}$ mode must contend with large continuum $b\bar{b}$ production by direct $\gamma\gamma$ fusion. The principal difficulty with this channel, however, is that the signal becomes insignificant for $m_H \gtrsim 200$ GeV. The W^+W^- and $t\bar{t}$ channels suffer from immense tree-level continuum backgrounds, and the top-quark has not yet been found, so the study concentrated on the $H \rightarrow ZZ$ decay channel.

Previous work on Higgs resonance production at $\gamma\gamma$ colliders, however, noted the absence of a tree-level background to $\gamma\gamma \rightarrow H \rightarrow ZZ$. The signal is itself a one-loop process, but should be of order α less-suppressed than the production of ZZ through box diagrams. Furthermore, the signal is almost entirely restricted to the interval $m_H \pm \Gamma_H$ in the invariant mass spectrum of $m(ZZ)$ because the Higgs width is very narrow for $m_H \lesssim 400$ GeV; for the visible decay channels, one can further reduce this background by requiring $m(ZZ)$ to be around the Higgs peak. If the continuum production represented the sole background, detection of the Higgs via $H \rightarrow ZZ$ would depend only on the total event rate. One shall demonstrate, however, the presence of additional backgrounds, which come into play when

detection of the gauge boson pair is taken into account. Bowser-Chao and K. Cheung at Northwestern University investigated the feasibility of detecting $H \rightarrow ZZ$ in light of these backgrounds, for the various decay modes of the gauge bosons, in DOE-309.

They showed that direct production of a heavy Higgs at $\gamma\gamma$ colliders offers a feasible discovery mode, provided that the energy of the underlying e^+e^- collider is not too much greater than m_H . Due to the backgrounds principally arising from the immense production of W^+W^- pairs, the optimal detection channel is $H \rightarrow ZZ \rightarrow q\bar{q}\ell^+\ell^-$. Although the continuum background $\gamma\gamma \rightarrow ZZ$ to this process is minimal, large backgrounds arise from the production of $\gamma\gamma \rightarrow q\bar{q}Z, \ell^+\ell^-Z$. An angular cut requiring the quark and charged-lepton pairs to be away from the beam-pipe can drastically reduce these backgrounds. With this acceptance cut and the Z -mass constraints on the quark and charged-lepton pairs, one should be able to discover a heavy Higgs-boson signal for m_H up to 300 GeV at a $\sqrt{s_{e^+e^-}} = 0.5$ TeV e^+e^- collider, assuming a nominal yearly luminosity of 10 fb^{-1} , and up to 350 GeV for a luminosity of 20 fb^{-1} . The upper limit of applicability of this mode is $m_H \lesssim 400$ GeV, for which one requires a luminosity of the order 100 fb^{-1} .

In DOE-006, Bowser-Chao, Cheung, and S. Thomas (also at the University of Texas) considered use of $\gamma\gamma$ colliders to search for charged Higgs. Study of the symmetry breaking sector of the standard model will be a prime target of future colliders. Any enlargement of the sector beyond the single $SU(2)_L$ Higgs doublet of the minimal standard model necessarily involves new physical particles. With two or more doublets, as required in supersymmetric theories, the physical spectrum includes charged Higgs bosons. Technicolor theories can also lead to fairly light charged technipions. In this work, the production and detection of such charged scalars (subsequently referred to as charged Higgs bosons) in the intermediate mass range $m_W \lesssim m_{H^\pm} \lesssim 2m_W$ at proposed high energy $\gamma\gamma$ colliders was considered.

The dominant decay modes depend on the charged Higgs mass, $m_{H^\pm}$. For an intermediate mass charged Higgs boson, the decay mode $H^+ \rightarrow ZW^+$ is not available. With the current limit on the lightest neutral higgs mass, $m_{h^0} > 48$ GeV, the mode $H^+ \rightarrow h^0W^+$ is closed for $m_{H^\pm} \gtrsim 130$ GeV. If LEP II pushes the bound on m_{h^0} to its range of detectability (about m_W), this channel is also closed for $m_{H^\pm} > 2m_W$. The mode $H^+ \rightarrow \gamma W^+$ is absent at tree level and should be correspondingly suppressed. For $m_{H^\pm} < m_t + m_b$, where the top quark mass is assumed to be $m_t \approx 150$ GeV, the mode $H^+ \rightarrow t\bar{b}$ will also be closed. With these assumptions, the dominant decay modes are $H^+ \rightarrow \nu\tau^+, c\bar{s}$. The decay $H^+ \rightarrow c\bar{b}$ is suppressed by the small mixing between second and third quark generations. Decays to other quarks and leptons are suppressed by small masses of the fermions.

To this extent, $\text{Br}(H^+ \rightarrow \nu\tau^+) + \text{Br}(H^+ \rightarrow c\bar{s}) = 1$ over the mass range considered. The three decay modes of the charged Higgs-boson pair, $H^+H^- \rightarrow \nu\tau^+\bar{\nu}\tau^-$, $c\bar{s}c\bar{s}$, and $\nu\tau^+\bar{c}s + c\bar{s}\bar{\nu}\tau^-$ may be used in a complementary fashion to cover the whole intermediate mass range. The last decay mode, where detectable, may be used to determine $m_{H^\pm}$ by reconstructing the invariant mass of the cs system.

The authors considered each mode in turn, including the respective dominant backgrounds. The mixed mode $H^+H^- \rightarrow \nu\tau^+\bar{c}s$, $c\bar{s}\bar{\nu}\tau^-$ was found to offer the most complete coverage for discovery, assuming a reasonable τ identification efficiency and that neither branching ratio is very small. It was also shown that the other two modes could be used for confirmation over a somewhat more limited region of parameter space. If one of the branching ratios is too small for the mixed mode, a charged Higgs could be detected in the remaining mode.

2.2.2 Low Energy Grand Unification

There is a recent realization of the possibility of constructing models where the unification scale could be as low as 10^7 GeV. One such model is based on the gauge group SU(15). The earlier work Palash Pal has shown that unlike the SU(5) model, it does not suffer from the monopole problem, and the gauge hierarchy problem is also much less severe. Pal has shown that such low unification scale is still consistent with known bounds on proton lifetime, neutron-antineutrino oscillation and neutrino mass. With Nilendra G. Deshpande and Evan Keith (both of the University of Oregon), Pal has also applied similar considerations to a larger group SU(16), which includes the possibility of neutrino mass and magnetic moment.

Experimentally, the interesting aspect of the model is that the intermediate scales are low, so that some of the related phenomena might be accessible to the Superconducting Super Collider. Recently, Pal has analyzed the implication of such models on rare K -decays like $K_L \rightarrow \mu^\pm e^\mp$ and $K^+ \rightarrow \pi^+ \mu^\pm e^\mp$. He showed (DOE-312) that the models predict a very rigid upper bound on these modes. The conclusion is true for a large variety of SU(15) and SU(16) model irrespective of the details of the symmetry breaking process. This may provide a crucial experimental test for these models with low scales of grand unification.

2.2.3 Neutrino Physics in a Material Background

This subject has gained a lot of importance since it has been realized that the consideration of neutrino dispersion relations in matter may be crucial in solving the solar neutrino problem.

