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THE UNIVERSITY OF TEXAS AT AUSTIN

PROGRESS REPORT

ON

"RESEARCH PROGRAM IN ELEMENTARY PARTICLE THEORY"

1980

The Center for Particle Theory
THE UNIVERSITY OF TEXAS AT AUSTIN

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Progress Report
on
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by
E. C. G. Sudarshan
and
Y. Ne'eman
Center for Particle Theory
Physics Department
Austin, Texas

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I. INTRODUCTION

This progress report of the Center for Particle Theory of the University of Texas at Austin reviews the work done over the period of July 1, 1980 to the present day and is part of the renewal proposal for the period from January 1, 1981 to December 31, 1981.

The academic staff of the Center has remained the same. Professor E.C.G. Sudarshan is on leave at Harvard University during this Fall semester. Dr. Tow, who had been a temporary faculty member, left in July to join the staff at Bell Laboratories.

Our research associate status is as follows: Dr. P. Morley, who was here last year, left in August for University of Lancaster, Lancaster, England. Our present research associates are Dr. S. Nandi, Dr. A. Stern, Dr. P. Valanju (also a part-time instructor in the Physics Department), and Dr. M. Gadella who is visiting from Spain.

Our Center has the pleasure to host a number of international visiting scholars. The distinguished Professor John C. Ward from Macquarie University, Australia is visiting for two months during the fall semester and will return next fall. Professor Y. B. Dai of the Chinese Academy of Science, Beijing, China plans to be here from December of this year to next May. Professor C. C. Chiang from Taiwan Normal University has already spent one productive year at the Center here as a visiting scientist. We are very glad that he can stay on for one more year. Professor Samuel Adjei of the University of Science and Technology, Kumase, Ghana, who visited here last year is spending this year at the University of Texas at San Antonio. This is geographically close enough to allow his collaborations with members of the staff to continue.

Finally the Center has also enjoyed the collaboration of several short-term visitors including Professors Parravicini and Gorini of Milan, Pasupathy and Mukunda of Bangalore, Singh of Bombay, Garcia of Mexico, Kielanowski of Warsaw and Kraus of Wurzburg.

II. RESEARCH REPORT

A. Particle Physics in Relativistic Astrophysics and Cosmology

In earlier work of Professor Sudarshan and collaborators on unstable particles, it was found that there is suppression of the decay for very short time intervals. In other words, if a decaying particle is observed in a short time interval, the decay probability is largely suppressed and in the limit that the decaying particle is continuously observed, the particle will not decay at all. This simple observation has an important implication in an interacting many-body system. In the discussion of the S-matrix, we usually consider the situation in which particles come from infinite past and after scattering particles are observed in infinite future. However, for finite time scattering processes, the scattering amplitudes are expected to be different from those for asymptotic scattering processes.

In the treatment of a many-body system the physical vacuum state is not empty but filled with particles with momentum under the Fermi sea. These background particles act as external observers and limit the time for successive scattering. For a superdense many-body system, the time limit for successive scattering can be very short. In this case the scattering matrix should not be the transition amplitude between two asymptotic states but between states separated within the time limit.

To find the properties of a many-body system we may make use of field theoretical technique. We may express physical quantities in terms of Green's functions. The Green's functions for an interacting many-body system are usually computed perturbatively without time limit on the successive virtual scattering processes. For superdense systems such as neutron stars, this kind of relativistic field theoretical treatment has been extensively investigated by Professor Gleeson and collaborators.

As we know, in the nonrelativistic treatment, the particle exchange mechanism can effectively be replaced by potentials. The nonrelativistic treatment of neutron stars has been studied by Baym, Bethe and Pethick and other authors. In relativistic field theoretical treatment, in addition to the particle exchange mechanism, there is important tadpole contribution due to the many-body background of the physical vacuum. It has been noticed

by Gleeson et al. that tadpole contribution is very important in comparison with the exchange mechanism contribution.

In addition to the tadpole contribution in field theoretical treatment, we should also take into account the fact that there is a time limit for successive scattering due to the many-body background. Thus the Zeno effect might affect the properties of a superdense matter such as neutron star.

Professors C. C. Chiang, A. M. Gleeson and E.C.G. Sudarshan and Dr. P. Valanju have investigated the Zeno effect for superdense matter such as neutron star. It is found that if we take into account the Zeno effect, the pressure due to boson exchange mechanism is increased and the pressure due to tadpole contribution is decreased as the density increases. The neutron star mass limit is then higher than that obtained by Baym et al. where only particle exchange mechanism expressed in terms of potential is considered and is lower than those obtained by Gleeson et al. where tadpoles are the main contribution. An important consequence of the Zeno effect in a superdense matter is that when the density approaches infinity the effective nucleon mass approaches the bare mass. This is physically plausible since for a system with infinite density there is no time for virtual scattering to take place and therefore there is no modification for the mass. The results of this work are presented in the Ph.D. dissertation of Dr. Valanju and are also in preparation for publication.

On relativistic heavy ion collisions, Professor Gleeson and Dr. Raha at Marburg, Germany, has completed their study of shock waves generated in nuclear matter by the collision of relativistic heavy ions. They have now modeled the finite size effects and produced temperature and angular distributions which are consistent with current experiments. Better experiments with heavier beam particles will test this approach more completely. This work is now written up and will appear shortly.

A project which Professor Ne'eman developed at the Center in 1969-72 with Y. Achiman and later with A. Aharony has now yielded useful applications. In it they showed at the time that most kinetic equations require unitarity rather than time-inversion symmetry as basic conditions. They also showed how the microscopic T-violation can interfere with macroscopic

effects.

Following Yoshimura (who first erred at just this point), Wilczek and Zee, Weinberg, Susskind and others have now used grand unification gauge theories to explain the asymmetry in the baryon charge of the universe and the ratio of baryons to photons. In doing these calculations, the Ne'eman-Aharony (1970) results have proved important. Some of the new work was also done at the Center. The various possibilities of baryon decay have been analyzed in a general interest paper (see "A Prognosis for the Photon").

For some time the cosmic mass density has appeared too small to close the universe; however, if neutrinos have mass this conclusion changes. Recently a number of authors have proposed on theoretical grounds that neutrinos should indeed be massive. Furthermore massive neutrinos could solve the "missing light problem," the apparent existence of nonluminous matter necessary for the gravitational binding of galaxies and clusters of galaxies. There have also been some recent experimental indications that neutrinos may have mass. In view of these developments it seems appropriate to reconsider the nature of a closed, cyclical cosmology. In DOE-ER-3992-408, Dr. Dicus, Dr. Teplitz and a graduate student, John Letaw, do this. In particular, they consider the effect on such a cosmology of the idea that protons may be unstable and that the cosmic ratio of baryons to photons may be calculable as long as one assumes that the universe was at one time hotter than 10^{15} GeV. Under these hypotheses they include the effect of entropy generation by stellar burning as well as by proton decay and compute the increase in the cosmic scale length, R , from cycle to cycle. Many others have considered scenarios for the "death of the universe" in both open and closed cosmologies. The new elements of the present work are: (1) taking seriously the possibility that entropy is conserved as the universe passes through its minimum radius, and (2) incorporating the implications of proton decay and the determination of the baryon to photon ratio.

The conclusion is that the universe keeps getting bigger on each cycle and the time for each cycle keeps getting longer. This determination

of the radius and lifetime of the cycles gives a measure of the probability of life in a given cycle since the chance of formation of life would seem to increase like the volume times the available time. In addition, the deceleration parameter rapidly gets closer and closer to its critical value (where the universe would be open but only just barely so), but never reaches the critical value. This offers an explanation for why the deceleration parameter seems to be so close to its critical value today; it is close to that value on almost all cycles (except a few very early ones) and there is nothing unique about the present cycle.

B. Phenomenology of Weak and Electromagnetic Interactions

In DOE-ER-03992-405 Professor Dicus, together with a visiting scholar, Dr. Samuel Adjei of the University of Science and Technology, Kumasi, Ghana, and Professor V. Teplitz of the Arms Control and Disarmament Agency, calculate the predictions of chiral symmetry for threshold production from nucleons by the weak neutral current of $N\pi\pi$ states. The results are applicable to experiments in progress, or in analysis, at several accelerators, for example the bubble chamber experiments of M. Derrick and his group at Argonne, the experiments of M. Murtagh and his group at Brookhaven, and those of P. Steinberg and his group at Fermilab.

Calculating weak dipion production near threshold is made difficult by the fact that strong final-state $N\pi\pi$ interactions are expected to have an important effect on the cross section. In this work, they take final-state interactions into account by making use of relevant results, experimental and theoretical, on strong two-pion production ($\pi N \rightarrow \pi\pi N$). Several authors, including Dicus, have studied the predictions of chiral symmetry for strong production; by comparing these predictions with observed cross sections the final-state $\pi\pi N$ interactions are determined for use in the present work.

An important motivation for the study of $\pi N \rightarrow \pi\pi N$ is the possibility of determining the chiral symmetry breaking parameter, ξ . ξ is fixed by the chiral transformation properties of the terms in the πN phenomenological Lagrangian that break chiral symmetry; because the pion has nonzero mass such terms must be present in the Lagrangian. There are important theoretical reasons for believing that ξ is zero, i.e., that the symmetry breaking term transforms like a chiral 4-vector. Other possibilities, for example $\xi = -2$ (transformation like a chiral tensor) have also been considered.

An important motivation for the present work is to investigate the possibility of determining ξ from the weak dipion production, or conversely, to gain dynamical insight from knowledge of ξ . They show that the predictions of the phenomenological Lagrangian for dipion production are independent of ξ . The final state interaction corrections are, however, strongly ξ -dependent; they are also large in certain reactions for both

cases ($\xi = 0$ and $\xi = -2$).

Another product of the present work is to resolve the question of whether these reactions, at threshold, could help fix the relative amounts of vector-isovector, vector-isoscalar, axial-vector-isovector, and axial-vector-isoscalar currents in the neutral current. The answer is that the kinematic restrictions, which must be imposed to ensure the dominance of chiral Lagrangian tree diagrams prevent this, because the one-pion exchange graphs dominate the amplitudes and these are purely axial-vector-isovector.

Ten years ago the known experimental information (partial decay rate, electron-neutrino angular correlations, and the proton, electron, and neutrino asymmetries) on the β decay of the Λ hyperon was used to fit the parameters in the matrix element of the weak, charged, hadronic current. The results were that the Cabibbo model gave a bad fit and that a good fit could only be attained by allowing the parameters to take values several (two to five) standard deviations different than those of the standard model. In DOE-ER-03992-406 Dr. Dicus and Dr. Adjei refit the Λ decay parameters using the current experimental values for the rate, correlation, and asymmetries, and while doing that, improve the theoretical expressions for these quantities. The old theoretical expressions turn out to be quite accurate but the new values of the parameters are quite different due to the improved experimental values. The change in the value of the parameters has been in the direction of bringing them into agreement with the Cabibbo model, but the errors have gotten smaller so that they still differ from the Cabibbo values by about the same number of standard deviations.

The cross section for $\bar{\nu}_\mu + p \rightarrow \Lambda + \mu^+$ depends on the same hadronic matrix element of the weak current as does the decay $\Lambda \rightarrow p + e + \bar{\nu}_e$, and Dicus and Adjei point out that this cross section at high energies, is most sensitive to precisely those parameters which seem to differ the most from their Cabibbo values. Thus measurements of this cross section can provide an independent determination of these crucial parameters.

M1 transitions in particular $p \rightarrow \pi\gamma$ have been investigated using the spectrum generating group (SG) approach which has been developed by Professor Bohm heading an international team of theoreticians (A. Garcia (Mexico), J. S. Nilsson (Goteborg), R. B. Teese (Munich), M. Igarashi, P. Kielanowski,

and J. Werle (Warsaw)). SG has two ingredients: (1) the Werle relation $[P_\mu M^{-1}, SU(n)] = 0$ (M - mass operator) and (2) the group properties of the current operators. (1) and (2) together result in coupling constants that depend upon the internal quantum numbers not only through the Clebsch-Gordan coefficients but also through suppression factors. That such suppression factors must occur for the radiative and leptonic decays of vector mesons has been phenomenologically established at least for $SU(4)$ (cf. e.g. B. G. Kenney, D. C. Peaslee and M. M. Nieto, Phys. Rev. D13, 757 (1976) and references cited there; D. R. Yennie, Phys. Rev. Letters 34, 239 (1976); G. J. Aubrecht II and M. S. K. Raxmi, Phys. Rev. D12, 2120 (1975)). In SG they follow from assumptions that have been fashioned for a different purpose, namely to describe the weak leptonic and semi-leptonic decays. A particular strength of SG is that it is only based upon a minimal set of easily acceptable assumptions, and does not use for its predictions specific internal properties, like magnetic moments of quarks. It was this feature which led to the suggestion of a purely magnetic $SU(3)$ scalar operator in the electromagnetic current, that provided the explanation of the experimental decay rate for $\rho \rightarrow \pi\gamma$.

This explanation of the M1 transitions for vector mesons had been attacked and the experimental value of $\Gamma(\rho \rightarrow \pi\gamma) = (35 \pm 10)$ keV had been doubted. During the past year the theoretical attacks have been proven false. The new measurement of $\Gamma(\rho \rightarrow \pi\gamma)$ gave first (49 ± 10) keV (cf. Lobkowitz et al, presentation at the Tokyo Conference) confirming the old experimental value and when the data were re-analyzed taking various theoretical corrections into account which increase this value, $\Gamma(\rho \rightarrow \pi\gamma) = (67 \pm 7)$ keV was obtained.

This together with the revised value for $\Gamma(\omega \rightarrow \pi\gamma)$ removes the glaring discrepancy between experiment and quark model prediction. However, with the new value for $\Gamma(K^* \rightarrow K^-\gamma)$, the ratio for $\Gamma(K^* \rightarrow K^-\gamma)/\Gamma(K^{*0} \rightarrow K^0\gamma)$ is now slightly off, and its deviation from the quark model prediction goes in the opposite direction than the deviation from $\Gamma(\omega \rightarrow \pi\gamma)/\Gamma(\rho \rightarrow \pi\gamma)$. Therefore $SU(3)$ scalar term cannot correct both, and one may have to take additional purely magnetic $SU(3)$ -tensor operators into account as suggested in Phys. Rev. D20, 1738 (1979). The main experimental support for this idea comes from the recent precision measurements of the hyperon magnetic moments.

The application of the SG approach to the hyperon decay data has been investigated again recently in collaboration with Dr. P. Kielanowski and Prof. J. Werle (University of Warsaw). Kielanowski found an ansatz for the weak hadronic current operator in the framework of the SG approach that does not require a Cabibbo angle for the description of suppression but obtains the suppression as a consequence of the mass differences. The new experimental value for the electron asymmetry α_e in $\Sigma^- \rightarrow ne\bar{\nu}$ (T. A. Romanowski et al) deviates again from the predictions of the Cabibbo model but is close to the value obtained in the SG approach (A. Bohm preprint DOE-ER-03992-402 1980). During his visit in Texas, Kielanowski also made a fit of the quark model and various versions of the bag model (R. L. Jaffe, K. Johnson et al, Phys. Rev. D12, 2060 (1975) and M. V. Barnhill III, et al, Phys. Rev. D21, 1916 (1980)) to the hyperon decay data to check whether the bag models would really be superior to the old quark model. The surprising result was that the bag model corrections do not really lead to the same improvement for the hyperon semileptonic decay as was the case for the baryon magnetic moments.

C. Strong Interaction Physics, QCD and Quark-Parton Physics

It is commonly believed that QCD is a viable candidate for the theory of the strong interaction. The applications of QCD to large q^2 phenomena have been relatively successful. This is presumably due to the fact that there is asymptotic freedom in this region, and hence perturbation theory is applicable. On the other hand, the situation in the small q^2 domain is less clear, where nonperturbative and confinement effects are presumably important. In the absence of a solution to the confinement problem at this point consideration of collision phenomena in this latter region which corresponds to the small p_T hadron production, would necessarily have to appeal to models, where the confinement aspect is taken into account in some phenomenological fashion.