Pal has recently written a comprehensive review of the solar neutrino problem, which has been appreciated a lot by researchers and newcomers in the field. Now he has been studying neutrino interactions in a material background. He was invited at the Moriond Conference, held in Villars, Switzerland, where he presented a review of the work done in this field. A written version of this talk (DOE-007) will appear in the proceedings of this conference. The general characteristics of the electromagnetic properties of a neutrino in a medium was discussed some time ago and a complete calculation of the leading order neutrino photon vertex was performed by Pal with José F. Nieves (University of Puerto Rico) and Juan Carlos D'Olive (Universidad Nacional Autónoma de México). However, all the implications of this calculation are yet to be discussed. Recently, with José F. Nieves (University of Puerto Rico), Pal showed that neutrinos have a small induced charge when they are in a medium (DOE-012).

2.2.4 Unitarized Models on Higgs Resonance

Higgs mechanism plays a crucial role in the unification electroweak theory. This mechanism also implies the existence of the Higgs particle. So far the Higgs particle has not been found. In the minimal standard model the bare mass of the Higgs is a free parameter. It is related to the coupling in the quartic interaction. It is well known that when the bare mass of the Higgs is large, the coupling is strong and here the gauge interaction of the Higgs and its interaction with fermions are relatively unimportant. The theory for this case is referred to as the strong coupling theory. In DOE-259 and DOE-275, Professors Chiu, Sudarshan and Bhamathi are concerned with the prediction of the unified electroweak theory when the coupling is very strong. At the energy scale of 1 TeV which is significantly above the masses of W and Z , the interaction of Higgs with the gauge bosons is predominantly with the longitudinal components of the gauge bosons. The longitudinal components simulate an isotopic triplet of scalars. One may draw analogy between the interaction among this triplet and that among the pion triplet. For the pion case, there is the $I = S = 0$, sigma resonance. Analogously one may expect the Higgs resonance in the W^+W^- and ZZ channels. Various approaches have been used to investigate the occurrence of Higgs resonance. A partial list would include: the N/D method, the $1/N$ expansion in the $O(2N)$ model, and various "unitarization schemes". For the latter one finds that the Higgs resonance is present in the Padé approximation and is absent in the K-matrix approach.

In DOE-275, Chiu, Sudarshan and Bhamathi constructed a relativistic Hamiltonian model for Higgs resonance. Resonance trajectories are studied as a function of the parameters

of the model. The presence of Higgs resonance over a wide range of parameter values is found. Also it is possible to have Higgs resonance with moderate width, which can be “readily” detected at the supercollider energies. The numerical results of the present model may be used as a phenomenological guide in the search of Higgs in the sub-TeV and TeV region. An optimistic scenario is as follows: Through the interplay between model prediction and measurements, the data confirms one of the line shapes of the present model. This implies the discovery of Higgs resonance and at the same time it also predicts quantitatively the resonance pole position on the second sheet. This work is published in Physical Review D.

Professor Chiu and his student S. Beane have continued their work on extending the chiral perturbation series into the resonance region through the use of unitarization and completeness sum rules. In DOE-306, they consider the scattering of Goldstone bosons in the range of intermediate energies, and in particular focus their attention on the scattering of pions in the ρ -resonance region. The chiral perturbation series is obtained to order E^4 from a chiral $SU(2) \times SU(2)$ invariant effective Lagrangian. At order E^4 , they isolate the low-energy manifestation of heavy particle exchange in the s -channel and find that the contributions of this type to the $I = 1$ and $I = 2$ amplitudes have a one parameter dependence. This observation provides a symmetry rationale for Chanowitz’s recent observation (Chanowitz, preprint LBL-32938 (1992)) that in a chiral model with an explicitly coupled ρ , the $I = 1$ and $I = 2$ channels are strongly correlated. In order to realize, in a quantitative way, the fact that in the resonance region the direct-channel dominates, they make use of a simple and intuitive unitarization scheme. This allows the derivation of a renormalization constant-independent relation for the $I = 1$ and $I = 2$ phase shifts. With the assumption of a ρ -resonance, this relation determines the position of a pole at euclidean momentum in the $I = 2$ channel. Through an analysis based on the theory of redundant poles and the Adler sum rule it is shown that this “tachyon” pole actually represents a physical contribution to the unitary amplitude which accounts for ρ and ϵ exchange in the u -channel.

As an extension of this research, S. Beane and S. Varma (DOE-009) have studied the possibility of the dynamical generation of a P-wave resonance in a strongly interacting linear sigma model with heavy fermions. This work is partially a response to a recent paper by Truong (Truong, Phys. Rev. Lett. **70**, 888 (1993)) which claims that intermediate states involving heavy quarks of a hypothetical fourth generation doublet provide enough binding to generate a p-wave resonance in strong W_L - W_L scattering. As emphasized by Truong, this question is of special interest since precision weak-interaction measurements constrain the spin-1 content of a strongly interacting Higgs sector via the S parameter upper bound.

The existence of a p-wave resonance can therefore exclude a fourth generation of heavy fermions. Beane and Varma argue that the Padé unitarization scheme, which is used by Truong and others, is inconsistent with the dictum that axiomatic principles are devoid of predictive power. In the present context, this dictum translates into the requirement that elastic unitarity alone should not uniquely determine any S-matrix element. A unitarization scheme is constructed that respects this requirement by relegating all predictive power to the neglect of classes of graphs that can be assumed small. This unitarization scheme does not alter the assumed spectrum of intermediate states, and therefore Beane and Varma conclude that elastic unitarity sheds no light on the existence of a heavy fourth generation of fermions.

2.3 Quantum Mechanics and Quantum Field Theory

2.3.1 Solvable Models of Hamiltonian Systems

To study scattering of resonances by particles Professor Sudarshan together with Professor Chiu and Professor G. Bhamathi constructed a Cascade model of interactions involving five fields, two of which (θ, ϕ) are light and the other (A, B, C) are heavy. This model is solvable explicitly. In particular in the three-particle sector $C\theta\phi$ have elastic and inelastic scattering and, in the latter domain, infinite degeneracy. They have found explicit solutions for both the scattering amplitudes and the generalized eigenvectors. These eigenvectors constitute the generalized Möller matrix which is unitary and diagonalizes the interacting Hamiltonian. In the three-particle sector, the eigenmodes of scattering are constructed and Newton's theorem verified. This work, DOE-279, has been published in the Physical Review.

In their solution of the Cascade model, Chiu, Sudarshan and Bhamathi found that the Lippman Schwinger asymptotic conditions need to be generalized when composite particles are included. Mr. Samir Varma, working under the supervision of Professor Sudarshan, has found the solutions to the Rearrangement model with the Hamiltonian

$$\begin{aligned}
 H = & m_A A^\dagger A + m_B B^\dagger B + m_D D^\dagger D + \int \omega \theta^\dagger(\omega) \theta(\omega) d\omega \\
 & + \int \nu \phi^\dagger(\nu) \phi(\nu) d\nu + \int f(\omega) A^\dagger B \theta(\omega) d\omega + h.c. \\
 & + \int f_2(\omega) D^\dagger C \theta(\omega) d\omega + h.c. + \int g(\nu) B^\dagger C \phi(\nu) d\nu + h.c. \\
 & + \int g_2(\nu) A^\dagger D \phi(\nu) d\nu + h.c.
 \end{aligned}$$

with the reactions

$$A \rightleftharpoons D + \phi \quad D \rightleftharpoons C + \theta$$

He is now computing the scattering amplitudes and eigenshifts.

The need to generalize the asymptotic condition is expected to appear in a more significant way in the rearrangement model. This work is carried out also in consultation with Dr. I. Antoniou of the University of Brussels and Professors Chiu and Bhamathi.