In this connection, Professor Chiu and collaborators have continued to explore the DTU (dual-topological unitarization)-parton model for hadron-hadron and hadron-nucleus collisions. As will be explained later, the DTU-parton model has a number of desirable features as a candidate for the confinement model. During this period, Mr. Tata collaborating with Dr. Takasugi, who is presently in Osaka University in Japan has continued his exploration on the ramifications of the recombination model.

At this stage, we believe that the bootstrap approach to strong interaction, combined with some "constituent" picture, continues to be the most attractive approach in understanding the small q^2 domain data, which constitute the dominant fraction of the strong interaction data at high energies.

Historically the original bootstrap approach advocated by Professor Geoffrey Chew and investigated by many other proponents had once been thought to be orthogonal to the quark model and the field theory approach. However, over the past one and half decades, through the discovery of the notion of duality, quark duality diagrams and dual resonance models and dual resonance field theory, one has found that the two approaches are closely related. In fact often they are complementary to each other. This bootstrap approach in its recently developed form is referred to as the dual topological-expansion and unitarization theory, or in short the DTU theory. This theory has already resolved a number of long standing puzzles: Why is the Pomeron intercept near

one? Why is its slope small? Why the Okubo-Zweig-Itzuka selection rule?... Furthermore, there are suggestive indications that DTU might not be far from the nonperturbative solution of QCD. For instance, the model gives the spectrum of a string, which may very well be the chromoelectric flux tube of QCD. Also DTU predicts a multiperipheral mechanism for multiparticle productions, which is reminiscent of the production due to the breakup of a stretched out string. Also, from the quark duality diagrams and further topological and unitarization considerations, the DTU formalism now has a parton model interpretation. (The DTU framework, plus the detailed parton interpretation is referred to as the DTU-parton model).

Toward the end of last year, Professor Chiu and Dr. Tow and collaborators proposed a DTU-parton model for hadron-nucleus collisions. (ORO-3992-376). To motivate our present progress, we recall briefly this proposal. Within the DTU-parton model, qualitatively, the multiparticles of the pp collision final states predominantly correspond to the tubelets due to the breakup of two flux tubes, one tube tied to the projectile diquark, and the other to the target nucleon diquark. Due to time-dilation effects, the breakup of the flux tube systems takes place over a long laboratory time.

This long lab-time feature gives rise to a new physical situation, when one considers hadron-nucleus collisions, which is not available in hadron-hadron collisions. In particular, there is now the new excited tube-nucleon collision, where, due to Lorentz dilation effects, there is no $q\bar{q}$ pair within the tube during the entire traversal of the projectile-tube system through the target nucleus. Therefore, in a proton-nucleus collision, if there are ν collisions involved, there would eventually be a total of $\nu + 1$ excited tubes in the final state. This simple picture of the DTU-parton model as applied to the proton-nucleus collision has recently been published in the Physical Review Letters.

Since their initial proposal, Professor Chiu and Dr. Tow have extended their model to antiproton-nucleus and also meson-nucleus collisions (DOE-ER-03992-397). From the systematics of topological expansions, they found that the dominant asymptotic contribution for $\bar{p}p$ case corresponds to the production of two tubes: one is substantially longer in the rapidity space than the other. This is in contrast with the pp case where the two

tubes have the same rapidity range. Despite this dissimilarity, they found that upon adding the contributions of all tubelets the inclusive distributions of pp and $\bar{p}p$ collisions turned out to be essentially the same. Furthermore, they demonstrated that within the plateau approximation for the single particle inclusive spectra, the assumption of a certain lower bound for the proper time of pair production would lead to the so-called $\bar{v}$ -universality. More specifically, consider hadron-nucleus collisions with various species of the projectile hadrons and the target nuclei. For each projectile, a companion nucleus is chosen such that quantity v for each pair is fixed at a common value. Then the single particle inclusive distribution for all pairs should be approximately the same.

Professor Chiu has presented the up-to-date summary on the theoretical status and the application of the DTU-parton model for hadron-hadron and hadron-nucleus collisions at the 20th International conference on high energy physics at Madison, last July, (DOE-ER-03992-409). The parton picture of color separation of a dual string and its subsequent breakup was used to motivate the DTU-parton model for high energy-small p_T multiparticle production in hadron-hadron and hadron-nucleus collisions. A brief survey on phenomenological applications of the model; such as the inclusive spectra for various hh processes, central plateau heights, hA inclusive spectra and the approximate $\bar{v}$ -universalities were discussed.

The organization of a "Europhysics Study Conference" at Erice, Italy, on "The small p_T physics" is underway. The tentative plan of the program, communicated by one of the organizers Professor R. Van de Walle of Nijmegen University in the Netherlands, involves CPT representation explicitly in more than one way. Our work on the DTU-parton model in connection with hadron-nucleus collisions will be one of the main topics in Professor Dar's lecture on hadron-nucleus collision models. Our work on the recombination model will be one of the main topics in Professor Hwa's lecture on Recombination models. Professor Chiu has already been contacted to speak on the DTU-parton model.

The DTU-parton model gives specific predictions on the x -spectra both near $x = 0$ and near $x = 1$. In particular near $x = 0$, the spectra have a central plateau, while near the kinematic boundary, i.e. near $x = 1$, a

triple Regge behavior. However, no simple prediction within the DTU framework is available in the intermediate x -region. The recombination model concerns itself with precisely this intermediate kinematic region.

Historically, the idea of correlating the quark structure functions in a hadron with inclusive low p_T single particle x spectra was first seriously considered by Van Hove and Pokorski. Then Ochs pointed out an intriguing similarity between the x distribution of the valence quarks in a proton, as obtained from the deep-inelastic data, and the single meson inclusive spectra in the proton fragmentation region. Das and Hwa subsequently developed a quantitative model based on a quark recombination mechanism which correlates the quark structure function to the single meson inclusive spectra. The major drawback of their approach was that the calculation of inclusive multimeson spectra required the introduction of rather ad hoc correlation factors into the multiquark structure functions (MQSF^S) of the hadrons.

Impressed by the simplicity of the recombination picture, Professor Chiu, together with Dr. Takasugi, Dr. Kaul and Mr. Tata, initiated a program to improve on the Das-Hwa formulation of the model with a view of applying it to the study of momentum correlations in multiparticle inclusive spectra. This led to the formulation of the generalized Kuti-Weisskopf (KW) model for the MQSF^S. In this model, the partons inside the hadron are considered to be uncorrelated except for overall momentum conservation. The MQSF^S are calculable without any ambiguity. This work which was published last year in the Physical Review D (ORO-3992-356) laid down the general framework for further exploration of the model.

In a subsequent paper, (Takasugi and Tata, ORO-3992-359) it was shown that the generalized KW model led to new power-counting rules for inclusive multimeson production in the fragmentation domain of colliding hadrons. Also, the parameter free predictions for two-pion inclusive production by pp collisions were in agreement with the UCLA-Saclay data.

The generalized KW method enabled Mr. Tata and Dr. Takasugi (who had moved to the University of Oregon and has since moved to the University of Osaka) to bring baryon production within the scope of the recombination model (Takasugi and Tata, ORO-3992-378). They used the proton MQSF of their earlier papers to extract the three-body recombination function from the $p \rightarrow \bar{p}x$ data

obtained at Fermi lab. Once again, they found that their results were insensitive to the details of the recombination function. They pointed out that the observed relationship, $\frac{x}{\sigma} \frac{d\sigma}{dx} (\pi^+ \rightarrow pX) \approx 2 \frac{x}{\sigma} \frac{d\sigma}{dx} (\pi^- \rightarrow \bar{p}X)$ was a natural consequence of the combinational factors that arise in the KW model because of the indistinguishable nature of the sea-quarks. Confirmation of this result would be a striking success for the KW method of generating the MQSF.

In recent months, Mr. Tata together with Dr. Takasugi has been examining the implications of the recombination model associated with generalized KW structure functions. They find that the assumed independence of the processes (i) "picking out" a quark system from the parent hadron and (ii) their subsequent recombination to form the produced particles leads to stringent restrictions on the structure functions. They also suggest a justification for the use of the "impulse approximation" for these "long time" recombination processes. (Takasugi and Tata, in preparation). In the same paper, it is pointed out that the use of the valence quark structure function of the proton obtained from the low q^2 e-p or ν -p data, or that the pion valence structure function as obtained from μ pair production data is theoretically suspicious. They have developed a method to extract these directly from the low p_T hadron production data. They have also extracted the intrinsic p_T distributions of the quark inside the proton and the pion. As pointed out earlier, the real test of the recombination model is the multiparticle correlation data. Takasugi and Tata have found that their parameter free predictions for inclusive $\pi\pi$ and πK production from pp collision is in good agreement with the recently available correlation data. They had earlier found that the model also yielded results in agreement with the data on inclusive baryon production in the fragmentation domains of the proton and the pion. They also note that the new power counting rules that emerge from the model are in adequate agreement with the data. It is of interest to note that their predictions for the $(1-x)$ power behavior of the various spectra are, in general, different from those obtained using the dimensional counting rules. Tata and Takasugi are, at present, engaged in carrying out a similar analysis for the kaon case.

In June 1980, Dr. Takasugi reported on the recombinations model associated with the generalized KW model (developed here at the University of

Texas), at the Multiparticle Conference, Brugge, Belgium. He also announced the results of the preliminary analysis carried out by him and Tata, on the structure of the kaon.

The success of the recombination model associated with generalized KW MWSF, together with the fact that the results are rather insensitive to the details of the recombination function, the main dynamical assumption of the model, suggests that the gross features of low p_T hadronic interactions can be simply explained. Excluded from the present analysis, of course, are those reactions where the correlation between the quarks cannot be neglected as done in the KW model. Examples of such reactions are $p \rightarrow pX$ or $p \rightarrow \Lambda^0 X$, wherein two (or more) valence quarks in the parent hadron recombine to form the produced particle. In any event, the extent to which the multiparticle production spectra deviate from the recombination model predictions may be regarded as a measure of the additional dynamics needed to explain these low p_T phenomena.

Next we turn to another aspect of hadron physics, which is related to the application of potential theory in quantum mechanics. In the past several years, nonrelativistic quantum mechanics has been used extensively to study the properties of heavy quarkonium systems. Although the quark anti-quark potential is presumably, of the confining type, it is not known in detail. Thus for example, while the Cornell group has obtained a satisfactory explanation of many of the properties of the charmonium system with a Coulomb plus linear potential, Martin on the other hand has obtained a successful fit to the charmonium spectra with a potential of the type $V(r) = A + B r^\epsilon$ with $\epsilon \approx 0.1$. Although given any $V(r)$, one can at least numerically compute to arbitrary accuracy any quantity of interest, it is worthwhile to ask how much can one learn about the system from a knowledge of the energy levels alone, since these are directly accessible from the experiments. With this in mind, in DOE-ER-03992-423 Pasupathy and Singh derive an exact quantization condition for the energy levels of a particle in a radial potential, assumed finite at the origin. This is used to derive corrections to the semiclassical JWKB quantization condition. They further relate the normalization integral of the wavefunction to the energy derivative of the wavefunction at the origin and use this expression to derive

the corrections to the semiclassical JWKB expressions for the wavefunctions at the origin. An application to the upsilon leptonic decay width is also given.

Both Dr. Nandi and Dr. Stern joined the Center for Particle Theory since the beginning of September. For completeness, we include here some of their recent work in QCD jets, and in extended objects which presumably are models of hadronic systems. Although these papers were completed prior to their coming to CPT, the topics serve to describe some of their initial research interests and the continuation of their work here.

In their work in QCD, Dr. Nandi and collaborators calculated the quantum-chromodynamic correction to jet (defined in the manner of Sterman and Weinberg) angular distribution in energetic e^+e^- annihilation to order α_s . Keeping exact dependence on ϵ and δ , they found deviations from the zeroth-order distribution, $1 + \cos^2\theta$ for relatively large values of ϵ and δ . (See S. Nandi and W. W. Wada, Phys. Rev. D21, 76 (1980)). This effect could be tested in the existing e^+e^- colliding beam facilities. They also studied the gluon jets in proton-proton collisions, using a charmonium model (See G. D. Arbrecht, II, S. Nandi and W.W. Wada, Phys. Lett. 86 B, (1979) 79).

Relativistic extended objects have been of considerable interest in particle theory because of their intimate connections to dual models. Their connections and/or relevance to gauge theories, which are now playing a central role, is more obscure. There is current speculation that extended objects such as relativistic strings may arise naturally in a gauge theory and that they may have some relevance to the question of confinement. In order to further study extended objects in the context of gauge theories, Dr. A. Stern in collaboration with Professor Balachandran (Syracuse) and Dr. Skagerstam (CERN) have developed a minimal interaction for the two systems. Upon coupling extended objects to gauge theories it was found that certain components of the gauge fields were required to vanish. These restrictions gave the extended objects properties which resemble superconductors. It was possible to obtain a dynamical description for electric as well as magnetic superconductors.

The above models were utilized in a study of the phase structure

in QCD. It was verified that a cavity imbedded in a magnetic superconducting region obeys the same dynamics as the MIT bag (with Skagerstam, CERN preprint TH.2793). The claim of 't Hooft that electric and magnetic phases cannot simultaneously coexist was also verified. An additional application was found in a study of glue-ring excitations in the (Copenhagen) QCD vacuum (with Skagerstam, CERN preprint TH.2936). Two spinless excitations with masses of the order of 1.7 and 2.3 GeV were suggested. It was argued that the glue-ring excitations are extremely unstable with a decay width of the order of the excitation energy.

In a separate work Professors Balachandran, Marmo (Naples) and Dr. Skagerstam and Stern (CERN preprint Th.2847) have investigated the coupling of extended objects to antisymmetric potentials $A_{\mu\nu}$ and $A_{\mu\nu\lambda}$. For the case of $A_{\mu\nu}$ the resulting dynamics appear analogous to the behavior of vortices and condensates of vortices in a superfluid. For the case of $A_{\mu\nu\lambda}$ the extended objects represent discontinuities in a nonpropagating scalar field formed from $A_{\mu\nu\lambda}$.

D. Quantum Field Theory, Quantum Mechanics and Fundamental Problems

Recently there have been a number of attempts to construct realistic interaction models based on four fermion interactions. Some authors have in fact allegedly constructed the Standard Glashaw-Salam-Weinberg model from four-fermion interactions alone. In these attempts, the boson fields, such as the gauge fields in the Standard model are treated as a composite system of fermion-antifermion fields. The usual argument to "justify" such an approach is based on the observation that the renormalized Lagrangian for a Yukawa-type of interaction can be identified with that for a fermion self-interacting system, when a composite condition $Z = 0$ is imposed on the Yukawa-type system. We point out that a mere comparison of the $Z = 0$ limits between two theories is not sufficient to ensure the equivalence of these two theories. To demonstrate this point Professor Sudarshan together with Professors Chiang and Chiu has studied in detail two soluble models, the Lee model and the separable potential model. The limit $Z = 0$ in the Lee model is achieved by imposing a finite cutoff in the continuum spectrum of the bare fields and taking the bare coupling to infinity. With the presence of a finite mass bound state below the continuum, the physical continuum extends up to the cutoff energy. And in addition, there is a bound state pole beyond the cutoff. As the bare coupling approaches infinity, the latter pole also approaches infinity.

Now the crucial point to note is that when the extra pole at infinity is included, the Hamiltonian (which is that of the Lee model) differs from that of the separable potential. On the other hand, when the infinity-pole is ignored, the remaining Hamiltonian coincides with that of the separable potential. The interesting point is that at any finite energy both the S-matrix and the wave function for the two theories are identical to each other. However, despite this identity, the two theories have a difference in the spectrum at infinity, which gives rise to different Hamiltonians. Thus we see that the argument of previous authors, which led to the claim of the equivalence, needs to be reexamined. This work is in progress.

Next we turn to investigations of Professor Sudarshan and his

collaborators on the new Dirac wave equation, Relativistic dynamics with world lines, the Heisenberg Condition and action-at-a-distance.

Some time ago, Dirac proposed a new wave equation for a spinless particle of positive energy and a definite mass. One of the problems associated with this new equation is that the particle does not interact with the electromagnetic field. Other authors have generalized this equation to describe higher spin particles, maintaining the positivity of the energy. However, within their approach interactions with the e.m. field is still not possible. Sudarshan, Mukunda and Chiang have investigated possibilities to overcome this difficulty. They found that if instead of harmonic oscillators using the para-harmonic oscillators for the internal degrees of freedom, the e.m. interaction could be allowed. The result of this investigation is in preparation for publication.

In any relativistic Hamiltonian theory there are ten generators of the Poincare group which can be realized canonically. The dynamical evolution is described by the Hamiltonian--one of the ten generators in Dirac's Generator Formalism. The requirement that the canonical transformations reproduce the geometrical transformation of world points generates the world-line conditions. Some time ago, Sudarshan and his collaborators observed that Dirac's identification of the Hamiltonian together with the world-line conditions leads to the No-Interaction Theorem. Thus relativistic interacting theories having world-line conditions should go beyond the Dirac theory, which turns out to have eleven generators. Sudarshan together with Mukunda has constructed a constraint dynamical formalism which describes an eleven-generator theory of N interacting particles in terms of $8(N+1)$ variables with suitable constraints (DOE-ER-3992-401). The $(N+1)$ th pair of four vectors is associated with the uniform motion of a center which coincides with the center of energy for free particles. In such theories dynamics and kinematics cannot be separated out in a simple fashion.

The conventional description of the exchange of some quantities between point particles is by means of local interactions of particles with a mediating field.

The field carries quantities from one particle at one space-time point to another at a different point. It is well known that instead of having local interactions mediated by a field, one may also describe interactions among particles via the action-at-a-distance. As a continuation of his earlier work, Professor Sudarshan together with Mr. Pitre has studied the problem of charge exchange among point particles. In particular, they have constructed an action-at-a-distance model which is equivalent to the system in which charge exchange between point particles is achieved through the exchange of a charge scalar field (DOE-ER-3992-407).

Lastly, there has been revived interest recently in the possibility of constructing composite fields from constituent fields. In some aspects the existence of composite particles is closely related to the bound state problems in quantum theory. Mr. Terry under the guidance of Professor Sudarshan has reexamined the derivation of the Heisenberg Condition to show why this condition is not an identity for potentials possessing redundant poles. Consideration of several such potentials for which exact solutions are known reveals that in the process of taking an asymptotic limit, the usual derivation of the Heisenberg condition improperly neglects a set of terms. These terms are just those necessary to turn the Heisenberg condition into an identity; more importantly, it is demonstrated that these terms come from the asymptotic expansion of the continuum wave function (DOE-ER-3992-404).

A program of work concerning accelerated detectors and the coordinate dependence of quantum field theory was completed by John R. Letaw in cooperation with Jonathan D. Pfautsch of the Center for Theoretical Physics (UT Austin). The object of this work was to explore further the questions that arose in treating scalar field quantization in rotating coordinates (DOE-ER-3992-382), in particular: Does a conjectural relation between the vacuum state and event horizons hold in all possible flat space coordinates? Can the canonical quantization methods be rigorously extended to nonstatic coordinate systems in flat space? What are the possible vacuum states in flat space?

As a first step a paper entitled "Stationary World Lines and the Vacuum Excitation of Noninertial Detectors" (DOE-ER-3992-398) was written by John Letaw. In this paper the Frenet equations were generalized to Minkowski space and solved for constant curvature invariants. The curvature invariants represent intrinsic properties of a world line, specifically, proper acceleration and angular velocity. Thus, the resulting world lines are designated stationary because the constancy of the invariants implies no local measurements can distinguish between two points. These stationary world lines were shown to be the timelike Killing vector trajectories in flat space-time. The Frenet equation approach therefore provides a simple classification of the Killing vector fields in terms of the curvature invariants. The spectra of vacuum fluctuations measured by detectors on these world lines were calculated and demonstrated to be non-Planckian except on uniformly accelerated world lines. One finds, in general, that detectors establish a Planckian equilibrium only in uniform acceleration.

A second paper entitled "The Stationary Coordinate Systems in Flat Space-Time" (OR0-3992-419) by John Letaw and Jon Pfautsch used the classification of Killing vector fields to exhaustively describe this class of coordinate systems. There are six systems: Minkowski, Rotating, and Rindler coordinates are well known. The three new systems were designated Pseudorotating, Rotating Pseudocylindrical, and Null Parabolic coordinates. Stationary coordinate systems are of interest in quantum field theory for several reasons. First, it is always possible to define a conserved energy on constant time hypersurfaces in these systems. In general, one expects the physics on these hypersurfaces to be identical at each time. In particular, a stable vacuum might be found.

The final paper, entitled "The Quantized Scalar Field in the Stationary Coordinate Systems of Flat Space-Time" (DOE-ER-3992-420), applies the previous two to the study of quantum field theory in nonstandard coordinates. It proved possible to solve the Klein-Gordon equation in all six systems simply in terms of Bessel and trigonometric functions. A particle interpretation was developed in the usual manner by second quantization, except

that one point of interest arose. Particle states were found to be associated with positive norm modes rather than positive frequency modes (the standard assumption).

What seemed to be a major difficulty of this problem--the unboundedness of the energy derived from the Hamiltonian from below--turned out to be harmless. The vacuum was defined as that state of the field with no particles, and it was found to be the state of zero energy and momentum. In all cases the stability of the vacuum was maintained in spite of the existence of lower energy states because energy and momentum could not simultaneously be conserved in a decay to one of these states.

By means of Bogolubov transformations it was shown that of the six vacuum states defined, there were only two different ones. The first (Minkowski) vacuum is found in Minkowski, Rotating and Null Parabolic Coordinates. The second (Falling) vacuum is found in Rindler, Pseudorotating and Rotating Pseudocylindrical coordinates. The Minkowski vacuum occurs when there is no event horizon, the Falling vacuum when the event horizon of Rindler Coordinates occurs. This suggests a close relationship between the event horizon structure and the vacuum. We point out also that our results show by exhaustion that there are only two vacua in flat space-time without boundaries.

The final, and perhaps most important, point was that any effort to define the vacuum by the observations of a single detector was necessarily incompatible with canonical quantum field theory. This follows because many difficult world lines are associated with the Rindler, Pseudorotating, and Rotating Pseudocylindrical coordinates. The excitation spectra of detectors on these world lines were found to be very different. For example, some were Planckian and some were not. Yet only one vacuum, the Falling vacuum, occurs in these systems. In fact a typical detector moving through the Falling vacuum will in general be excited; thus its excitation cannot be a gauge of the vacuum. This result was emphasized in a short paper entitled "Incompatibility of the Observer-Based Vacuum with Canonical Quantum Field Theory" (DOE-ER-3992-410).

Next we turn to unstable quantum states and the problem of irreversibility.

To the extent that unstable states have been considered from the point of view of the theory of open systems the interaction with the environment including the measuring devices would be of significance in their time evolution. One can then justify the derivation, obtaining for the survival probability an exponential behavior at all times based on physical arguments concerning the reduction of the density matrix of the system due to the interaction with the environment. In this context, the Markovian approximation leading to a semigroup law for the density matrix and consequently to an exponential decay law may be justified by the usual argument based on the separation of two typical time scales for the system and the surroundings.

In S-matrix theory, resonances appear also as singularities of the continuation of an appropriate family of matrix elements of the resolvent or of operators connected to the resolvent. Such treatments apply equally well in two different classes of models in both of which the Hamiltonian is envisaged as a sum $H = H^0 + V$ of a "free" part plus an "interaction" V . For the sake of simplicity, consider the case of a two-body resonance. Then H^0 is the Hamiltonian one would ascribe to the two particles if they were non-interacting and V represents their interaction potential which may give rise to peaks in the scattering cross section ascribed to the presence of a pole of the second sheet continuation of the S-matrix at the point $Z_0 = E_0 - i(\Gamma_0/2)$. In an alternative approach, which suggests itself more naturally when one wishes to describe long-lived unstable states, one considers H^0 as the hypothetical Hamiltonian of the system plus its decay products in the absence of the interaction V which is responsible for the decay. In these models, H^0 has one or more eigenvalues m_0 embedded in the continuum. As V is switched on, the corresponding stationary states may become unstable and the eigenvalues are absorbed in the continuum. Granted suitable analyticity properties, the poles of the resolvent reduced to the proper eigenstates of H^0 move off the real axis to points $Z_0 = E_0 - i(\Gamma_0/2)$ into the second sheet, close to the unperturbed energies m_0 . There are of course physical situations in which both features of the above description appear, for example in the case of the scattering of electrons off He^+ atoms, where the cross section has peaks occurring at the energies of the autoionizing states. A

simple treatment which unifies the two models outlined above has allowed interpretation of resonances as isolated eigenvalues of a suitable non-self-adjoint analytic continuation of the Hamiltonian, thereby providing also a natural dense set of vectors in the Hilbert space (the analytic vectors of the group of dilatations) for which the expectation values of the resolvent can be continued to the second sheet and exhibit poles exactly at the location of the resonances. A physically motivated selection of the matrix elements of the resolvent which are to be continued is of crucial importance. The main object of the study is the survival amplitude $A(t) = (\phi, \exp(-iHt)\phi)$, $t \geq 0$, where H is the total Hamiltonian of the system. In two preceding papers, a detailed study has been carried out of the structure of $A(t)$ in a simple analytic resonance model.

Assuming the existence at the point $z_0 = E_0 - i(\Gamma_0/2)$ of a simple pole of the second sheet continuation in the lower right quadrant of the matrix element $(\phi, R(z)\phi)$ of the resolvent $(H - z)^{-1}$, Sudarshan and collaborators deform the integration contour. In certain special cases, using a procedure of analytic continuation which formally corresponds to a deformation of the spectrum of the Hamiltonian in the complex plane, they have shown elsewhere that the representations of the survival amplitude can be interpreted in a formal way as an expansion of the unstable state over a "complete set" of generalized eigenvectors of the Hamiltonian, which corresponds to a continuum of complex eigenvalues z along the contour Γ plus a "discrete" and likewise complex eigenvalue z_0 at which the second sheet continuation of the S-matrix exhibits a pole. In this way $z_0 = E_0 - i(\Gamma_0/2)$, with mass E_0 and width Γ_0 , and ascribe to it the corresponding generalized eigenvector $F(z_0)$ of the Hamiltonian. Sudarshan along with Gorini and Parravicini gives a rigorous mathematical foundation to this interpretation in terms of complex eigenvalues and eigenvectors of the Hamiltonian in the framework of the theory of self-adjoint operators in rigged Hilbert spaces. We do this in a way which provides an immediate technique for the analytic continuation of the resolvent across the absolutely continuous spectrum, so that we are able to associate to each other isolated singularities of the continued resolvent, "pure exponential" contributions to the survival

amplitude of decaying states and complex eigenvalues of the Hamiltonian H which are characterized by the fact that they are isolated singularities of analytic families of eigenvectors of H . In order to get rid of the arbitrariness in the location of such singularities, they tie their formalism to S-matrix theory, thus providing also a "deformalization" of the formal theory of scattering. Even though physicists have liked to think intuitively of resonances as states associated to "complex eigenvalues" of the Hamiltonian, it was not until Grossman's paper appeared that such an idea was given rigorous ground. Professor Sudarshan's approach is close to his. By extending a self-adjoint operator A to the dual of a suitable nuclear space, it is possible to associate to A various "complete sets" of generalized eigenvectors corresponding to complex eigenvalues. Even if the spectrum of A is absolutely continuous, these complete sets will in general contain both a "continuum" as well as a "discrete" contribution, the latter arising from singularities of the analytic family of eigenvectors.

This formalism is applied to nonrelativistic scattering theory. We consider a Hamiltonian of the form $H = H^0 + V$ on a Hilbert space $\mathcal{H}$ and a suitable nuclear space Φ densely and continuously embedded in $\mathcal{H}$. We assume Φ to be in the domain of H^0 and H and that both H^0 and H map Φ into itself continuously. Then, under suitable assumptions regarding the analyticity properties of the eigenvectors of the absolutely continuous parts of the operators H^0 and H extended to the dual space Φ' , we show that the second sheet singularities, in the lower half plane of the S-matrix and of the resolvent of H , as a continuous operator from Φ to Φ' , are the same as the singularities of the second sheet continuation of the stationary scattering states. Whenever these singularities are poles z_0 , which can be interpreted as resonances of the system, certain coefficients of the Laurent expansion of the eigenvectors of H about z_0 are themselves eigenvectors (and possibly associated vectors) of H with z_0 as eigenvalue. They form the "discrete" part of a suitable complete set of eigenvectors of the restriction of H to its subspace of absolute continuity, with complex eigenvalues. These "discrete" eigenvectors are the stationary states of H which are responsible for the leading exponential decay of the resonant wave packet.

They implement the above theory in the example of the Friedrichs model with a suitable analytic potential function, by providing explicitly a nuclear space Φ which fits all the required purposes and show that the same formalism goes through for the class of degenerate potentials, which have applications in nuclear physics (see also the accompanying proposal for complementary descriptions on the ongoing investigations).

A. Bohm discovered in 1976 that in the Rigged Hilbert Space formulation, decaying states can be described by generalized eigenvectors of the self-adjoint energy operator with complex eigenvalue, which have a Breit-Wigner energy distribution. This not only simplified the calculations but also established the link between the S-matrix description of a resonance pole and the usual description of states by vectors in a linear space. In a paper that will appear in J. Math. Phys. it is shown how these complex energy eigenvectors lead to the Fermi Golden Rule.

In a work started while visiting the Solvay Institute in Brussels, A. Bohm obtained exponentially decaying and growing "Gamow state vectors" from the pair of second sheet poles of the S-matrix, immediately below and above the real axis, respectively. To accomplish this, he used a transformation from the generalized eigenvector decomposition with respect to the continuous spectrum of the energy operator H into a pair of new generalized eigenvector decompositions, in which the contributions from the resonance poles is explicitly contained as one of the generalized basis vectors. A transformation from the continuous energy representation of the density matrix into a new representation in which the exponentially decaying part is separated had been suggested by the Brussels group of I. Prigogine and in this way it was shown that the "Gamow state vectors" establish the link between the S-matrix and density matrix transformations in statistical mechanics.

In a paper published in Letters Math. Phys. 3, 455 (1979), it was shown that the "Gamow vectors" are, unlike the Dirac kets, not defined as functionals on the entire space of physical states. But "Gamow states" must be considered separately as functionals on the subspaces of earlier and later physical states. As a consequence of this the dynamical group of time

development splits on the functionals over these two subspaces into two dynamical semigroups.

Investigations of the mathematical questions connected with these problems have been begun by A. Bohm in collaboration with M. Gadella, who is visiting the Center for Particle Theory with a fellowship from the Spanish government. A publication of some results in this area is in preparation.