2.3.2 Analytic Continuation and Generalized Quantum States and Theory of Neutral Kaons

The method of analytic continuation of the spectrum and the state space of quantum systems discovered by Sudarshan, Chiu and Gorini has been applied to the study of the Lee model and the Cascade model by Professors Chiu and Sudarshan. They have obtained not only resonances poles but also complex branch cuts which can be identified as amplitudes for scattering of resonances of particles. These are shown to be analytic continuation of the amplitude for scattering of a bound state of particles. Various kinds of analytic continuations are described. A general theory of analytic continuation of inner product spaces is presented clarifying that the analytic relation is between dense sets. The choice of the dense sets defines the analytic continuation. The duals, considered as antilinear functionals form the bra vector space $\tilde{\mathcal{G}}$ while the analytically continued space itself $\mathcal{G}$ is a distinct space. It is the dual pairs which are involved in the analytic continuation. This paper, DOE-276, has been published in the Physical Review.

Professors Chiu and Sudarshan have constructed a theory of kaon decay and other systems like $B^0\bar{B}^0$, $C^0\bar{C}^0$ based on analytic continuation and the complex spectral representation of the self-adjoint Hamiltonian of the system. While most of the results are not different from the Weisskopf-Wigner-Lee-Oehme-Yang complex Hamiltonian, there are essential corrections. This is not only for the short-term (Zeno) corrections but also the tiny regeneration of K_s from K_L in the vacuum as earlier suggested by Leonid Khalfin. Another consequence is a refined version of the Bell-Steinberger relation. This work is in course of publication (DOE-296). They have also found that there is a close anathematical connection with the Livsic construction in functional analysis. Some of these ideas were presented in an invited talk (DOE-011) at the Conference on Unified Symmetry in the Small and in the Large at Coral Gables in January 1993. Chiu and Sudarshan have also studied the Lorentz transformation properties of decaying systems beyond the narrow-width approximation usually used to deduce the relativistic time dilation of lifetimes. This work is in progress.

2.3.3 Perturbation Theory on Generalized Quantum Mechanical System

Recently, Petrosky, Prigogine and Tasaki investigated the Friedrich-Lee model based on perturbation theory. They found that the spectrum of the system may be described as a sum of a discrete resonance state and a continuum spectrum along the positive real energy. This conclusion differs from the earlier work of Sudarshan, Chiu and Gorini based on the analytic continuation of the exact solution of the model. There they found that accompanying the discrete resonance state, the continuum spectrum must be defined along a contour in the complex energy plane which passes below the resonance pole. It is curious; what is the origin of this difference?

A closer look reveals two important ingredients in their analysis; first is the use of perturbation theory and second the expansion of the wave function in powers of the imaginary part of the resonance energy. Sudarshan, Chiu and Bhamathi avoided any divergence difficulty by doing perturbation theory in the complex energy plane.

In DOE-310, they present a general formalism for doing the perturbation theory in the complex energy plane where the notion of the generalized quantum mechanical systems is used. This formalism is applied to the Friedrich-Lee model. It reproduces the results of the exact situation where the spectrum of the generalized quantum mechanical system consists of a discrete complex energy pole and a continuum spectrum (which passes below this discrete pole) in the complex energy plane. This spectrum disagrees with the results of Petrosky et al. mentioned above. They also investigate the role of the “complex delta” function in the description of a resonance state. The unboundedness of the spectrum appears to be a necessary condition to give rise to a pure exponential decay.

2.3.4 Coherent States

Sudarshan has studied coherent states associated with shift operators as obtained in deterministic chaos. A weighted shift operator is one which has the following action on a basis $\{e_n, 0 < n < \infty\}$:

$$\eta e_n = f(n)e_{n+1}$$

where $f(n)$ is the weight. The standard creation operators of a harmonic oscillator

$$a^\dagger |n\rangle = \sqrt{n+1} |n+1\rangle$$

has $f(n) = \sqrt{n+1}$. The coherent states labeled by a complex number z are defined by

$$|z\rangle = \sum_n \left(\prod_{m=0}^{n-1} f(m) \right) \eta^n |0\rangle, \quad \eta^\dagger |0\rangle = 0.$$

These states are eigenstates of $\eta^\dagger$:

$$\eta^\dagger |z\rangle = z |z\rangle$$

The range of values z is defined by the convergence of the sum. For $f(n) = \sqrt{n+1}$ all values of z are allowed. For the unweighted shifts $f(n) = 1$, the range is $|z| < 1$. These states called "harmonious states" provide a basis. The theory of these harmonious states and the diagonal representations is presented in a paper DOE-308 which is in course of publication in the International Journal of Theoretical Physics. They are particularly important for the theory of deterministic chaos.

2.3.5 Quantum Group $SU_q(2)$

In collaboration with Professor Babu Joseph of Cochin University of Science and Technology, Sudarshan has investigated the quantum group $SU_q(2)$ and showed that all its representations can be obtained by an "innovation" on the representation of $SU(2)$ Lie algebra has the commutation relations

$$\begin{aligned} [J_-, J_+] &= -2J_3 \\ [J_3, J_\pm] &= \pm J_\pm \end{aligned}$$

while $SU_q(2)$ has

$$\begin{aligned} [J'_-, J'_+] &= \frac{-e^{qJ'_3} - e^{-qJ'_3}}{e^q - e^{-q}} \\ [J'_3, J'_\pm] &= \pm J'_\pm \end{aligned}$$

The innovation consists of realizing

$$\begin{aligned} J'_+ &= g(J_3)J_+ ; \quad J'_- = J_-g(J_3) \\ J'_3 &= J_3 \end{aligned}$$

It is then shown that there exists a $g(J_3)$ such that the $SU_q(2)$ is satisfied. This work is being prepared for publication. When there are many degrees of freedom, the theory is richer and promises interesting applications for corrections to the Debye theory of specific heats and the blackbody Planck spectrum.

2.3.6 Vacuum Polarization by Solitons

Siamak S. Gousheh, working under the supervision of Professor Sudarshan, has been working on vacuum polarization of fermions. He has collaborated with Rafael Lopez-Mobilia on this project. They computed the vacuum polarization of fermions by solitons of any topological charge in $(1 + 1)$ dimensions by a modification of the adiabatic method of Goldstone and Wilczek. They obtained solutions which continuously interpolate between the adiabatic and nonadiabatic regimes and have investigated the effect of the scale of variation of the solitons on the vacuum polarization (VP) that they induce and have verified that energy level crossing occurs only for sharply varying solitons. However, they showed explicitly that in all cases, every time the topological charge (TC) of the system increases by one, one unit of fermion number escapes from the system, thereby showing that the adiabatic results of Goldstone and Wilczek hold even in the nonadiabatic case. Hence they verified that in the adiabatic case $VP = -TC$ for all TC . They, however, obtained the surprising result that even in the nonadiabatic case, the solitons *will* polarize the vacuum provided that they have a high enough TC (although in this case $|VP| < |TC|$). Only the infinitely sharp solitons can never polarize the vacuum. They also showed that during the entire process of building up a soliton of any TC , the total “number” of eigenfunctions of the Hamiltonian is conserved, the total spatial density of the spectrum remains uniform and the eigenfunctions remain complete. Their work, DOE-311, has been submitted to Physical Review for publication.