E. Groups, Gauges and Grand Unified Theories

During a recent visiting appointment at the Max Planck Institute in Munich, Professor Bohm worked on the amalgamation of an $SO(4,1)$ gauge theory of extended objects with his earlier de Sitter model of hadrons. This work is carried out in collaboration with Dr. W. Drechsler, who was visiting the University of Texas from the Max Planck Institute in Munich. Drechsler has developed the $SO(4,1)$ gauge theory in the geometrical language of fiber bundles of Cartan type, and the joint efforts of Bohm and Drechsler were to unite these two different mathematical descriptions of the same intuitive physical idea. The geometrical language of Drechsler suggests that we expand the concept of space-time beyond its conventional form to include internal coordinates which have a dynamical meaning. It pictures a hadron as an excitation of the de Sitter fiber with 10^{-13} cm radius attached to the points of Minkowski space. In the earlier algebraic and group theoretical language the de Sitter model leads to the relativistic rotator spectrum and the intuitive picture was that hadrons are miniature de Sitter spaces of 10^{-13} cm attached to the space-time points. To obtain the spectrum these ideas have to be combined with the spectrum-generating group approach using infinite dimensional generalizations of the Dirac matrices. Such an algebraic structure has recently also been suggested (under the name of dynamical stability group) by Biedenharn and van Dam (Phys. Rev. D14, 405 (1976)), however, without using the $(4+1)$ -de Sitter constraint. A preliminary comparison of the predictions from the de Sitter constraint (using variable de Sitter radius) with the experimental data for $I = 0$ and $I = 1$ mesons has been performed. This de Sitter model requires three 4^{++} mesons between the U and the S region for which there is some evidence. That the U-meson has $S^P = 4^+$ had already been predicted by the earlier restricted version of this model many years ago, which now seems to be verified by the experimental data. These preliminary results have been presented in an invited talk at the Conference on "Group Theoretical Methods in Physics," November 1979, in Zvenigorod, USSR, in a lecture series at the Summer Institute in Turkey in July-August 1979, and in various other talks given by A. Bohm and W. Drechsler in the USSR,

Europe and South America.

Since the report of the new experimental data on high spin meson resonances (L. Montanet, 20th International Conference on High Energy Physics, Madison, Wisconsin, 1980), a new comparison between the predictions of the de Sitter model and the experimental values has been performed. The three 4^{++} resonances predicted by the model now appear to be established. A 5^{--} and a 6^{++} resonance have also been found with the masses in agreement with those predicted by the model. In addition, there is some evidence for a 3-resonance around 1850 MeV, which is also required by the model.

The description of known quantum-mechanical systems by fiber bundles has been considered by Mr. P. Moylan (Fortsch. Phys., August 1980; ORO-3992-375; ORO-3992-403) as a preparatory study for the application of these methods in particle physics. Based on the concept that a composite system can be viewed, at least in a certain range of energies, as an elementary particle, Moylan has been able to give a description of the hydrogen atom in terms of a fiber bundle over the configuration space of the center of mass. The fiber bundle makes clear the $O(4)$ symmetry of the problem, since the fiber over a point in the base space is the homogeneous space $S_3 = SO(4)/SO(3)$. In this description it is possible to replace the usual description of two particles moving in a $1/r$ potential by a description of the hydrogen atom as a free elementary particle moving in a fiber bundle erected over space. In the same paper he also has discussed a fiber bundle description for the nonrelativistic rotator. Moylan presented this fiber bundle description of the hydrogen atom at the IX International Colloquium on Group Theoretical Methods in Physics at Cocoyoc, Mexico in June, 1980.

Recently, Professor J. C. Ward showed (PNAS 75, 2568 (1978)) that the Dirac equation could be derived from considerations of minimal curvature, extending Einstein's gravitational Lagrangian. Riemann space-time is taken as the base-manifold of a fiber bundle, with the 4-dimensional representation of $Sp(2)$ as fiber. In the special-relativistic limit, the connection is expanded over the Dirac algebra and yields the Dirac Lagrangian

with electromagnetism.

Professor Ward has now generalized this approach by using the appropriate Clifford algebra in an $O(10)$ fiber. The Lorentz subgroup fits together with an internal chiral symmetry. Higgs fields are recuperated from the dimensional reduction of some of the other generators.

Dr. C. K. Jue and Professors C. C. Chiang and E.C.G. Sudarshan have investigated the theory of supersymmetry with internal symmetry in great detail. They have constructed a superalgebra with full conformal symmetry and $SU(N)$ internal symmetry. The possible extension of supersymmetry to parasupersymmetry has also been discussed. The variations of superfields under supersymmetry transformation have been studied. In order to study interaction of the multiplet fields, they first study the Lagrangian formalism for superfields with $SU(N)$ internal symmetry. It is found that in contrast to earlier investigation by other authors, for the case of $SU(2)$ internal symmetry they may construct a Lagrangian free of ghosts without imposing any constraint condition on superfields. For $SU(N)$ with $N \geq 3$, it is necessary to impose a constraint condition on the superfields in order to eliminate the ghosts. Equations of motion for the ordinary fields have been explicitly studied for $SU(3)$ and $SU(4)$. It has been demonstrated that for higher spin fields the equations of motion are equivalent to Bargmann-Wigner equations. (DOE 3992-394, 395 and 396). Part of the results have been presented at the ninth International Colloquium on the Group Theoretical Methods in Physics, Cocoyoc, Mexico (June 23-27, 1980).

The chiral V-A interaction and Maxwell electrodynamics have been combined into the standard unified electroweak model but this contains one parameter referred to as the Weinberg angle. At a higher level of unification one could expect this angle itself to emerge as a definite prediction of the theory. The new Grand Unified Theories (GUT) do precisely this; but there still remains the choice of the GUT group and the relevant representations. It has turned out that at the level of unifying all interactions both the $SU(5)$ and the $SO(10)$ groups yield very similar predictions when the multiplets are chosen appropriately. This had led Professor Sudarshan to conjecture that this result is a Smushkevich theorem

for GUT models. This conjecture has been proved in great generality, starting from Schur's lemma for a variety of groups with particular application to the Weinberg angle in GUT models by Dr. Bajaj and Professors Pasupathy, Rajasekharan and Sudarshan. They have shown how to apply it to nonstandard models also, like the $SU(2/1)$ model of Professor Ne'eman. It turns out that the unrenormalized value of $\sin^2\theta_w$ is $3/8$ for $SU(5)$, $O(10)$, $E(6)$, etc., while it is $1/4$ for $SU(2/1)$.

Bajaj, Pasupathy, Rajasekharan and Sudarshan also studied the classification of GUT models. Type A models have quarks and leptons in different multiplets and therefore have no leptoquarks, diquarks, etc., and no proton decay. They may be subdivided into type A1 with only one Z_0 besides the photon (for example $SU(2/1)$) and type A2 with more than one Z_0 (for example $SU(3)$). Type B models have both quarks and leptons in the same representation, type B1 with only one Z_0 (for example $SU(5)$) and type B2 with more than one Z_0 (for example $SO(10)$). In terms of their predictions for immediately relevant quantities, type A1 is more or less identical with the standard $SU(2) \times U(1)$ model. Type A2 has similar results for νN but for the reaction $e^+e^- \rightarrow \mu^+\mu^-$, they differ. For B1 and B2 it seems essential to take into account the renormalization effect since the symmetry values are reached only at very high energies. This paper (DOE-ER-3992-391) is in course of publication in *Pramana*.

During the last year, among different directions, Dr. Nandi worked on Grand Unified Theories (GUT). His work involved: the understanding of the observed relations among the masses of quarks and leptons using $SU(5)$ and $SO(10)$ GUT and calculating the mixing angles among the fermions which govern their productions and decays in weak processes; calculating neutrino masses and mixings in $SO(10)$ relevant for neutrino oscillations experiments; and attempting to understand the observed replication of fundamental fermions in the form of families. Presently he continues his research in these directions.

Quark-lepton mass relations and mixing angles were studied using $SU(5)$ and $SO(10)$ GUT together with discrete symmetries. The Georgi-Jarlskog mass relations $m_\mu/m_e = 9 m_s/m_d$, $m_\tau = m_b$ were obtained using two

5 and one $\underline{45}$ Higgs representations and a discrete symmetry. The Kobayashi-Maskawa mixing angles were found to be $S_2 = -(m_c/m_t)^{\frac{1}{2}}$ and $S_3 = -(m_u/m_t)^{\frac{1}{2}}/S_1$ where $S_1 = \sin$ of the Cabibbo angle. The b-quarks were predicted to decay predominantly into c-quarks with lifetime of $\tau_b \approx 10^{-13}$ sec (see S. Nandi and K. Tanaka, Phys. Lett. 92B, 107 (1980)). Mixing angles and CP-violation was also studied in $SU(2)_L \times U(1)$ gauge model supplemented by permutation symmetry S_3 for six quarks (see S. Nandi and K. Tanaka, Phys. Rev. D21, 2684 (1980)).

Recent experiments indicate that neutrinos may have masses of the order of eV, with large mixing among themselves. In $SO(10)$ GUT, since there is an extra neutral lepton, neutrino mass arises naturally. Nandi and collaborators assumed that the left-handed neutrino acquires a small mass via the Gell-Mann-Ramond-Slansky mechanism. They then computed the neutrino mixing angles in terms of the mass ratios of up-quark families in the $SO(10)$ gauge model supplemented by a discrete symmetry. They found large $\nu_\mu - \nu_\tau$ mixing (see S. Hanna, K. Milton, S. Nandi and K. Tanaka, DOE-ER-1545-282; Phys. Lett. B, in press)).

One outstanding problem in particle physics is the replication of fundamental fermions in the form of the $(5^* + 10)$ -plet of $SU(5)$ families. In their study of fermion mass matrix using $\underline{45}$ representation of Higgs, Nandi and collaborators found that the number of such families has to be six in order to obtain acceptable quark-lepton mass ratios (see P. H. Frampton, S. Nandi and J.J.G. Scanio, Phys. Lett. 85B, 225 (1979)). Also, following the guidelines suggested by H. Georgi, they proposed a $SU(9)$ superunified model which contained three to six $SU(5)$ families naturally, and the mass relations among the fermions of different families were obtained. The guiding principle was to minimize the number of Higgs scalars necessary to obtain mass relations (see P. H. Frampton and S. Nandi, Phys. Rev. Lett. 43, 1460 (1980)).

F. Super(geometry and algebra) and Unification

"Supers" (Algebras, Groups, Manifolds), Supergravity and the Geometric Role of Ghosts

Since 1974, Professor Ne'eman has been interested in the unification of the fundamental interactions, with a special effort devoted to gravity, an interaction which has not yet been renormalized, or even well understood at the quantum level. Superalgebras and supergroups appeared most appropriate new tools, since they opened the way to a unification of internal and space-time symmetries. Moreover, they contained the promise of new constraints that would remove the arbitrariness relating to Higgs fields: representations, couplings, etc.

In 1974, the Corwin-Ne'eman-Sternberg paper (Rev. Mod. Phys. 47, 573 (1975)) provided the key to the mathematical understanding of the new symmetries, and leading directly to the successful classification of all simple superalgebras and supergroups by V. Kac and I. Kaplansky. The complete proof, by Kac, in fact utilizes one or the main results of the CNS paper, the proof of the Poincaré-Birkhoff-Witt theorem for the superalgebras, a foundation for their representation theory.

The direct applications to supersymmetry seemed very promising for the renormalization aspects. In the spring of 1976, Ne'eman co-invented supergravity with M. Gell-Mann as an algebraic structure (though certainly not in a field theory sense, as was done by Freedman, Ferrara and van Nieuwenhuizen and by Deser and Zumino). This is how Gell-Mann and Ne'eman also saw directly the $N = 8$ limit of extended supergravity. It took the Lagrangian models two years to reach this stage, attained first by Freedman in an approximate fashion and then by Cremmer Julia and the late Joel Scherk, following a suggestion by W. Nahm. They used the method of dimensional reduction, revived by Ne'eman for internal symmetries (following Klein and Kaluza) in 1965 (Y. Ne'eman and J. Rosen, Ann. of Phys. 31, 391 (1965); and Rev. Mod. Phys. 37, 227 (1965)).

In 1977, Ne'eman introduced with T. Regge a new geometrical construct, the soft group manifold (SGM) (Ne'eman and Regge, Phys. Letters 74B, 54 (1978), and Rivista del Nuovo Cimento 1, No. 5, 1-42). This was done so as

to provide an "arena" for the gauging of the Poincaré and super-Poincaré groups--or other groups whose action is not restricted to the internal degrees of freedom (including extended supersymmetry). The understanding of the geometry and physics of the SGM were since greatly improved; the process in which the SGM undergoes spontaneous fibration, as a result of the equations of motion, was described in 1978 in a paper with Dr. J. Thierry-Mieg (Ann. of Physics 23, 247 (1979)). The mathematical definition has been further refined recently in a paper with Thierry-Mieg and Takasugi (to be published in the Physical Review) in which the main result relates to the geometrical identification of the ghost-fields needed for unitarity.

The SGM is an object which is less constrained than a fiber bundle. In fact, one may visualize a sequence: group manifold (GM), principal bundle (PB), SGM. The GM is rigid, with all motions fixed by the Cartan-Maurer equations for the left-invariant (or right-invariant) forms τ

$$d\tau + \frac{1}{2}[\tau, \tau] = 0 .$$

From these equations, one may derive the left- (or right-) invariant generator Lie algebra A whose basis a_i is orthonormal to the τ^i : $\tau^i \lrcorner a_j = \delta_j^i$. In a PB, one has at least 5 givens $(P, \mathcal{K}, G, \pi, \cdot)$: P the bundle manifold, whose dimensionality $n = m + t$ is the sum of m , that of the base space $\mathcal{K}$, and t , that of the Lie group G . π is the vertical projection and the dot (right-multiplication on P), defines a mapping from A , the Lie algebra of G , into P_* , the tangent to P . The opposite direction is spanned by the Lie algebra-valued connection ω , again through geometric contraction

$$\omega^i \lrcorner a_j = \delta_j^i .$$

The holonomic dimensionalities are $[n]$, whereas the anholonomic indices i, j go from 1 to t . The curvatures are two-forms defined by ($\hat{d}$ is the full n -dimensional exterior derivative):

$$\hat{d}\omega + \frac{1}{2}[\omega, \omega] = \Omega .$$

However, applying an equivariance condition to the kernel of the ω map, one can show that Ω is a "horizontal" two-form, i.e. that when contracted with a vertical (anholonomic) vector-field, it will yield a vanishing result. This means that upon separating $\hat{d} = d + s$, and $\omega = \phi + \chi$, d and ϕ horizontal and s and χ vertical, one can write:

$$\Omega_{ij} = 0, \quad \text{or } s\chi + \frac{1}{2}[\chi, \chi] = 0$$

$$\Omega_{i\mu} = 0, \quad \text{or } s\phi_\mu - D_\mu \chi = 0$$

These are the Cartan structural equations for a PB. With Jean Thierry-Mieg (a doctoral student of Ne'eman at Paris XI-Orsay in 1978), Ne'eman identified the χ with the renormalization ghosts introduced by Feynman and DeWitt and perfected by Faddeev and Popov in the unitarization of Yang-Mills theories. The Cartan equations yield the Becchi-Rouet-Stora (BRS) constraints which guarantee unitarity (see for example Y. Ne'eman and J. Thierry-Mieg, PNAS 77, 720 (1980)). The identification has recently been extended to the SGM, in the above-mentioned paper with Takasugi.

The SGM has only three givens $(\mathcal{L}, G, \gamma)$. $\mathcal{L}$ is a manifold of the same dimensionality as G , and γ is a set of frames on $\mathcal{L}$ upon which G acts in the adjoint representation. Using γ as a map from $\mathcal{L}_*$ yields $\mathcal{A}$, the algebra of Lie-derivatives Λ on $\mathcal{L}$,

$$\gamma^A \lrcorner \Lambda_B = \delta_B^A, \quad d\gamma + \frac{1}{2}[\gamma, \gamma] = \Gamma$$

or expanding over the γ ,

$$d\gamma^A + \frac{1}{2}(f_{BC}^A - \Gamma_{BC}^A)\gamma^B \wedge \gamma^C = 0$$

$$[\Lambda_B, \Lambda_C] = (f_{BC}^A - \Gamma_{BC}^A)\Lambda_A.$$

A Lie derivative Λ_A is an anholonomized general coordinate transformation, $\varepsilon^A = \varepsilon_{\gamma_M}^M \Lambda^A$, $z^M \rightarrow z^M + \varepsilon^M$ (z^M is the $\mathcal{L}$ variable). Ne'eman and Regge showed

that "local-supersymmetry," the transformation defining supergravity, is $\epsilon^\alpha \Lambda_\alpha$, where α is an anholonomic spinor index, for G the super-Poincaré group. Ne'eman and Thierry-Mieg showed that for a certain category of groups (or supergroups) containing space-time $\mathcal{R}$ as the parameters of translations, and choosing the Lagrangian to be locally invariant under a subgroup $F \subset G$, with $\mathcal{R} \subset \mathcal{H}/F$, causes a spontaneous fibration: $\mathcal{H}$ becomes a PB on mass shell, with $\mathcal{H} = \mathcal{H}/F$.

Ne'eman and Thierry-Mieg have applied SGM gauging to various extended supergravity models.

Recently, Ne'eman has shown how the soft-group manifold formalism may assist in ensuring unitarity in a renormalized theory of gravity and supergravity. Basically, he proved (see paper with E. Takasugi and J. Thierry-Mieg, to be published in Phys. Rev.) that the geometric identification of the renormalization ghosts and Becchi-Rouet-Stora equations which they had proved for a principal bundle may be extended to the soft group manifold. The geometric method of identifying the ghosts has also proved useful in a modern version of the Kalb-Ramond field (see Ne'eman's BRS paper at the Cocoyoc, Mexico Conference on Group Theoretical Methods in Physics). The entire method was reviewed as an invited paper at the Madison XX International Conference on High Energy Physics (see paper) and at the Clausthal International Conference on Differential Geometry Applications to Physics.

In another work (see paper with J. Thierry-Mieg in Marcel Grossman symposium), Professor Ne'eman showed that the geometric identification supplies the most natural set of signs for the Feynman diagrams with ghost-loops in supergravity.

Affine Gravity, World-Spinors and Strings

In 1977, Ne'eman initiated a parallel research program relating more directly to the dynamics of gravity and the possibility that these might be interrelated with strong interactions. Indications of such a connection came from four sources: (1) the 1965 result of Dothan-Gell-Mann-Ne'eman (Phys. Letters 17, 148 (1965)) showing that Regge recurrences (strong

interactions) fitted $SL(3,R)$ representations, and that this algebra is generated by the (orbital) deformations current, corresponding in fact to the time-derivatives of gravitational quadrupoles.

(2) The Salam-Strathdee ideas of "strong-gravitation" mediated by the f^0 "particle."

(3) The fact that the f^0 and other spin-two trajectories seemed to play a crucial role in the high-energy quark model results (Cabibbo-Horwitz-Ne'eman, Phys. Letters 22, 336 (1966)) and in scaling (Gomberoff-Horwitz-Ne'eman-Reddy, Phys. Letters 52B, 74 (1974)).

(4) The string picture, with its flat spin-two limit fitting gravitation.

In collaboration with F. W. Hehl and E. A. Lord, Ne'eman showed in 1978 (Phys. Letters 71B, 432 (1978)) that gauging $\overline{GL}(4,R)$ would indeed result in a dynamical role for hadronic currents which would include spin (and explain $SU(6)$ -type results), deformations (i.e. Regge excitations) and the scale current. For all of these to be intrinsic rather than orbital (i.e. and thus to include spinor trajectories, etc.), the group $\overline{GL}(4,R)$ had to have spinorial representations. This had been erroneously considered as an impossibility by the General Relativity establishment since the twenties. A first dent into this wall had been achieved by Ne'eman in collaboration with D. W. Joseph in 1970, showing the existence of a spinor representation of $SL(3,R)$ with spins $1/2 + 5/2 + 9/2 + \dots$. In a series of papers during 1978-1980, Ne'eman, partly in collaboration with Dj. Sijacki, cleared up the situation and showed that the "metilinear" (covering) groups $\overline{GL}(n,R)$ and $\overline{SL}(n,R)$ do have double-valued representations, and provided explicit constructions for the relevant ones of $\overline{GL}(4,R)$ and $\overline{GL}(3,R)$ (PNAS 74, 4157 (1977) and PNAS 76, 561 (1979) with 77, 1761 (1980); Ann. of Phys. 120, 292 (1979)). What is now missing is a wave equation for such an infinite spinor. This will surely involve the gravitational field.

Note that $\overline{SL}(3,R)$, which is connected with the stability group of $\overline{GL}(4,R)$, is the group conserving a 3-volume, and would thus fit a confinement situation. With Dj. Sijacki and T. Sherry, Ne'eman has investigated the (infinite) super-affine algebras $gs\overline{L}(3,R)$ and $gs\overline{L}(4,R)$ and shown that

$\overline{\text{gs}}\mathbb{I}(2,R)$ is indeed the algebra of the string. The $n = 3,4$ cases should correspond to membranes and lumps. This calls for a study of the dynamical identifications. Meanwhile, other version of $\overline{\text{gs}}\mathbb{I}(3,R)$ have been investigated, especially those with a central element, since this plays a role in renormalization (J. Math. Phys. 21, 1312 (1980)).

Poincaré Gravity

Following this program in the direction of gravity itself, Ne'eman suggested (in collaboration with the Hehl group; Phys. Letters 78B, 102 (1978)) a new gravity Lagrangian, based upon the gauging of the Poincaré group. This was then shown to possess a "teleparallelism" limit which can only be distinguished from Einstein's theory in 5th order ppn as was recently proved by Schweizer, Straumann and Wipf in Zurich. At the same time, the new model does contain "strong-gravity" naturally and has been shown (in a linearized approximation) to lead to confinement. However, Szegin and van Nieuwenhuizen have shown that in its present form the theory is not ghost-free. What appears to be needed is a spontaneous-breakdown version with no explicit symmetry breaking.

Internal Supergroups and Unification

The weakness of present GUT's ("grand" unification theories) as "solid" physical theories resides in the complete arbitrariness of the parameters of spontaneous symmetry breakdown. Ne'eman's original interest in supersymmetry aimed at the discovery of mathematical restrictions on the Higgs-Goldstone fields, their couplings, masses, etc. However, ordinary supersymmetry failed to provide such answers.

In 1979, Ne'eman introduced a new approach, using a supergroup as an internal symmetry. The supergroup $SU(2/1)$ provides a constraining frame for the Weinberg-Salam theory, removing much of the arbitrariness (Phys. Letters 81B, 190 (1979)). The key restriction resides in the fact that the Goldstone-Higgs multiplet is constrained by belonging to a supermultiplet with the Faddeev-Popov ghosts! This was then shown to be a

feature of other Goldstone models, including chiral $SU(3) \times SU(3)$ (PNAS 77, 720 (1980) with J. Thierry-Mieg). The Higgs masses are of the order of the W-mass (about 240 GeV). These predictions were reviewed by L. Wang at the Brookhaven Meson Spectroscopy Conference in April.

Quarks, which were first thought to lie outside the model, turned out to be precisely predicted by it. Indeed, a 4-dimensional representation (fitting precisely (u_L, d_L, d_R, u_R)) had been constructed by Rittenberg et al. as a mathematical example back in 1977. Ne'eman reported on the theory at the Salamanca International Conference on Application of Differential Geometry to Physics and on the experimental predictions at the Blacksburg workshop on weak interactions (see Proceedings).

One effort has been directed at further unification, so as to include $SU(3)_{\text{color}}$ or even the entire strong interaction. With D. Fairlie and Dj. Sijacki, Professor Ne'eman found that no such appropriate framework existed without violating baryon number. More recently an extremely satisfactory answer was found and presented as an invited paper at both the Europhysics Conference (Erice) on Unification (see paper) and at the Madison XX International Conference on High Energy Physics (see paper).

With S. Sternberg, Ne'eman has extended his internal superunification method to $SU(5 + k/1)$, showing how to construct representations of the $SU(m/n)$ supergroups. $SU(5 + k/1)$ provides exactly for 2^{k+1} generations $(\nu_L, e_L; e_R, \nu_R; q_L^1 q_L^2, q_R^2 q_R^1 \times 3 \text{ colors})$, half of which have a left-isospin and the other half a right-isospin. Even k appear to fit better the symmetry breakdown mechanisms, so that $k = 2$ or 4 left- and 4 right-handed generations appear most suitable. Color $SU(3)$ is imposed uniquely by the quark charges, and the right-handed electron neutrino is optional (see PNAS 77, 3127 (1980)). Ne'eman and Sternberg reported on these results at the Cocoyoc, Mexico recent Ninth International Conference on Group Theoretical Methods in Physics (see paper on color in internal supersymmetry).

APPENDIX A
TITLES OF DOE REPORTS
SINCE DOE-ER-03992-392

DOE-ER-03992-390	Measuring Processes in Quantum Mechanics I. Continuous Observation and the Watchdog Effect; K. Kraus
DOE-ER-03992-392	The University of Texas at Austin <u>Progress Report</u> "Research Program in Elementary Particle Theory" Sudarshan and Ne'eman
DOE-ER-03992-393	The University of Texas at Austin Research Proposal "Research Program in Elementary Particle Theory" Sudarshan and Ne'eman
DOE-ER-03992-394	Superfields with Internal Symmetry; Jue, Chiang and Sudarshan
DOE-ER-03992-395	Superfields with Internal Symmetry II. Lagrangian Formalism for Superfields with SU(3) Internal Symmetry; Jue, Chiang, and Sudarshan
DOE-ER-03992-396	Superfields with Internal Symmetry III. Lagrangian Formalism for Superfields with SU(4) Internal Symmetry; Jue, Chiang and Sudarshan
DOE-ER-03992-397	$\bar{\nu}$ - Universality in High Energy Hadron-Nucleus; Collisions, Chiu and Tow.
DOE-ER-03992-398	Vacuum Excitation of Noninertial detectors on Stationary World Lines; J. Letaw
DOE-ER-03992-399	Lagrangian Formalism For Superfields with Internal Symmetry; Jue, Chaing and Sudarshan
DOE-ER-03992-400	Constraint Dynamics of Particle World Lines; Mukunda and Sudarshan
DOE-ER-03992-401	Form of Relativistic Dynamics with World Lines; Mukunda and Sudarshan
DOE-ER-03992-402	New Experimental Evidence for a New Interpretation of Flavor SU(3); A. Bohm
DOE-ER-03992-403	Fiber Bundles in Non-Relativistic Quantum Mechanics: The Hydrogen Atom; P. Moylan
DOE-ER-03992-404	The Asymptotic Form of the Continuum Wave Functions and Redundant Poles in the Heisenberg Condition; P. Terry

DOE-ER-03992-405	Neutral Current Two Pion Production from Nucleons; Adjei, Dicus and Teplitz
DOE-ER-03992-406	Λ Beta Decay and the Cross Sections $\bar{\nu}_{\mu} + p \rightarrow \Lambda + \mu^{+}$ Adjei and D. Dicus
DOE-ER-03992-407	Charge Exchange in Relativistic Action-at-a-Distance Pitre and Sudarshan
DOE-ER-03992-408	Calculations of the Cycle Expansion Factor for a Closed Cyclical Cosmology; Dicus, Letaw and Teplitz
DOE-ER-03992-409	A Review on DTU-Parton Model for Hadron-Hadron and Hadron-Nucleus Collisions; C. Chiu
DOE-ER-03992-410	Incompatibility of the Observer-Based VAcuum with Canonical Quantum Field Theory; Letaw and Pfautsch
DOE-ER-03992-411	Geometrical Gauge Theory of Ghost and Goldstond Fields and of Ghost Symmetries; Ne'eman and Thierry-Mieg
DOE-ER-03992-412	Sequential Internal Supersymmetry; Ne'eman and Sternberg
DOE-ER-03992-413	Geometric Ghosts and Unitarity; Ne'eman
DOE-ER-03992-414	Color in Internal Supersymmetry Unification; Ne'eman and Sternberg
DOE-ER-03992-415	Gauge-Theory Ghosts and Unitarity - Progress in the Geometrical Treatment; Ne'eman
DOE-ER-03992-416	A Prognosis for the Proton; Ne'eman
DOE-ER-03992-417	Soft-Group Manifold Structure of Supergravity and the Proof of Unitarity; Thierry-Mieg and Ne'eman
DOE-ER-03992-418	Fireball Model for Baryonic Inclusion Spectra in Particle-nucleus and Nuclei-nucleus Collisions at High Energy; Bogatskaya, Chiu, et al.

DOE-ER-03992-419 The Stationary Coordinate Systems in Flat Spacetime;
Letaw and Pfautsch

DOE-ER-03992-420 The Quantized Scalar Field in the Stationary Coordinate
Systems of Flat Spacetime; Letaw and Pfautsch

DOE-ER-03992-421 Soft-group-manifold Becchi-Rouet-Stora Transformations
and Unitarity for Gravity, Supergravity and Extensions;
Ne'eman, Takauchi, and Thierry-Mieg

DOE-ER-03992-422 Unification Through a Supergroup; Ne'eman

DOE-ER-03992-423 Higher Order JWKB Expressions for the Energy Levels
and the Wavefunction at the Origin; Pasupathy and
Singh

APPENDIX B
RESEARCH HISTORIES OF THE SCIENTIFIC STAFF
OF
THE CENTER FOR PARTICLE THEORY
SINCE DOE-ER-03992-392

RESEARCH HISTORY

Yuval Ne'eman - Professor of Physics and
Co-Director, Center for Particle Theory

Yuval Ne'eman has combined several careers besides the one in Physics. The circumstances of Israel's emergence into Statehood in the midst of a struggle for survival made him dedicate to purely military activities, the first twelve years after getting his degree in Engineering. He achieved stature as one of Israel's top thinkers in the domains of Strategy and Defense Policy.

His scientific career was initiated in 1961, working in London (Imperial College) where he had made the transition in 1958-61 and obtained a Ph.D. from London University. Here he conceived and published his theory of Unitary Symmetry, which can now be considered as the foundation of most developments in Particle Physics in the last two decades. Returning to Israel he conceived the idea of a fundamental sub-particle triplet, with the observed nucleons and hyperons being constituted of various combinations of three such basic units. This idea, further developed by M. Gell-Mann and G. Zweig (with the units christened as "quarks") is now the key to our further dynamical understanding of the hadrons.

Ne'eman pursued his research in Israel first at the Atomic Energy Commission Laboratories, where he became Scientific Director, and then as a Professor of Physics at Tel-Aviv University, where he founded the Physics Department. He later became University President (1971), leaving the Presidency after four years, in order to serve as Senior Advisor to the Minister of Defense (acting as Deputy to the Minister in all Defense Policy) yet again in combination with the position of Chief Defense Scientist. He resigned from these positions after a year, on a matter of National Policy, and has held no Government or University responsibilities since the beginning of 1976. Since 1968, (and except for the year 1975), Ne'eman has held a half-time position as Professor of Physics at the University of Texas, Austin, where he founded the Center for Particle Theory of which he is now a Co-Director. This arrangement (similar to one made by the University of Texas at the same period with Prof. I. Prigogine, with respect to the Center for Statistical Mechanics) was part of the University's drive for excellence,

which brought about the creation of several such research Centers at the time. Ne'eman has also spent several years as a Guest Professor (or Fairchild Distinguished Fellow) at Cal Tech, and has been a guest for shorter periods at IAS Princeton, at SUNY Stony Brook, the IHES Paris and CERN.

Returning to Ne'eman's research contributions, it was in a 1962 paper of his with three of his students that the first clear cut demonstration was given of the experimental good fit of Unitary Symmetry in Strong reactions, in which the previously favored "Sakata model" had failed. Later on, in 1964 he suggested "the Fifth Interaction" that the SU(3)-breaking effect observed in the mass spectrum was due to an interaction with a relatively long lived vector-meson resembling the ϕ . It should be noted that the ψ -J particle discovered in 1974 fits most of the characteristics predicted in that paper (even the mass, though the reasons quoted for such a mass in the paper were irrelevant in the final result). For the leptons, a reordering in their systematics in connection with the Weak Interaction (1962) was later used by A. Salam in developing his (1968) version of the Gauge Theory of Weak and Electromagnetic Interactions. A 1964 article with M. Gell-Mann proved that the algebra of Weak and Electromagnetic Charges is isomorphic to a doubled SU(3) (or to "Chiral" Unitary Spin). This was the algebra used in all the 1965-68 work on "Current-Algebra". With A. Joseph, Ne'eman classified in 1969 all representations of the algebra of local current densities.