2.3.7 Other Topics

2.3.7.1 Uncertainty Principle. Steve Maxson, working under the supervision of Professor Sudarshan, has completed work on minimum uncertainty states of a system with two degrees of freedom as correlated states. In DOE-297, Professor Sudarshan investigated the close relationship between the zero point energy, the uncertainty relations, coherent states, squeezed states and correlated states for one mode. This group-theoretic perspective enables the parametrization and identification of their multimode generalization. In particular, the generalized Schrödinger-Robertson uncertainty relations are analyzed. An elementary method of determining the canonical structure of the generalized correlated states is presented. This paper was presented at the Second International Workshop on Squeezed States and Uncertainty Relations at the Lebedev Institute in Moscow in 1992. In this work, the time evolution of these minimum uncertainty states is described generally. The invariance of the uncertainty relations (whether minimum or not) under linear canonical transforma-

tions is shown, and a new representation of the group of canonical transformations of the two-mode oscillator is constructed which uses the quantum correlation coefficients.

2.3.7.2 Homotopy in Classical Dynamics. Panayotis Panayotaros has completed and submitted a thesis on the role of homotopy in classical dynamics.

2.3.7.3 Quantum Envelope of Classical System. Some years ago, Sudarshan had discovered how to embed classical canonical dynamics with n degrees of freedom in a quantum system with $2n$ degrees of freedom by adjoining to the dynamical variables $\{q_j, p_j\}$ also the elementary vector fields $\{\frac{\partial}{\partial q_j}, \frac{\partial}{\partial p_j}\}$. In a paper presented in honor of Susuma Okubo's sixtieth birthday (proceedings edited by Ashok Das, World Scientific, 1992), Sudarshan showed how this quantum envelope of a classical system can be utilized to construct a dynamical theory of measurement. He has also used it to reformulate the Poincaré catastrophe and the problem of deterministic chaos in "Large Poincaré Systems." Much of this work is under preparation for publication. The question is related to the problem of quantum decoherence = whether a pure quantum state can become a mixture under Hamiltonian evolution. Bhamathi and Sudarshan have done some work on this which is being prepared for publication.

2.3.7.4 Cherns-Simons Field Theory. Professor C. R. Hagen (Rochester) and Professor Sudarshan have investigated the quantization of Cherns-Simons field theory on a torus T^2 and find that there is a consistent quantization possible without any quantization of the coupling constant (Rochester preprint UR-1308, DOE-321).

2.3.7.5 Chirality Invariance and $V - A$. Professor Robert Marshak (Virginia) and Professor Sudarshan have traced the ideas of chirality invariance in the context of the V-A Theory in a research review titled "Chirality Invariance and the Universal V-A Theory of Weak Interactions" prepared in honor of the Seventieth birthday of Jaime Tiomno.

Samir Varma finished his work on calculating finite temperature radiative corrections to Compton Scattering and it was published in Phys. Rev. **D46**, 3630.

3 Titles of DOE Reports Since DOE-ER-40200-296

DOE-ER40200-297	Uncertainty Relations, Zero Point Energy and the Linear Canonical Group, by E. C. G. Sudarshan
DOE-ER40200-298	Off-Shell Tree Amplitudes in Hikkó's Closed String Field Theory, by Akinobu Ukegawa
DOE-ER40200-299	Proposal 1993
DOE-ER40200-300	Progress Report 1992
DOE-ER40200-301	Use of Decision Trees and Neural Nets in Top Quark Detection, by David Chao and Debra L. Dzialo
DOE-ER40200-302	The Search for Higgs Bosons of Minimal Supersymmetry: Impact of Supersymmetric Decay Modes, by Howard Baer, Mike Bisset, Duane Dicus, Chung Kao and Xerxes Tata
DOE-ER40200-303	Multilepton Signal With Associated Jets as Signature of a Heavy Higgs Boson at Hadron Supercolliders, by David Bowser-Chao and Duane A. Dicus
DOE-ER40200-304	Status of Rare K Decays, by Jack L. Ritchie
DOE-ER40200-305	Final-State Interaction of Longitudinal Vector Bosons, by S. L. Basdevant, E. L. Berger, D. Dicus, C. Kao, and W. Willenbrock
DOE-ER40200-306	Sum Rule Constraints for Goldstone Boson Scattering in the Resonance Region, by S. R. Beane and Charles B. Chiu
DOE-ER40200-307	The Effects of a Strongly Interacting Higgs Sector on $\gamma\gamma \rightarrow W_L^+ W_L^-, Z_L^0 Z_L^0$ Scattering, by A. Abbasabadi, David Bowser-Chao, Duane A. Dicus, and Wayne W. Repko
DOE-ER40200-308	Diagonal Harmonious State Representations, by E. C. G. Sudarshan
DOE-ER40200-309	Detection of the Heavy Higgs Boson at $\gamma\gamma$ Colliders, by David Bowser-Chao and Kingman Cheung
DCE-ER40200-310	Perturbation Theory on Generalized Quantum Mechanical Systems, by E. C. G. Sudarshan, Charles B. Chiu and G. Bhamathi
DOE-ER40200-311	Vacuum Polarization by Solitons in $(1 + 1)$ Dimensions, by Siamak S. Gousheh and Rafael Lopez-Mobilia
DOE-ER40200-312	K -Decays as a Crucial Test for Unified Models With Gauged Baryon Number, by Palash B. Pal
DOE-ER40200-313	Progress in Gravity, by Yuval Ne'eman
DOE-ER40200-314	Geometric Higgs Fields as $SU(2/1)$ Superconnections, by Yuval Ne'eman

DOE-ER40200-315	Improved Energy-Momentum Currents in Metric-Affine Spacetime, by R. Hecht, F. Hehl, J. Dermott McCrea, E. W. Mielke and Y. Ne'eman
DOE-ER40200-316	QCD Foundations for Hadron Regge Trajectories, by Yuval Ne'eman and Djordje Sijacki
DOE-ER40200-317	Avoiding Degenerate Coframes in an Affine Gauge Approach to Quantum Gravity, by E. W. Mielke, J. Dermott McCrea, Y. Ne'eman and F. W. Hehl
DOE-ER40200-318	Hadrons in an $SL(4, R)$ Classification II. Mesons and C, P Assignments, by Dj. Sijacki and Yuval Ne'eman
DOE-ER40200-319	Universal $SU(2/1)$ and the Higgs and Fermion Masses, by Yuval Ne'eman
DOE-ER40200-320	Setting a Geometry for Four-Dimensional Conformal Fields, by Yuval Ne'eman
DOE-ER40200-321	Comments on "Operator Algebra in Chern-Simons Theory on a Torus", by C. R. Hagen and E. C. G. Sudarshan
DOE-ER40200-322	Progress Report - 1993
DOE-ER40757-001	Proposal - 1994-1996
DOE-ER40757-002	Coupled Channel Vector Boson Scattering in the Method, by Vigdor L. Teplitz and Duane A. Dicus
DOE-ER40757-003	Structure of the Geometric Group, by Joseph Godfrey and Yuval Ne'eman
DOE-ER40757-004	The Geometric Phase in Quantum Physics, by Arno Bohm
DOE-ER40757-005	Classification Theorem for Principal Fibre Bundles, Berry's Phase, and Exact Cycle Evolution by Arno Bohm, Louis J. Boya, Ali Mostafazadeh, and Gerd Rudolph
DOE-ER40757-006	Detecting an Intermediate Mass Charged Higgs at $\gamma\gamma$ Colliders, by David Bowser-Chao, Kingman Cheung and Scott Thomas
DOE-ER40757-007	Neutrino Interactions in Matter, by Palash B. Pal
DOE-ER40757-008	Direct-Channel Dominance in Goldstone Boson Scattering in the Resonance Region, by Silas Beane and Charles B. Chiu
DOE-ER40757-009	Strongly Interacting W 's and Z 's and the Elastic Unitarity Constraint, by S. R. Beane and S. Varma
DOE-ER40757-010	Complex Frequencies, Analytic Continuation and Equivalent Spectra in Generalized Quantum Theory, by E. C. G. Sudarshan
DOE-ER40757-011	Rigorous Quantum Theory of Kaon Decay, by E. C. G. Sudarshan
DOE-ER40757-012	Induced Charge of Neutrinos in a Medium, by Palash B. Pal and José Nieves

Progress Report
of
Tasks B and C
Experimental

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1 Introduction

Calendar year 1993 is the fourth full year of DOE funding of experimental high energy physics research at the University of Texas at Austin. Several milestones were passed during this period (or will be — this report is being written in May, 1993). Among them are the publication of final results from Expt. 791 at the AGS facility at the Brookhaven National Laboratory; this experiment has proved to be the most sensitive search for rare kaon decays ever conducted. An upgrade of this experiment, Expt. 871, is far into the construction phase and an engineering run will be carried out during June and July (1993) at the AGS. Analysis of a side experiment, E888, which used the E791 spectrometer to search for an H dibaryon, is making steady progress. We are also participating on the GEM experiment at the SSC.

These topics are discussed in this progress report. We provide a common progress report for Tasks B and C of this grant, since both of these tasks fund a common experimental program. Much of the discussion in this progress report is redundant with that in our three-year renewal proposal. This is because we believe the renewal proposal needs to be self-contained and that our recent activities are relevant for assessing that proposal.

AGS Expt. 791 has been recently completed. It achieved the best sensitivity for the decays $K_L^0 \rightarrow \mu e$, $K_L^0 \rightarrow e^+e^-$, and $K_L^0 \rightarrow \mu^+\mu^-$ of any experiment to date. Over 700 $K_L^0 \rightarrow \mu^+\mu^-$ events were observed and upper limits on the other two modes, which were not observed, were set near the 10^{-11} level. Our new experiment, E871, of which Ritchie is co-spokesman, will improve on E791 by more than an order of magnitude. E871 is a collaboration of UC Irvine, Stanford, UT Austin, and the College of William and Mary.

Rare kaon decay studies provide some of the most promising opportunities to observe physics beyond the Standard Model and to test the high-order predictions of the Standard Model. An extensive discussion of the physics motivation behind our experiments AGS E791 and AGS E871 can be found in our renewal proposal. A general discussion of experiments in this field can be found in the review of Ritchie[1]. Here, we provide a summary of AGS E791 results and compare them to competing experiments.

At the end of this report, we attach the paper which described our final AGS E791 $K_L^0 \rightarrow \mu e$ result, published recently in Physical Review Letters. We also attach our final $K_L^0 \rightarrow e^+e^-$ paper, which has been submitted to Physical Review Letters. A final $K_L^0 \rightarrow \mu^+\mu^-$ paper exists in the draft form, but has not yet been submitted for publication.

2 Results of AGS E791

In this section, we summarize the results of AGS E791. Much of this discussion also appears in our 1994-1996 renewal proposal.

Three experiments have been active over the last few years in the search for the rare modes $K_L^0 \rightarrow \mu e$, $K_L^0 \rightarrow \mu^+ \mu^-$, and $K_L^0 \rightarrow e^+ e^-$. They were AGS E780, KEK E137, and AGS E791.

AGS E791 was a collaboration of UCLA, UC Irvine, Los Alamos, Stanford, Temple, UT Austin, and William and Mary. It took physics data in three consecutive years of running — 1988, 1989 and 1990. No $K_L^0 \rightarrow \mu e$ or $K_L^0 \rightarrow e^+ e^-$ candidates were found. Table 1 shows, for comparison, the final results for these modes from both AGS E780 and KEK E137, along with AGS E791. Table 2 lists the results on $K_L^0 \rightarrow \mu^+ \mu^-$ for these experiments; to provide some perspective on the progress in this type of research, the older $K_L^0 \rightarrow \mu^+ \mu^-$ experiments are also included in Table 2. As is clear from the tables, E791 was very successful. Our new experiment, E871, will improve upon E791 by more than an order of magnitude.

The AGS E791 spectrometer is shown in Figure 1. The experiment was performed in the B5 neutral beam at the AGS. Protons ($3\text{--}5 \times 10^{12}$ per spill) with 24 GeV in energy were incident on a one interaction length copper target. A neutral beam was defined by a series of collimators centered at a 2.75 degree angle from the incident proton beam direction. Two dipole sweeping magnets removed charged particles from the beam. The decay volume was a region extending from roughly 10 meters from the target to the most upstream drift chamber at 18 meters from the target. Most of the collimation channel and the entire decay volume were under vacuum. The beam volume within the spectrometer was filled with helium. Tracking was performed by 5 drift chamber modules (each module made 2 x and 2 y measurements). The regions between drift chambers were filled with helium to

	AGS E780[2]	KEK E137[3]	AGS E791[4, 5]
$K_L^0 \rightarrow \mu e$ limit	1.9×10^{-9}	9.4×10^{-11}	3.3×10^{-11}
$K_L^0 \rightarrow e^+ e^-$ limit	1.2×10^{-9}	1.6×10^{-10}	4.1×10^{-11}

Table 1: Results from recent $K_L^0 \rightarrow \mu e$ and $K_L^0 \rightarrow e^+ e^-$ searches.

Source	Year	Events	BR (10^{-9})
Clark <i>et al.</i> [6]	1971	0	< 1.8
Carithers <i>et al.</i> [7]	1973	6	14^{+13}_{-7}
Fukushima <i>et al.</i> [8]	1976	3	$8.8^{+10.7}_{-5.5}$
Shochet <i>et al.</i> [9]	1977	16	$8.1^{+2.8}_{-1.8}$
AGS E780 (Schaffner <i>et al.</i>)[2]	1989	8	—
KEK E137 (Inagaki <i>et al.</i>)[10]	1991	179	7.9 ± 0.7
AGS E791[1]	1992	708	6.9 ± 0.4
Unitarity bound	—	—	$\simeq 6.8$

Table 2: Summary of $K_L^0 \rightarrow \mu^+ \mu^-$ experiments.

reduce multiple scattering and particle interactions. Each of the two dipole magnets provided $\Delta p_T \simeq 300$ MeV, but with opposite sign. Downstream of the final drift chamber, a finely segmented scintillator hodoscope, a gas threshold Čerenkov counter, another hodoscope and a large lead glass array followed in sequence. The scintillation counter hodoscopes provided the signals used in the lowest level (fast logic) trigger. The Čerenkov counter also provided a fast signal, corresponding to the presence of an electron, which was used in the low level trigger. The lead glass provided an electron energy measurement which was used for offline $\pi : e$ discrimination. A meter of steel followed the lead glass to stop all particles except muons. Behind the steel, a segmented scintillation hodoscope provided a fast muon signal for the low level trigger. Finally, muons were stopped in a segmented absorber stack with large proportional wire chambers spaced throughout the stack. This “rangerfinder” provided a muon range measurement which corresponds to a 10% measurement of momentum.

High rate capability was achieved by fully-custom high speed front-end electronics[11, 12], a massively parallel readout architecture[13], and a multi-level trigger system. Trigger decisions were made in two stages. A low level fast logic trigger was based on the scintillation counter hodoscopes, the Čerenkov counter, the muon hodoscopes, and meantimer signals from the upstream drift chambers. A high level trigger was based on rudimentary event reconstruction using drift chamber hits. This was carried out in a farm of eight SLAC 3081/E processors[14].

Figure 1: Plan view of the E791 spectrometer.