In the further development of the quark model, Ne'eman identified in 1966 (together with N. Cabibbo and L. P. Horwitz) the algebraic pattern behind all high energy quark-model results, a doubling of Unitary Symmetry which preserves in fact the Unitary spins of Quarks and of Antiquarks separately in these regimes. Note that the currently popular Zweig-Itzuka-Okubo rule, used to explain the slow decays of ϕ , ψ and of the recently discovered T , are part of this algebra, which also predicts the famous Levin-Frankfurt $\sigma(\pi N)/\sigma(NN) \rightarrow 2/3$, etc.. In a series of articles between 1967 and 1974 Ne'eman succeeded in providing this phenomenological algebra with a deeper theoretical foundation, based on an extension of the ideas of bilocal current operators and the null-plane expansion. This explanation can now be considered "definitive", as a logarithmic approximation of the presently favored QCD, for instance.

Another line of work dealing with the Strong Interactions, but with many applications in other fields, was initiated by Ne'eman in 1965 in two articles with M. Gell-Mann and Y. Dothan. This pointed out the role (till then unnoticed) of non-compact groups which reproduce the set of all solutions of certain problems in Quantum Mechanics in one single representation (the idea was suggested independently by E. C. G. Sudarshan and by A. Barut and A. Bohm). This approach, followed in 1966 by an application to S-matrix singularities, was later much in use in the development of Dual Models by G. Veneziano and others, who have also applied extensively another 1966 idea of Ne'eman's (with N. Cabibbo, L. Horwitz and J. J. J. Kokkedee). The suggestion was that high energy phenomena were dominated by a "Pomeranchuk trajectory" whose intercept differed from one by a small number (the direct experimental prediction of diminishing cross sections failed, but the idea is now applied to the "unrenormalized" trajectory)

One particular suggestion of the 1965 Dothan-Gell-Mann-Ne'eman paper had dealt with $SL(3R)$ as a model for the hadron excitation bands represented by Regge trajectories. With D. W. Joseph, Ne'eman showed in 1970 the existence of double-valued spinor representations of that group. In 1976, the subject acquired new dimensions: the existence of these band-spinors provided for intrinsic shear currents, thus going beyond the 1965 Dothan-Gell-Mann-Ne'eman representations, which corresponded to time-derivations of Gravitational Quadrupoles (an idea which was tested in deformed Nuclei by L. C. Biedenharn and collaborators in 1972). With F. Hehl and E. C. Lord, Ne'eman now showed that such shear, together with scaling and spin densities would constitute the intrinsic hypermomentum tensor of General Relativity. In the metric affine extension of G. R., the shear-scale-spin tensor is coupled to the connection, in addition to the coupling of the energy-momentum to the metric. In an intriguing phenomenological observation, Ne'eman noted that it was just these three currents which appeared to be approximately conserved in the quark model: spin-independence ($SU(6)$), scaling and the pattern of Regge bands. However, since $SL(3R)$ is the algebra of volume preserving deformations, this may just correspond to confinement.

This recent work has led Ne'eman to a discovery in General Relativity: the existence of (infinite) Spinor representations of the Group of

General Coordinate Transformations ("bandors"). Almost any textbook in GR has stated that the G.C.T.G. has no spinor representations, so that this was a real innovation and may yield many applications (there is already one important mathematical application by B. Kostant).

In other work in Nuclear Physics and Astrophysics, Ne'eman suggested in 1968 the existence of hypercollapsed nuclear isomers. The idea was independently suggested by A. Bodmer in 1970 and by T. D. Lee (in the context of Boson condensation) in 1972.

In General Relativity, Ne'eman invented White Holes ("Lagging Cores") to explain quasars in 1965, and developed the idea in 1967 and 1972.

The discovery of CP (or T) violation led Ne'eman (1969-1974) to a Statistical Mechanics study of the possible interrelation of the microscopic arrow of time with the thermodynamical one and with Cosmology.

Since 1974, the discovery of Supersymmetry has led Ne'eman to the development (with S. Sternberg) of the Mathematical theory of Graded Lie Algebras. With M. Gell-Mann he has analyzed the Group Structure of Supergravity, independently of its discovery in field theory by D. Z. Freedman and collaborators. More recently, with T. Regge, he had developed a Geometric Theory of Gauges, for Groups acting on Space-Time. The theory reproduces General Relativity and Supergravity but also provides new insights about possible modifications or generalizations.

Ne'eman is a Foreign Associate of the U.S. National Academy of Sciences and of several other Academies. He has published three books and about 150 publications in Scientific Journals.

Since 1977, Ne'eman has worked on a reformulation of the theory of Gravity. The aim is to develop a version that would be fully renormalizable. It could be very different from Einstein's at the quantum level, provided its macroscopic limit is close enough to General Relativity. With F. W. Hehl, J. Nitsch and P. Von der Heyde, Ne'eman published in 1978 a first version of such a theory, the "Poincare Gauge Theory" (PGT). It has since been shown that it indeed has a "teleparallelism" limit which can only be distinguished from GR at the 5th ppN level. Beyond the above-mentioned indications of a possible link between Metric Affine Gravity and Quark confine-

ment, the PGT appears to contain a "strong" confining term directly. With Dj. Sijacki, Ne'eman has meanwhile further developed the understanding of $\overline{\text{SL}}(4, \mathbb{R})$ or $\overline{\text{GL}}(4, \mathbb{R})$ band-spinors, and has outlined what an Affine theory of Gravity should look like.

With the discovery of a third generation of quarks and leptons, Ne'eman called for the abandonment of the idea of an ordinary simple group to provide the generation structure and also for a view in which quarks and leptons are themselves composite objects. The idea has generated some interesting models, especially one by Harari and Shupe.

In 1979, Ne'eman invented a new type of gauge theory, using a supergroup internally. The resulting supersymmetry is a symmetry of the quantum Lagrangian, rotating fields to ghosts. The supergroup $\text{SU}(2/1)$ provides a perfect embedding of the Weinberg-Salam ($\text{SU}(2) \times \text{U}(1)$) in a simple group, therefore highly constraining all free parameters and many otherwise arbitrary choices. With S. Sternberg, he has extended this group in 1980 to $\text{SU}(5+k/1)$, to include color. It predicts a set of 2^{k+1} identical "copies" (or generations) of the 15 basic quarks and leptons.

With J. Thierry-Mieg, Ne'eman has identified the geometric role of the renormalization "Faddeev-Popov" ghosts, thus providing a further advance in the imposition of Unitarity. He has since shown that this applies to non-internal gauges such as gravity as well.

RESEARCH HISTORY

E. C. G. Sudarshan - Professor of Physics and
Co-Director, Center for Particle Theory

E. C. G. Sudarshan got his B.Sc. (Honors) and M.A. Degrees in Physics at the University of Madras and his Ph.D. in Physics at the University of Rochester. His interests and research contributions cover a broad sweep of physics but all along Particle Theory has held the center stage. From an early stage in his career as a physicist he has generously given of his time and energy in assisting, directing, instructing and counseling numerous physicists many of whom have gone on to make a name for themselves. He considers himself sometimes as a teacher, sometimes as a research worker, but always as a scientist.

He started his research career with the study of multiple scattering in nuclear emulsions at the Tata Institute of Fundamental Research. His interest in more fundamental problems of what has now come to be known as Particle Physics started here and came into its own during the two years he spent as a graduate student at the University of Rochester. His doctoral work led to the discovery of the now classic V-A interaction. He formulated the first statistical theory of antinucleon annihilation and introduced the Lorentz-invariant phase space density for statistical theory of meson production. The first application of broken symmetry in particle physics, the equal spacing rule for magnetic moments of isospin multiplets was derived by Marshak, Okubo and Sudarshan during this period. This application naturally led to Okubo's work on unitary symmetry and the Gell-Mann-Okubo mass formula.

Professor Sudarshan spent the two years 1957-1959 as a Research Fellow at Harvard University with Professor Julian Schwinger. Inspired by Schwinger he studied quantum theory of higher spin fields and demonstrated a general theorem on the existence of secondary constraints and consequent problems of quantization of higher spin fields with special reference to the inconsistency of spin $3/2$ fields in an external electromagnetic field. This work, which was completed in collaboration with Kenneth Johnson, has been the impetus for a whole new area dealing with relativistic wave equations, particularly the work of Velo and Zwanziger on the acausality of higher spin field propagation; and of Arthur Wightman and his various associates on the problem of wave equations

in external fields.

A different area of research concerned itself with analytic properties of field theoretic amplitudes. In collaboration with Walter Gilbert and Stanley Deser he developed a new family of integral representations which have come to be called the DGS representations.

The work on weak interactions continued with the increasing confirmation of the universal V-A theory. He collaborated with the Rochester group in elucidating many of the subtle properties of weak interactions, in particular, the SU(2) properties of weak currents. Among them are the first announced connection between the axial vector hadronic current and the pion source, the first characterization of the $I = \frac{1}{2}$ current rule for strangeness changing decays and the consequences of $\Delta I = \frac{1}{2}$ for K^0 decay.

Sudarshan returned to Rochester as an Assistant Professor on the University faculty in 1959 and was promoted to the rank of Associate Professor in 1961. During this period, he moved into new territory. Anticipating the great interest in Lie groups, he formulated classical mechanics in terms of Lie groups; this interest has now completed its promise in a new book on Classical Dynamics written in collaboration with Narasimhiengar Mukunda and published by John Wiley in 1974. In collaboration with two students, Thomas Jordan and Douglas Currie, he investigated relativistic Hamiltonian theories and proved a fundamental no-go theorem which has come to be called the No Interaction Theorem. He laid the plans for a systematic study of irreversible quantum processes considered as stochastic dynamics of quantum mechanical systems. This work has been continued, in collaboration with T. Jordan, P. M. Mathews and, particularly, Vittorio Gorini, and has received the attention of mathematicians who call them positive and completely positive maps.

The study of particle physics was continued during this period. Robert Marshak and George Sudarshan published a thin volume of the Theory of Elementary Particles, which documented the insights of the late fifties and early sixties. Along with Susumu Okubo and Robert Marshak he found the general solution to a class of integral equations in the course of a study of lambda hyperon decay: this solution is now known in the literature as the Omnes' Solution. Unitary symmetry came to be discovered during this time and Okubo developed his celebrated mass formula as a more substantial application of

broken symmetry. During this time, Sudarshan and his co-workers developed a general theory of sum rules using the so-called Smushkevich method; these were some of the earliest derivations of consequences of unitary symmetry. Particularly notable are the results on electromagnetic moments and mass differences.

During this period, the most important new undertakings were the formulation of two new concepts: that of quantum theory with indefinite metric and the theory of tachyons. While Dirac had pointed out the possibility of an indefinite metric and Pauli had reviewed it, the first serious work on this was by Suraj Gupta in quantum electrodynamics. Sudarshan took up this work but showed how it could be applied to remove divergences from local field theory and yet retain the conventional probability interpretation of quantum mechanics. Along with Arons and Han he applied it to quantum electrodynamics. The developments in the area were reviewed in his report to the Solvay Conference in 1968. Since that time, the subject has received wide attention due to the eloquent advocacy of T. D. Lee. In their papers Lee and Wick raised the possibility of use of complex bare masses: this turns out to be an excellent idea though the manner in which they implemented their program led to violation of Lorentz invariance. This difficulty was pointed out by Sudarshan and co-workers.

The idea that particles may travel with speeds exceeding that of light in a relativistic theory, which Sudarshan proposed in the fifties, was met with strong criticism and it was published only when it was rewritten subsequently in collaboration with Bilaniuk and Deshpande. Many authors have now taken up the theme; tachyons along with magnetic monopoles and quarks and conspicuous by their absence on the scene.

During his Rochester years, Sudarshan contributed to quantum field theory, particularly in reference to the possible existence of multiple vacuum states within the Wightman framework. His work with Bardakci showing the trivial S-matrix for a scalar field theory with a polynomial source predates the work of Borchers. His work on parastatistics in collaboration with Ryan is one of the clearest derivations. But the most important contribution to quantum field theory was to be quantum theory of optical coherence in which he showed that there is a complete equivalence between the semiclassical theory

of partial coherence and the results of quantum electrodynamics. In collaboration with Leonard Mandel and Emil Wolf, he also gave a formulation of photoelectric counting distribution. The fundamental insights gained in this area are summarized in the book QUANTUM OPTICS, coauthored with John Klauder, published in 1968.

In 1964-1965 Sudarshan was Guest Professor at the Institute of Exact Sciences, University of Bern; he also made guest visits to Brandeis University and the Institute of Mathematical Sciences in Madras. During this period, he showed in collaboration with O'Raifeartaigh and Santhanam and with Leutwyler, that if certain consequences of symmetry (the Smushkevich type sum rules) hold, then a symmetry follows. He also showed that this was related to, but distinct from, the Cutkosky mechanism of induction of symmetries. The principle is closely related to the algebra of currents, and used as such by Cook, Goebel and Sukita and by Kuriyan and Sudarshan for strong coupling theories. During this time, the question of combining internal symmetry and the Lorentz group was triggered by McGlinn. Sudarshan proved two basic no-go results of this type of questions and introduced Lochlainn O'Raifeartaigh to the problem which he subsequently solved completely.

In 1965 Sudarshan joined Syracuse University as Professor of Physics and helped create an active, though small, high energy theory group there. The work on higher symmetries was now taken up in earnest. During this time, Lochlainn O'Raifeartaigh discovered his theorem and Moo-Young Han did his work on the Han-Nambu model. Noninvariance groups were discovered during this time by Sudarshan along with Mukunda and O'Raifeartaigh. Jacob Kuriyan, Narasimheingar Mukunda and George Sudarshan did some pioneering work on the theory of unitary representations of noncompact groups, which has come to be known as master analytic representations. Relativistic $SU(6)$, the orbital excitation model of $SU(6) \times O(3)$ were discovered during this time. So was the theory of Primary Interactions, which gave a natural basis for vector dominance models.

But his most important contribution during this time was to current algebras. Krishnan Raman and George Sudarshan generalized the Ward-Takahashi method to the case of nonabelian symmetries and derived the generalized Ward-Takahashi Identities from which follow a host of results including the Adler-Weisberger relations and the Tomozawa-Weinberg-Raman scattering length rela-

tions. This basic result and its application to pion-nucleon scattering are published in Physics Letters and the Physical Review.

In 1968 Sudarshan spent a semester as a Visiting Professor at the Centre for Advanced Research in Physics and Astrophysics at Delhi University. During this period, he formulated a theory of tachyon fields incorporating the reinterpretation principle in collaboration with Jawharlal Dhar; and a review of superluminal physics along with Olexa-Myron Bilaniuk. The celebrated theorem of Pauli on the connection between spin and statistics presupposes the restriction to finite component relativistic fields. Sudarshan reexamined this question and showed that it is possible to derive the relation between spin and statistics from the symmetry between emission and absorption. He showed, in two papers presented to the Nobel Symposium and to the Indian Academy of Sciences, that ultimately the connection between spin and statistics is traceable to the rotation group in three dimensions for which the fundamental bilinear form is symmetric for tensor fields and antisymmetric for spinor fields.

During this period, Sudarshan got seriously interested in philosophy, particularly, the nature of causality, time, coherence, perspective and cognition. These concerns and the fruits of this study have strongly influenced him in his understanding and presentation of physics. It is curious that both tachyons and quantum theory with indefinite metric raise questions in these philosophical domains.

The University of Texas at Austin invited him to become Professor of Physics in 1969 and to assume the post of Co-Director of the Center for Particle Theory in 1970. In association with Yuval Ne'eman he founded a strong group of particle theorists at Austin of which he continues to be a member. Together with Relativity and Astronomy there is an exciting and active group now which has the honor of having John Wheeler and Ilya Prigogine.