The event analysis consisted of basically four steps: (1) pattern recognition using drift chamber hits to identify tracks in the spectrometer, (2) fitting the event to obtain the best tracking and momentum information, (3) imposition of particle identification criteria from the Čerenkov counter, lead glass, muon hodoscope and muon rangefinder to classify the event, and (4) imposition of final fiducial-type cuts to insure events were fully contained within the detector volume and that the kinematic measurements were of high quality.

The decay $K_L^0 \rightarrow \pi^+\pi^-$ has the same topology as $K_L^0 \rightarrow \mu e$, is copious by modern standards, and its branching ratio is well known. It is useful as an indicator of detector performance and a heavily prescaled sample is used as the branching ratio normalization. Figure 2 shows a comparison of data and our detector Monte Carlo for parent kaon momentum and vertex z position for $K_L^0 \rightarrow \pi^+\pi^-$ events.

A useful quantity, denoted by Θ_K , is the angle the reconstructed K_L^0 makes with respect to the line from the target to the decay vertex. This quantity will be zero (within measurement resolution) for decays with no missing particles, but will usually be much larger in cases where there is missing transverse momentum due to missed neutrinos. Figure 3 (left box) shows Θ_K^2 versus $\pi\pi$ invariant mass for a sample of $K_L^0 \rightarrow \pi^+\pi^-$ events. A gaussian fit to the mass distribution after a cut requiring $\Theta_K < 1$ mrad, shown in Figure 3 (right box), yields a mass resolution of 1.4 MeV.

E791 recorded data during 1988, 1989, and 1990. The combined data sets yielded a single event sensitivity for the $K_L^0 \rightarrow \mu e$ decay of 1.5×10^{-11} . The sensitivity was measured by counting observed $K_L^0 \rightarrow \pi\pi$ events, which have the same topology as $K_L^0 \rightarrow \mu e$. The detector acceptance for these two decay modes is similar and many systematic effects (such as pattern recognition efficiency) are common to both modes.

Figure 4 shows a scatter plot of the square of the transverse momentum imbalance versus reconstructed mass for $K_L^0 \rightarrow \mu e$ candidates. No events appear in the signal region, allowing a 90% confidence upper limit of 3.3×10^{-11} to be set. This is the lowest sensitivity ever achieved in a kaon experiment. E791 has also searched for and set limits on $K_L^0 \rightarrow e^+e^-$, shown in Figure 5, and observed a large sample of $K_L^0 \rightarrow \mu^+\mu^-$ decays, shown in Figure 6. Figure 7 shows a comparison of data and our detector Monte Carlo for parent kaon momentum and vertex z position for $K_L^0 \rightarrow \mu^+\mu^-$ events. Table 2 gives the E791 measurement of the $K_L^0 \rightarrow \mu^+\mu^-$ branching ratio, along with all measurements from other experiments.

The searches for rare kaon decays, because of their long lifetimes and the extremely small

Figure 2: A comparison of $K_L \rightarrow \pi\pi$ data to Monte Carlo for both parent K_L momentum (top) and the vertex z position (bottom). The solid line is data.

Figure 3: $K_L^0 \rightarrow \pi^+ \pi^-$ events. Figure 4: Scatter plots of the square of the transverse momentum imbalance versus reconstructed mass, for $K_L^0 \rightarrow \mu e$ candidates (1989+1990).

Figure 5: Scatter plots of the square of the angle, Θ_K , between the parent K_L^0 direction and that of the reconstructed K_L^0 versus invariant mass, for $K_L^0 \rightarrow e^+e^-$ candidates (1989+1990).

Figure 6: $K_L^0 \rightarrow \mu^+\mu^-$ events from the full E791 data sample.

Figure 7: A comparison of $K_L \rightarrow \mu^+ \mu^-$ data to Monte Carlo for both parent K_L momentum (top) and the vertex z position (bottom). The solid line is data.

branching ratios to which experiments is now sensitive, are likely to have greater sensitivity to new physics than current searches in heavy meson or τ decays (see for example the review of Marciano[15]). Searches for forbidden muon decays (such as $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$) are complementary to searches in the kaon system, rather than redundant, because kaon decays involve quarks in the initial state (indeed, quarks from different generations). In some models, this difference is important. A search for the kaon decay $K^+ \rightarrow \pi^+ \mu^+ e^-$ provides complementary information to a $K_L^0 \rightarrow \mu e$ search, since the former is sensitive to a scalar or vector current, while the latter is sensitive to a pseudoscalar or axial-vector current. For completeness, Table 3 gives the current experimental limits on a number of possible lepton flavor violating decays and the associated references.

Decay	Branching ratio (90% C.L.)	Reference
$\mu \rightarrow e\gamma$	$< 4.9 \times 10^{-11}$	Bolton et al., 1988[16]
$\mu \rightarrow eee$	$< 1.0 \times 10^{-12}$	Bellgardt et al., 1988[17]
$\tau \rightarrow \mu\gamma$	$< 4.2 \times 10^{-6}$	Cinabro et al., 1992[18]
$\pi^0 \rightarrow \mu e$	$< 1.6 \times 10^{-8}$	Lee et al., 1990[19]
$K_L^0 \rightarrow \mu e$	$< 3.3 \times 10^{-11}$	Arisaka et al., 1993[4]
$K^+ \rightarrow \pi^+ \mu^+ e^-$	$< 2.1 \times 10^{-10}$	Lee et al., 1990[19]
$K^+ \rightarrow \pi^+ \mu^- e^+$	$< 6.9 \times 10^{-9}$	Diamant-Berger et al., 1976[20]
$D^0 \rightarrow \mu e$	$< 1.0 \times 10^{-4}$	Albrecht et al., 1988[21]
$B^0 \rightarrow \mu e$	$< 4 \times 10^{-5}$	Avery et al., 1989[22]

Table 3: Current limits on several lepton flavor violating decays.

3 AGS E871

The UT Austin group has taken a leading role in several areas of E871. For example, the Monte Carlo studies using the Oak Ridge code CALOR89 that were used to investigate a number of beam plug design issues were done by our group. We provided the specialized low-energy neutron and photon detectors that were used to measure leakage from the plug in beam tests at the AGS. (This work is the subject of a NIM article which is in preparation.) Our group is responsible for construction, installation, and support of three detector systems: straw tracking chambers, a lead glass array, and large scintillator hodoscopes for muon identification. We briefly discuss these topics below.

3.1 Plug Studies

A novel feature of AGS E871 is the plan to stop the neutral beam inside the spectrometer. This is accomplished by locating a beam dump, or plug, in the upstream-most dipole spectrometer magnet. The AGS E871 spectrometer is shown in Figure 8. The plug will reduce rates in detector elements downstream of the spectrometer magnet in which it is located, by eliminating K_L^0 decays inside the spectrometer, beam scraping on detector frames, neutron interactions in the gas, etc. The net effect will be clearer particle identification. Also, the enormous reduction in dose to the lead glass (to levels well below E791, even at the increased AGS Booster intensity) will make it possible to re-use that glass. However, leakage from the plug will cause some excess rate in tracking chambers which are close to the plug itself. Therefore, optimization of the plug design is critical to the experiment. We have carried out beam tests of the plug at the AGS in 1991 and 1992. Extensive Monte Carlo simulations, using the Oak Ridge code CALOR89, have been used for some guidance, although our major conclusions are based on experimental measurements.

The plug consists of a core of non-magnetic heavymet, a tungsten-copper alloy of density 18 g/cm³, backed up by copper, and surrounded with 0.5% borated polyethylene, a thin layer of a highly (30%) borated material (trade name Boroflex), and finally by a layer of lead. In some locations, the borated polyethylene is replaced with a composite material containing zirconium hydride. This material provides similar hydrogen density to polyethylene, but has much higher density. This material was tested with beam at the AGS in 1992. The dense

Figure 8: Plan view of the E871 detector.

core attenuates hadronic showers quickly; the polyethylene/zirconium hydride moderates neutrons escaping the metallic core. Once thermalized, neutrons are captured on the boron. The lead prevents the 480 keV photons, produced when the thermal neutrons are captured, from escaping. The nominal depth (in the beam direction) of heavimet was 112 cm, followed by 40 cm of additional copper. The requirement that the plug be narrow in the horizontal x direction, to preserve the E871 acceptance, is what makes the plug design difficult. The nominal width of materials is 30 cm of heavimet, 5 cm of polyethylene on each side, 0.32 cm on Boroflex of each side, and 0.64 cm of lead on each side — making a total width of 42 cm. The beam enters a tunnel before interacting in the plug. The depth of the tunnel is 80 cm; the upstream 50 cm consists of polyethylene layered with lead and the final 30 cm of the tunnel consists of heavimet. During the course of our beam tests, the dimensions of the plug, thickness and type of the shielding materials, composition and size of the tunnel, etc., were varied to gain an understanding of detector rates as a function of the details of plug construction. Figure 9 shows a cross section view of the plug.

Two types of beam test data were taken: data with the E791 spectrometer to measure detector rates in various plug configurations and measurements with specialized detectors to address the specific questions of leakage of soft particles from the plug. The data from which detector rates were measured were taken by triggering the E791 detector with a pulse generator, providing events which were effectively random with respect to any beam associated process. Figure 10 shows the layout of the E791 spectrometer. The plug was located in the 96D40 spectrometer magnet. Data were usually taken with the magnetic field both on (i.e., at a field of about 1.2 Tesla, within 10-15% of the full field planned for E871) and off — and in some cases with the polarity reversed.

The normalization of detector rates to the beam flux onto the plug was done in several different ways. The most reliable is to count two-track vertices (V 's) in the decay volume, using the two upstream E791 drift chambers. This method normalizes to kaon flux, which should be fixed with respect to neutron flux. A limitation of this method is statistical since most pulser tapes contain only a few hundred V 's. Other methods were not statistically limited, but suffered from systematic variations. For example, two scintillation counter telescopes act as 90° monitors for the proton target. While the two telescopes track each other closely, comparisons with other monitors show that they are sensitive to changes in targeting.

Figure 9: Cross section view of the AGS E871 beam plug.

Figure 10: Plan view of the E791 spectrometer used for plug tests. The upstream dipole magnet was not used. The downstream 96D40 dipole, where the plug was located, was run at a field of about 1.2 Tesla — about 10-15% below the full E871 field. The locations at which the neutron and photon detectors were located are indicated by the circles enclosing the letters A, B, C, and D.

The specialized detector measurements were made to investigate the flux and energy distributions of low energy neutrons and photons from the plug. These detectors consisted of:

- Liquid scintillators. Because of the difference in shape of pulses caused by neutrons and photons, these detectors can separate neutrons and photons in the energy range of about 0.1 MeV to 10 MeV for photons and 0.6 MeV to 10 MeV for neutrons. The pulse height spectra can also be unfolded to provide some information on the energy spectra. The liquid scintillators were partly surrounded by plastic scintillators, which provided the ability to veto charged particles.
- Bonner spheres. These are spherical polyethylene neutron moderators which enclose a LiI(Eu) scintillator. By counting thermal neutron captures on the lithium for a series of different sized spheres, it is possible to obtain information on the neutron energy spectrum from thermal energy up to about 25 MeV.
- ^3He counters. These are gas counters which count very low energy neutrons through the interaction $^3\text{He}(n,p)^3\text{H}$, which has a 4000 barn cross section at thermal energy and decreases inversely with the neutron's velocity. In our case, neutrons were observed from thermal energy up to about 20 eV.
- Solid state germanium detector. This detector provides high resolution measurements of photon energy spectra.

Data were taken with these detectors for most of the plug configurations tested. However, the Bonner sphere measurements, which are time consuming, were made only after major plug modifications.

The neutron and gamma detectors were read out with a stand-alone data acquisition system, so that V 's cannot be used to normalize these measurements. However, a number of scalers generated from signals from the E791 detector, as well as the 90° telescopes and other beam associated quantities, were recorded and can be used for normalization and cross checks.

The purpose behind operating the neutron and photon detectors was two-fold: (1) understanding the physics of the plug (for example, comparisons with the CALOR89 Monte

Carlo) requires direct knowledge of the low energy particles escaping the plug and (2) understanding the sources of detector rates is very difficult without knowledge of the fluxes of low energy particles.

Prior to the plug test, we were very concerned about neutrons as a major source of detector rates. We now believe that the interaction of neutrons in detectors is not a problem indicating the basic plug design is highly successful. A strong statement regarding photons is more difficult. Photons in the energy range covered by the liquid scintillators, from about 100 keV up to 10 MeV, do not account for a significant fraction of the rate in drift chambers or scintillators.

Figure 11 shows a scatter plot of ADC pulse heights (from an early short gate and a long late gate) from one of the liquid scintillators. The separation between the neutron and photon bands can clearly be seen. The calibration of these detectors was established with radioactive sources (^{22}Na for photons and ^{252}Cf for neutrons). Since charged particles also register in the liquid scintillators, these counters were operated between two plastic scintillators which could veto charged particles. In addition to vetoing, however, the coincidence of the liquid scintillator with the plastic scintillators could also count the charged particle flux. Therefore, with these detectors we ultimately have measurements of the neutron, photon, and charged particle fluxes — at least over the energy ranges covered by these detectors.

Figure 12 shows the results of a Bonner sphere measurements of neutrons for two configurations of the plug at a location upstream of the plug where one of the E791 drift chambers — DC3 — is normally located; this is the position B indicated in Figure 10. Figure 4 shows the number of neutrons versus energy from thermal energy up to 25 MeV. Also shown for comparison are results of the Monte Carlo simulations.

We can compare the Bonner sphere results to ^3He counters at the low energy end of the spectrum and to the liquid scintillator pulse shape discrimination measurements in the range of 0.6 to 10 MeV. We find in both cases that the agreement is typically good to 25% for the full set of Bonner sphere measurements. Having a full neutron spectrum, it is then possible to estimate detector rates from neutron interactions by integrating the measured spectrum against known neutron interaction cross sections.

The beam tests have given us confidence that we can operate tracking chambers close to the plug. Measurements using E791 detectors have confirmed that rates in particle identification detectors downstream of the spectrometer magnets will be much lower in AGS E871

Figure 11: Pulse shape discrimination of neutrons and photons using the liquid scintillators. The vertical axis is the pulse height from a “prompt” gate, which is 50 ns wide and is timed to coincide with the peak of the phototube pulse. The horizontal axis is the pulse height from a “delayed” gate, which is 100 ns wide and is timed to cover the tail of the phototube pulse.

Figure 12: Neutron flux versus energy as measured with Bonner spheres and predicted by the CALOR89 Monte Carlo for two plug configurations (metal only and fully shielded). The vertical scale gives neutron flux in units of neutrons/cm² per 10¹² protons on target. The horizontal scale is neutron kinetic energy. Both the horizontal and vertical scales are logarithmic.

(even at higher beam intensity) than in E791. These data also provide a unique opportunity to compare actual data on leakage to the CALOR89 Monte Carlo, which is in wide use and is relied upon heavily in many situations for the design of calorimeters, shielding, etc. A full discussion of these measurements will be published in a NIM article, which is in preparation.