During these years, Sudarshan has continued his work in particle physics. Along with co-workers, he analyzed high energy scattering data for tachyonic resonances, studied the analytic properties of transition amplitudes in indefinite metric theories and the question of violation of causality in such theories. The study of quantum theory of fields with spin $3/2$ was taken up in collaboration with Bruce Mainland; they showed that not only the

Heisenberg equations of motion but the entire Poincare Lie algebra is properly realized by the field.

The problem of action-at-a-distance in relativistic theories was reinvestigated. Since he had proved the no-interaction theorem in local relativistic theories, this was only just! He showed that every action-at-a-distance theory can be embedded in a local field theory in a natural manner; and that any finite theory of this kind automatically implied an indefinite metric. A general theory of physically meaningful indefinite metric theory was the natural follow-up and this work has been carried out as the theory of "shadow states". Shadows are states that are involved in formulating the dynamics but not involved in the unitarity sum.

Together with J. P. Hsu and two students, Allen Underwood and Enrique Mac, Sudarshan studied unified gauge theories and gave an alternate formalism using Lagrange multiplier fields; and applied it to construct a number of models. In most cases this method gives rise to different and, often, simpler Lagrangians, but essentially the same S-matrix as given by the usual theory.

Description of higher spin particles continues to be a problem and relativistic wave equations are actively being studied. William Hurley and George Sudarshan have studied a general class of such equations giving unique mass and unique spin. A new class of "barnacled wave equations" have been introduced and studied. Aslam Khalil has completed a doctoral thesis on generalizations of this scheme and related topics.

Multiple particle production at high energies is an active field of interest. In collaboration with Charles Chiu and K. Wang, he has formulated a hydrodynamical theory of multiparticle production with frame-independence.

Dynamical maps have been investigated in collaboration with Vittorio Gorini. The extremal maps of a two-level system have been obtained. Like finding the unitary representations of a noncompact group, this is a "first". For completely positive maps the use of Choi's theorem enables one to find all the extremal elements in a simpler manner. In collaboration with Drs. V. Gorini and A. Frigerio of the University of Milan and Dr. A. Kossakowski of the University of Torun he has completed a review article on quantum Markovian equations.

Particle physics concepts have application to other fields and several such applications have been carried out. The competition between species can be modeled by coupled fields and one can thus generate Hamiltonian models of "interaction" between biological species. This work is done in collaboration with S. N. Biswas. The temporal behavior of a repeatedly observed quantum system is a fascinating topic and certain features of this were investigated in collaboration with Professors Charles Chiu and Baidyanath Misra. Misra and Sudarshan have already shown that continuous observation, followed in quantum mechanics, leads to a Zeno's paradox. This has naturally led to a closer study of unstable systems and their time evolution and the results are presented in a paper by Misra, Chiu and Sudarshan. Sudarshan has also shown how it introduces an interaction between a classical and a quantum system and thus provides a basis for measurement theory by embedding the classical system in a quantum system with continuous superselection rules. Sudarshan and Mukunda have shown that Nambu dynamics is essentially Hamiltonian dynamics, seen in a new perspective.

The problem of measurement in quantum theory has been the subject of discussion for many decades, but this was always done without a premise statement of the interaction between a quantum system and the classical measuring apparatus. Sudarshan has recently succeeded in discovering an embedding of classical dynamics in a quantum dynamics with continuing superselection rules. Several papers on this has been published in collaboration with R. Misra, S. Gautam and T. Sherry.

The study of time evolution of unstable systems has served as a trigger to crystallize some of Sudarshan's long standing interest in the analytic continuation of the state space of quantum theory. A general theory is formulated for analytic functionals as the framework of such a theory. Work on this topic is continuing, though two papers have already been completed in collaboration with V. Gorini and G. Parravicini.

The physics of consciousness has always fascinated Sudarshan, both in its metaphysical and empirical aspects. The research work done at MERU in Switzerland, discussions with Professor G. Globus at the University of California at Irvine and Professor D. Shainberg of New York University, as well as Professor B. Josephson at Cambridge have contributed to a focusing of this interest. Continuing discussions with Professors John Wheeler and Ilya Prigogine

and their guests at the University of Texas, including Professors Stapp, Minsky, Scully, Peres, and d'Espagnat on measurement theory and artificial intelligence and further discussions with Dr. H. Mathews at the University of Texas serve to elucidate and delimit the general problem. This work is still in its infancy.

Quarks are enigmatic entities and perhaps they do not obey ordinary statistics. Sudarshan has continued his study of parastatistics in collaboration with Mukunda and Mehta; and of finding completeness theorems for coherent states for parabose fields. He has also found a new family of coherent states in terms of which the density matrix of an illumination field can be expressed as a weighted sum of projections. A related completed work is the pursuit of light rays in wave optics including quantum electrodynamics and radiative transfer.

The space-time development of physical processes is of particular interest to Sudarshan. He has pursued a study of it in hadron dynamics and quantum optics. The quantum Zeno's paradox can be made to manifest itself in successive collisions inside a nucleus. P. Valanju, C. Chiu and Sudarshan have developed the theory in a paper recently completed. The application of these ideas to the possible modification for the equation of state of matter at very high densities as obtains in the interior of stars have been studied in collaboration with P. Valanju and C. C. Chiang.

The unification of bosons and fermions into a single multiplet is possible in the framework of supersymmetry which extends the usual symmetry formalism to accommodate a graded Lie algebra with spinor generators. Along with Jue Changkeun and C. C. Chiang, Sudarshan has studied superfields with internal symmetry in a series of three papers which clarifies much of the existing literature as well as provide for the consideration of higher spin equations.

The relationship of the symmetry of the equations of motion (automorphisms) and the symmetry of the realized physical theory (internal automorphisms) has been studied extensively in recent years with particular reference to spontaneous and dynamical breakdown. In collaboration with Balachandran, Mukunda, Nilsson and Zaccana, Sudarshan has discovered a new mechanism of reduction of the internal automorphisms of a system and illus-

trated it for a $GL(3,R)$ model. The $GL(3,R)$ automorphism group carried by a triplet of pairs of variables automatically implies the internal automorphisms to be reduced to a 3-parameter subgroup and one pair of canonical variables.

The interaction of relativistic particles with local generators of the Poincare group in which the particle trajectories are world lines has been the subject of study by Currie, Jordan and Mukunda two decades ago when they proved the fundamental no-interaction theorem. Sudarshan and Mukunda have recently restudied this problem with particular reference to Dirac's constraint dynamics. They are able to show how to construct two classes of such theories, but it is essential to extend Dirac's ten parameter Lie algebra into an eleven-parameter Lie algebra; this work also elucidates the failure of earlier attempts to find invariant world lines within the ten generator formalism of Dirac.

In collaboration with Balachandran, Mukunda, Nilsson and Zaccaria, Sudarshan has investigated the conditions under which one can pass from the Hamiltonian system to an action principle in a global manner. This problem is reduced to the context in which the closed 2-form of the Hamiltonian formalism is also exact. In these cases where it is not exact one can show the equivalence to path space dynamics which can be reduced to a classical fiber bundle.

Grand unified theories continue the direction of unification beginning with the V-A theory which unified hadronic and leptonic weak interactions; and the standard unified electroweak $SU(2) \times U(1)$ theory. One consequence of these theories is that the Weinberg angle which is arbitrary in the standard theory gets definitively fixed in these GUT theories. Sudarshan and collaborators have investigated the problem and shows that the fixing of the Weinberg angle depends only on the grand multiplet structure and not on the GUT group.

Sudarshan is a Fellow of the Indian National Science Academy and a Fellow of the American Physical Society. He is the author of three books, one on elementary particle physics, one on quantum optics and one on classical mechanics. Sudarshan has also pursued the close identity of spirit between Indian philosophical thought and twentieth century physics, particularly modern particle physics. This work has not so far been published in research papers.

RESEARCH HISTORY

Arno Bohm - Professor of Physics

As a student at the Freie Universitat Berlin in 1962, Arno Bohm worked on axiomatic quantum field theory. He applied the axiomatic field theory of Bogojubov, Medvedev and Polivanov to quantum electrodynamics and showed that the asymptotic form of the currents agrees with the expressions of the re-normalized theory. This was later published in a paper with Polivanov. (Nuov. Cim. 40, 1110 (1965)).

During the period 1963-1964, Arno Bohm was an instructor at the Institute of Technology in Karlsruhe, where he worked on problems of elementary particle phenomenology (calculation of pion-nucleon scattering phase shifts).

In 1964 as a Research Associate at the University of Marburg, Arno Bohm started work on group theoretical methods in particle physics and continued this work with A. O. Barut at the International Centre for Theoretical Physics in Trieste, where A. Bohm was an IAEA Research Fellow, 1964-1966.

During this time, he suggested (together with A. O. Barut, Phys. Rev. 139B, 1107) using groups not only as symmetry groups but to describe all states of a physical system by an irreducible representation of a group ("Dynamical group"). The same suggestion was later made by Mukunda, O'Raifeartaigh, Sudarshan ("non-invariance group") and Dothan, Gell-Mann, Ne'eman, who coined the presently accepted name of "spectrum generating group" for it.

During the same time, he also worked on the mathematical methods of quantum mechanics. He made the suggestion to formulate quantum mechanics in the Rigged Hilbert Space with algebras of continuous operators and thus give a mathematically rigorous presentation of the Dirac formalism in quantum mechanics. (A similar suggestion was made independently by J. E. Roberts).

While A. Bohm was a research associate at Syracuse University, during 1966-1968, he gave the construction of the Rigged Hilbert Space for representations of Lie groups and the proof that the space of differentiable vectors for semi-simple Lie groups is a nuclear space. (J. Math. Phys. 8, 1551 (1967)). (The same construction was suggested later by B. Nagel). His major effort during this period was devoted to working on his suggestion to use the connection between the deSitter group and Poincare group for the problem of the

mass spectrum of elementary particles. This led to the introduction of an elementary length of $1/3 \cdot 10^{-13}$ cm and the idea that hadrons are miniature deSitter spaces of infinite time and finite ($1/3 \cdot 10^{-13}$ cm) space extension. (Years later the same picture for hadrons was also obtained by differential geometrical arguments using fibre bundles by W. Drechsler, Fortsch. Phys. 23 (1975).

A Bohm continued the work on the deSitter model, when he came in 1968 as an associate professor to the University of Texas. In 1969 a representation of the full relativistic symmetry (a combination of the Poincare algebra, C, P, T and an infinite dimensional generalization of the Dirac γ -matrices) was introduced, which was called Generalized Dirac Representation, because it describes baryons and mesons in the same way as the space of the solution of the Dirac equation describes the electron (Phys. Rev. D3, 367). This was combined with the above deSitter model for the description of the hadron spectrum (Phys. Rev. D3, 377; Phys. Rev. Letters 23, 436).

In 1970-1971 A. Bohm extended his idea of a quantum mechanical description (i.e., by an algebra of operators) of particle properties to include the algebra of charges. This was in a certain way a continuation of the work he had done previously together with E. C. G. Sudarshan on the semi-leptonic and leptonic decay of hadrons. In the spring of 1971, while A. Bohm was visiting scientists at the Max-Planck Institute in Munich, it was shown that the resulting algebraic model has many structures in common with the algebra of currents. During 1971-1972, this algebra of transition operators was applied to a unified description of the radiative and leptonic decay of vector mesons, partially in collaboration with J. Nilsson at the Institute for Theoretical Physics in Goteborg.

As a continuation of this program, A. Bohm suggested in 1974 to use a minimal set of assumptions: 1) Poincare invariance and C, P, T properties; 2) SU(3) as a spectrum generating group; 3) V-A for the operators that describe the transitions (currents) to calculate weak leptonic and electromagnetic decay properties. Work has been done in three areas of this research program. Together with M. Igarashi and J. Werle (University of Warsaw) the weak leptonic decay of pseudoscalar mesons investigated. Together with A. Garcia (Mexico), J. S. Nilsson (Sweden) and R. B. Teese, the hyperon leptonic

decays were studied and an improvement of the Cabibbo model was suggested. Together with R. B. Teese and graduate students at Texas this program was applied to the calculation of electromagnetic decays of vector mesons in the framework of SU(4).

This resulted in two discoveries: First that - as expected - the explanation of the decays $V \rightarrow e\bar{e}$ and $V \rightarrow P\gamma$ required in addition to the Clebsch Gordan coefficients a suppression factor of the same kind used for the weak decays; and second, that the Gell-Mann-Nishijima formula for the electromagnetic current operator is good for the $V \rightarrow e\bar{e}$ decays but may be insufficient for the radiative decays. This led to the postulation of a purely magnetic SU(3) scalar term in the electromagnetic current operator, the necessity of which has recently been confirmed by the Rochester experiment of $\rho \rightarrow \pi\gamma$. The resulting theoretical scheme then allowed to fit all existing radiative decay rates. An application of this scheme to the Hyperon Magnetic Moments, however, gave an indication that an SU(3) scalar term in the electromagnetic current may not be sufficient to explain the recently obtained precision values.

In connection with the writing of a text and monograph on Quantum Mechanics the Rigged Hilbert Space formulation of Quantum Mechanics was again taken up. It was suggested that decaying states be described by generalized eigenvectors of an essentially selfadjoint Hamiltonian with complex eigenvalues and a Breit-Wigner energy distribution (Gamow vectors), an idea which had also been independently proposed in a different form by Baumgartel and which has presently become quite popular. In a review paper that stresses the advantages of the Rigged Hilbert space formulation of quantum mechanics it was shown that these Gamow vectors are the unifying entities of S-matrix poles, quasistationary states and resonance phenomena.

Another old idea that has been taken up again is to consider hadrons as micro-deSitter spaces attached to the space-time points and to derive a mass spectrum in this connection. This idea has reappeared as a gauge theory of strong interaction with SO(4,1) as the gauge group and has been combined with the dynamical stability group idea using SO(3,2) as the spectrum generating group. The minimal coupling has been generalized to an operator form which relates the Poincare group to a deSitter group and gives a spectrum that compares well with the experimental data.

During an Inter-Academy exchange visit in Moscow a collaboration has been started with V. Shelest, A. Sukhanov and others on a book which has been given the working title "Quantum Physics of Atoms, Nuclei and Elementary Particles" and which is to appear as a revised version of the book "Quantum Mechanics".

A. Bohm gave a series of lectures at the Summer Institute in Turkey July-August 1979 on Gauge Groups and Spectrum Generating Algebras. In November, 1979 he also visited various research institutes in the Soviet Union within the US-USSR Academy Exchange Program and gave a number of lectures on the Rigged Hilbert space formulation of decaying states, on Spectrum Generating $SU(n)$ and its application to radiative decays and on Spectrum Generating Algebras and $SO(4,1)$ gauge groups.

RESEARCH HISTORY

Austin Gleeson - Professor of Physics

Dr. Gleeson's research interests have been in the general area of elementary particle formalism and phenomenology. Although many of the investigations, such as, studies of kinematic effects and different direct phenomenological data fittings are worth while in their own right, this review will treat only the most significant research accomplishments.

His thesis (University of Pennsylvania 1965) was a detailed calculation of the process of single pion production processes using the analytic S-matrix method. It was and is the most complete ab initio calculation of this process undertaken. It is the only treatment of this problem in which the threshold cuts which arise from unitarity constraints are handled appropriately.

From 1965 to 1969 Dr. Gleeson was on the staff of the Physics Department at Syracuse University. While there as both a postdoctoral research associate and as an assistant professor, he developed several new research topics. In a paper titled "Weak Axial-Vector Currents and the Baryon Field" he was the first to propose and test the chiral algebraic structure of the baryon fields. This paper is based on an extension of the methods developed for the Algebra of Currents by Adler and Weisberger. This analysis is a first step in the identification of the chiral structure of the fermion systems and preceeded by a few years the subsequently developed general chiral symmetric methods for the analysis of strong interactions.