3.2 Straw Tracking Chambers

Fine segmentation of drift chamber cells is highly desirable in AGS E871 in order to reduce occupancies to reasonable (about 1% or lower) levels. For the tracking planes near the plug, we are designing and building straw chambers with small diameter straws. We plan to operate these chambers with fast CF_4 -based drift gases. Studies are underway (lead by K. Lang) at UT Austin to design, develop, and test such chambers. Significant progress has been made through a series of prototypes and we expect to converge on the final design in the next few months. A major milestone will be beam tests of 96 channel prototypes at the AGS this summer (June-July, 1993). The straw chamber work is being done in collaboration with Stanford University, which is focusing mainly on the electronics design and fabrication. Table 4 shows the parameters of the currently planned system. More extensive discussion of this project can be found in the Task C section of our 1994-1996 renewal proposal.

3.3 Lead Glass Array

The principle function of the lead glass in E871 is electron identification. The UT Austin group has undertaken to fully refurbish the E791 lead glass for use in E871. This involves: (1) providing a new support frame, (2) replacing low-performance phototubes, (3) curing radiation damaged blocks via UV annealing, (4) rewrapping all blocks, (5) the construction of new phototube bases, including the addition of an amplifier to make muon signals accessible, (6) providing a new laser-based flasher system for drift monitoring, and (7) construction of a new light-tight temperature controlled enclosure to house the array. Most of these tasks are either complete at this time or nearing completion. A subset of the lead glass array will be instrumented for tests during the E871 engineering run during June-July, 1993. Full completion of the lead glass upgrade is expected by early fall.

Category	Value
Straw	5 mm
Straw Material	25 μm Mylar
Adhesive Material	4 μm
Anode Material	1000 Å of Cu
Wire Diameter	20 μm
Straw Material	Au plated W
Straw Winding	copperized 0.5 on clear 0.5 mil
Total Thickness	4.37×10^{-4} of r.l. per view
Gas pressure	1 atm
Max. Drift Time	25 nsec in $\text{CF}_4 - \text{isoC}_4\text{H}_{10}$
<u>Number of Straws:</u>	(per side)
Station I	820
Station II	860
Station III	550
Station IV	1020
Total Number of Straws	6500
<u>Configuration:</u>	close - pack ($x = \text{vertical}$; $y = \text{horizontal}$)
Station I	x, x', x'', y, y'
Station II	x, x', x'', y, y'
Station III	x, x', x''
Station IV	x, x', x'', y, y'
<u>Lengths:</u>	
Station I	$x : 78.0 \text{ cm}; y : 86.3 \text{ cm}$
Station II	$x : 87.0 \text{ cm}; y : 87.0 \text{ cm}$
Station III	$x : 113.0 \text{ cm}; y : - - -$
Station IV	$x : 118.0 \text{ cm}; y : 92.5 \text{ cm}$

Table 4: Main features of proposed upstream tracking chambers based on straw drift tubes.

3.4 Muon Hodoscopes

Six planes of large scintillator hodoscopes have been assembled and installed in the muon rangefinder at different depths. We purchased new scintillator and PMTs for the planes (x and y measuring) which will be used in the trigger and reused the muon hodoscope scintillator and PMT's from E791 for the remaining planes. Since signals from the proportional rangefinder chambers are only latched (rather than sent to TDC's), these scintillators will provide a large improvement in our timing of muon tracks in the rangefinder. The trigger planes have been located at a depth corresponding to slightly less than 1 GeV in muon momentum. This is lower than the corresponding threshold in E791, which was 1.6 GeV, and it results in some increased acceptance (about 10%).

4 BNL Expt. 888

The E871 collaboration was joined by physicists from Princeton, UCLA, and BNL to conduct a search at the AGS in 1992, using the E791 spectrometer, for an H dibaryon. The H is a hypothetical six-quark ($uuddss$) state. The E888 experiment consists of two distinct searches for the H . One uses the E791 spectrometer to look for single $\Lambda \rightarrow p\pi^-$ decays in the neutral beam in the vacuum decay region. These Λ 's could come from H decays such as $H \rightarrow \Lambda n$. This search method is sensitive to H 's with lifetimes in the range of 10^{-7} to 10^{-9} seconds. The second search involves significant rearrangement of the E791 spectrometer and looks for H interactions which produce two Λ 's through diffractive dissociation in an active (scintillator) "dissociator" placed in the neutral beam. This method is sensitive to H lifetimes above 10^{-8} . Analysis is underway and one UT Austin graduate student (B. Ware) is working on this analysis for his Ph.D. thesis.

5 SSC Research

The UT Austin group is part of the GEM (Gammas, Electrons, and Muons) collaboration. The principal goals of the experiment are to emphasize precise measurement of photons, electrons, and muons in SSC interactions. The GEM collaboration has recently submitted its Technical Design Report to the SSC Laboratory. We were involved at an early stage of planning for the trigger system. In the last year, our large AGS E871 construction responsibilities have made it impossible to devote significant effort to GEM. When AGS E871 construction and installation is completed, our GEM activity will increase.

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7 List of Recent Publications

1. "Rare K Decays," J. L. Ritchie and S. G. Wojcicki, to be published in the October, 1993, issue of Reviews of Modern Physics.
2. "Improved Upper Limit on the Branching Ratio $B(K_L^0 \rightarrow e^+e^-)$ ", K. Arisaka *et al.*, submitted to Phys. Rev. Lett.
3. "Improved Upper Limit on the Branching Ratio $B(K_L^0 \rightarrow \mu^\pm e^\mp)$ ", K. Arisaka *et al.*, Phys. Rev. Lett. **70**, 1049(1993).
4. "Status of Rare Kaon Decays", by J. L. Ritchie, Proceedings of the XXVI International Conference on High Energy Physics, (Dallas, TX - August, 1992), in press (preprint DOE-ER40200-304).
5. "High Quality Muon Detection for the SSC", W. X. Gao *et al.*, Univ. of Rochester preprint UR-1240, January, 1992.

8 Recent Invited Talks

Ritchie:

1. Raporteurs talk on Rare K Decays, to be given at the Lepton-Photon Symposium, Cornell, August, 1993.
2. Sambamurti Memorial Lecture, to be given at BNL, July/August. 1993.
3. "Review of Rare K Decays," Invited talk at the 1992 International Conference on High Energy Physics (Dallas, Texas), August 8, 1992.
4. "E871 - Very Rare K_L Decays," Presentation to Dept. of Energy Review Panel, Brookhaven National Laboratory, April 15, 1992.
5. "Progress on Rare K_L Decays," High Energy Physics Seminar, Department of Physics, Indiana University, Feb. 13, 1992.

6. " $K_L \rightarrow \mu e$ ", talk to HEPAP 1992 Subpanel on the U.S. High Energy Physics Research Program, Brookhaven National Laboratory, January 25, 1992.

Lang:

1. "Searches for Rare K_L^0 Decays, presented at the XXVIIIth Rencontres de Moriond, Feb., 1993.
2. "Searches for Rare K_L^0 Decays, presented at the CERN, Feb. 11, 1993.
3. "Searches for Rare K_L^0 Decays, presented at the PSI, Feb. 12, 1993.

9 Recent Publications, Attached

1. AGS E791 final $K_L^0 \rightarrow \mu e$ result, published in February, 1993, Physical Review Letters.
2. AGS E791 final $K_L^0 \rightarrow e^+e^-$ result, submitted to Physical Review Letters.

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