In "Non-invariance Group by Bootstrap and Regge Behavior", Dr. Gleeson with R. Musto developed and applied a method, later to be called finite energy sum rules, for the investigation of the algebraic structure of meson baryon coupling strengths. This paper is important as regards both its method and intent. The method of finite energy sum rules was later applied by others to solve the problem of balancing the resonance pole versus Regge pole saturation of the intermediate energy cross sections and led to the concept of duality in the strong interactions. The intent was the first use of high energy or Regge behavior to constrain the low energy coupling strengths or more generally to extend the algebraic system in which to express the strong interaction coupling strengths.

As mentioned above the application of finite energy sum rules to phenomenology of intermediate energy amplitudes lead to the hypothesis of duality. An amplitude which exactly satisfies the constraints of duality was independently proposed by Gleeson and Meggs in "Infinite Sequence of Resonance Poles and Regge Asymptotic Behavior" and by Veneziano. This amplitude walled the Veneziano representation has served as the classic example for the analysis of an exact dual model and provided the basic framework for the development of dual models of the strong interactions.

In a series of papers, Gleeson, Meggs and Parkinson proposed tests of several alternative possibilities to the complete duality that was the current style. The present theoretical difficulties in formulating a realistic dual theory have subsequently made most of the discussion of these questions moot, although they were important at the time.

With Professor Sudarshan, Dr. Gleeson worked on the formulation of a reasonable complete physical interpretation of complex energy negative-metric theories. This work dovetailed nicely with a new interest in this topic brought about by a new model by T. D. Lee and G. C. Wick which used these methods to regulate relativistic field theories. Dr. Gleeson and Professor Sudarshan with collaborators showed in "Analyticity Covariance, and Unitarity in Indefinite Metric Quantum Field Theories" that the Lee-Wick program was untenable.

In the past few years Dr. Gleeson has initiated with R. Bowers a program for the development of a realistic model of superdense matter. This model when applied to cold systems such as neutron stars, is the only model containing the full complement of baryon constituents which produces star models sufficiently rigid and yet causal which satisfies the present astronomically obtained bounds for mass and moment of inertia for these objects. These models of superdense matter have also been applied to relativistic heavy ion collision. A model based on an expanding evaporating ball of hot relativistic nuclear-matter has been used to analyze the currently available data on high energy heavy ion collisions.

RESEARCH HISTORY

Charles B. Chiu - Associate Professor of Physics

Dr. Chiu completed his Ph.D. thesis work in high energy experimental physics, at the University of California at Berkeley in 1965. His thesis is on "Pion-nucleon charge exchange angular distribution, from 500 to 1300 MeV." This work provided additional constraints to the determination of pion-nucleon phase shifts. After this work, he joined the theoretical group at the Lawrence Radiation Laboratory in Berkeley. This marked a transition in his research career. Since then, he has been working on theoretical physics problems. During his stay in the theoretical group (1965-1967), he worked on different aspects of the Regge pole model. He was one of the first authors who recognized the experimental confirmation on the "nonsense-wrong-signature zero" in the Regge pole theory. During this period, through several collaborative papers, he worked on the classification of sense-nonsense choosing mechanisms in the Regge pole theory and the different Regge pole solutions for pion-nucleon and nucleon-nucleon scattering.

For the period 1967 through 1968, Dr. Chiu worked in the theory division at CERN as a visiting scientist. During this period, he and Dr. J. Finkelstein proposed and developed the "hybrid model" for hadron two-body scattering at small as well as large momentum transfer regions. This model is similar to the "Weak cut model". He and Dr. J. Finkelstein also derived the ϕ - ω ideal mixing from the exchange degeneracy condition. During this period, he and Dr. A. Kotanski clarified the connection between the Regge pole phase factor and the "Schmid loop".

For the period 1968 to 1969, Dr. Chiu worked in the Cavendish Laboratory, Cambridge, England, as a senior research fellow. He continued to investigate the large momentum transfer scattering phenomena. He delivered a review paper on nonforward scattering in the Theoretical Physics Meeting at Rutherford Laboratory in December, 1968. An extended version of this work was later published in the Reviews of Modern Physics. During this period, Dr. Chiu collaborated with Dr. R. J. Eden and Mr. M. B. Green. They developed the phase contour model which provides a general framework for the description of the phase of hadron amplitude satisfying the general properties: crossing, analyticity, unitarity and Regge asymptotic behavior, etc.

From 1969 to 1971, Dr. Chiu worked at Caltech. From 1969 to 1970, he was a research fellow, and from 1970 to 1971, the Richard Case Tolman Senior Research Fellow there. During these two years, he studied the high energy collision phenomena from the point of view of Regge poles and cuts. He made a systematic survey on the strong points and the weak points of the Regge pole model, and also the inadequacy of cut models. A summary of this survey was presented at the American Physical Society meeting, November, 1970, sponsored by the CPT group here. An extended version of this work was later published in the Nuclear Physics. During his stay at Caltech, he was also a co-organizer of the Caltech conference on high energy phenomenology, and a co-editor of the conference proceedings, in which the need for a phenomenological approach to the strong interaction physics is stressed. Through collaborative work, Dr. Chiu investigated the factorization property of the dual resonance propagator and derived the "generalized ward identity" in the dual resonance model. He and Dr. Robert Heinman formulated the statistical bootstrap model with spins, and demonstrated the relation between the angular momentum spectrum of the dual resonance model and that of the statistical bootstrap model.

Dr. Chiu joined the Department of Physics at the University of Texas at Austin in 1971 as an Assistant Professor. During 1971-1972, he continued to work on the systematics of two-body scattering phenomena at high energy. Based on the statistical bootstrap model, he proposed a "strong central absorption prescription" for two-body scattering, which qualitatively accounts for the successes and the failures of the Regge pole model. He contributed a review article on the "Evidence of Regge Pole Model in Hadron Collisions" published in Annual Review of Nuclear Sciences, 1972. He reformulated the statistical bootstrap model, found analytic solutions, and gave new physical interpretation to the model. Influenced by local research interest on shadow state theory, with Dr. C. C. Chiang, he also worked on the mass renormalization problem based on the dispersion relation and the Feynman diagram techniques.

During 1972-1973, Dr. Chiu's main research interest was directed toward the formulation of a bootstrap model which accounts for hadron interaction dynamics. An input to the bootstrap model involves the multiparticle production physics, as well as two-body scattering physics, with the unitarity

relation playing a crucial role linking the two-body scattering amplitude to 2 to n amplitudes. As a first step toward this goal, he began to explore various phenomenological models for multiparticle productions. Collaborating with Dr. K. H. Wang, he developed an independent cluster emission model for multiparticle production. Collaborating with Dr. R. Gleiser, Dr. Chiu further investigated the ramification of his modified statistical bootstrap model.

During 1973-1974, with his general interest in multiparticle production models, he was intrigued by the rise of the total cross section in the ISR region. During this year, he worked on the application of the absorption to the popular models of multiparticle productions: the multiperipheral model and the independent emission model. He and Dr. K. H. Wang and, at an early stage also joined by Dr. R. Gleiser, developed the absorption formalism for multiparticle production and achieved to demonstrate that the "absorbed independent cluster emission model" provides a unified description to the elastic data including the rise of the total cross section, the inclusive data and the multiplicity distribution data. This, to our knowledge is the first phenomenological model which simultaneously accounts for such varieties of data. During this period, Dr. Chiu, together with his student E. Ugaz, found an empirical "fixed-power-extrapolation scheme" for the single particle inclusive distribution in the fragmentation region in high energy multiparticle productions. A similar behavior is also found for a hypothetical example of the dual resonance model. With this fragmentation distribution within the framework of the Regge-Mueller model the inclusive rapidity-distribution is specified at all energies. Based on the independent cluster emission model, the specified inclusive distribution leads one to predict the energy dependence of the average multiplicities, and of a temporary rise of the total cross section and the multiplicity distribution. They are all in reasonable agreement with the data.

During 1974-1975, his main research was on the investigation of hydrodynamical models for multiparticle production in high energy hadron collisions. He views hydrodynamical models as providing a general statistical approach to final state interactions among multiparticles, which are produced within a small space-time volume. He, together with E. C. G. Sudarshan and K. H. Wang, proposed a new hydrodynamical model -- the frame independence symmetry model

for multiparticle production. In contrast to Landau's model, where one assumes there is initially a global thermal equilibrium, within this new proposal the initial thermal equilibrium of matter is reached only at the local level. At high energies, Landau's version violates the uncertainty principle, but this new proposal does not suffer the same criticism. Further on, he and K. H. Wang investigated the pion momentum distribution at 90° in pp collision based on this new model and the notion of evaporation. With the parameters of their model completely specified from a fit to the data at 1500 GeV incident laboratory energy, predictions at other energies ranging from 25 to 1500 GeV show a characteristic anti-shrinking energy dependence and are in good agreement with the data. They have also investigated several technical points of hydrodynamics: e.g., the hydrodynamical model with massless constituents and the constraints imposed on a hydrodynamical system when it undergoes a conical expansion.

During 1975-1976, Dr. Chiu continued his research in the cluster production model. He and K. H. Wang further developed the model applying to the charge transfer distribution, two-particle correlation function, and the rapidity-gap distributions. They concluded that the data require a certain characteristic correlation effect within a cluster for a wide range of cluster decay models. In a separate investigation he, together with Dr. D. Tow, found that if one assumes some $N\bar{N}$ cluster production, the observed rise of the single pion inclusive cross section in the central region at ISR energies may be correlated to the corresponding rise in the $\bar{p}$ inclusive cross section. Along the line of strong interaction dynamics, he, together with Dr. D. Tow and Mr. M. Hossain, formulated a simple SU(3) breaking scheme for the dual bootstrap model. The solutions found are in reasonable agreement with the cross section and the multiplicity data. Stimulated by the work of Prof. R. Logan and his collaborators on the statistical bootstrap model with spin proposed earlier by Chiu and Heinman, Dr. Chiu further investigated this model and clarified the assumptions required to give rise to shrinking peripheral peaks.

Another problem investigated in this year is in collaboration with Prof. E. C. G. Sudarshan and Dr. B. Misra. It is on the time development of an unstable quantum system based on the Lee model. In this work, a characteristic time scale prior to the onset of the exponential decay was discovered, which provides an important clue toward the clarification on the long standing

Zeno's paradox for unstable particle decay.

During 1976-1977, Dr. Chiu's research was in three areas: the strong interaction physics, space-time transformation and special relativity, and formal quantum theory. The bulk of his research is in the first area. Dr. Chiu together with Dr. D. Tow and Mr. M. Hossain continued his work in the dual bootstrap program. They investigated the momentum transfer dependence of Regge trajectories obtained from bootstrap model and further investigated the phenomenological ramifications of their solutions. Dr. Chiu together with Dr. S. Matsuda found an interesting way to correlate multiparticle productions to the intermediate states of the Pomeron diagram in the dual resonance model. Dr. Chiu, together with Professor G. Bialkowski and Dr. D. Tow, proposed a new space-time description for hadron-nucleus collisions. In this new picture, particles at the instance of creation are immature and their maturity rate is enhanced in the presence of other hadronic matter, such as within a nucleus. The model has been very successful. With its only parameter -- the mean maturity time, the model accounts for varieties of data in hadron-nucleus collisions. Dr. Chiu, together with Professor T. E. Kalogeropoulos and Professor E. C. G. Sudarshan showed that existing data confirms our theoretical expectation that the intrinsic parity of the antiproton is negative. Dr. Chiu also furthered his investigation in hydrodynamical model. Using the technique of the information theory, he with Professor C. S. Lam and Dr. K. H. Wang derived equations of motion of hydrodynamical model from a bag-like Lagrangian.

In the second area, Dr. Chiu, together with Dr. J. P. Hsu and Dr. T. Sherry, has studied problems related to space-time transformation. Within the framework of the special theory of relativity the speed of light signals measured by two stable clocks properly arranged is predicted to vary due to the motion of the earth. They further investigated a formalism previously pioneered by Dr. Hsu -- a new space-time transformation based on the notion of the universal time. In the third area, as a continuation of his interest in unstable quantum system, he, together with Professor E. C. G. Sudarshan and Dr. V. Gorini, developed a generalized quantum theory in which one identifies decaying states as complex energy eigenvectors. They also found interesting correlations between the small time behavior of the unstable system with the high energy behavior of the spectrum of the system.

During 1978-1979, Dr. Chiu continues his research in dual unitarization bootstrap program. Together with Dr. D. Tow and Dr. M. Hossain, he found a simple solution to the bootstrap equation which satisfies the famous Lee-Veneziano relation. Also, together with Dr. D. Tow, he has investigated the compatibility of the bootstrap solution with the Real/Im data which together with other factors has triggered some later interest of including $B\bar{B}$ intermediate states in the bootstrap program.

Dr. Chiu also continued his interest in interactions involving nuclear targets. He, together with Professor E. C. G. Sudarshan and Mr. Prashant Valanju demonstrated how the notion of quantum zeno paradox may be applied to hadron-nucleus collisions. In their work they have also considered finite size effect in hadron-nucleus collisions. The latter consideration has now provided a possible link between their model and the parton model. Together with Professor G. Zinovjev and his collaborators in Kiev, Dr. Chiu has investigated a fireball model for baryonic inclusive spectra in hadron-nuclei and nuclei-nuclei collisions at high energies. The model gives reasonable description to the available data.

During this year, his new interest in research has been in the direction of QCD, parton model and QCD jets. On the theoretical side, he, Dr. R. Kaul and Dr. E. Takasugi have studied the solution for meron configurations which has some bearing to the understanding of confinement related problem. In the direction of parton model, with Dr. E. Takasugi and a student, X. Tata, he studied the problem of multiquark structure function. Within the model, conservation of momentum is strictly imposed. This enables them to investigate the constraint of conservation of momentum in the parton model.

Since August 1978, Dr. Chiu spent his one year leave at Max Planck Institute in Munich. During his stay at MPI, he has been very interested in the nonperturbative QCD problem and small p_T -component of jets. He and Professor Nussinov have investigated the problem of $q\bar{q}$ pair production based on Feynman diagram approach. This work enabled him later on to extract further phenomenological implication of the flux tube model and to demonstrate the agreement of the flux tube model prediction and the e^+e^- data.

Dr. Chiu and Dr. J. Szved observed that if one assumes that the confinement mechanism sets in after some finite color separation, one should

expect a two component picture for the quantum-chromodynamic jets: the angular component and the fixed transverse momentum component. The present data is consistent with such an interpretation.

While at the Max Planck Institute, intrigued by the exciting research in the area of cold neutron physics, Dr. Chiu had also the opportunity to collaborate with Professor Leo Stodolsky in the investigation of the feasibility of building a gigantic neutron interferometer using cold neutrons. In the course of this investigation, they discovered a theorem, which among other things, neatly demonstrates the theoretical reason behind those cancellations hitherto noticed in different matter wave interferometry.

Since his return from Germany in August 1979, Dr. Chiu and Dr. Don Tow have been collaborating with physicists in Peking, China, Professor He Zou-ziu and his colleague Chao Wei-qin on a simple space-time description of hadron-nucleus collisions at high energies. The model is based on the two-sheet description of soft multiparticle production in hadron-hadron collisions, and can be formulated in a parton framework. This zero parameter model agrees well with the general features of hadron-nucleus data.

In the process of generalizing their model to hadron-nucleus collisions with arbitrary projectiles, Chiu and Tow recognized that their previous model is a special case of a more general model based on the ideas of: the Dual Topological Unitarization Theory (DTU) and the confinement string together with estimates on the rate of the breakup of the strings based on for instance the Schwinger formula. This subsequently prompted Chiu and Tow to discover an improved formulation of the DTU-parton model for hadron-nucleus collision. A brief survey of the phenomenological application of the model including the so-called $\sqrt{s}$ -universality phenomena was presented by Chiu at the XXth International Conference on High Energy Physics at Madison.

Chiu together with Sudarshan and Chiang has investigated the alleged equivalence of Yukawa-type theories and four-fermion interaction theories. Based on the equivalence premise, some authors have constructed the Yang-Mills Theory, the Glashaw-Salam-Weinberg Theory and the SU_5 grand Unified Theory from four fermion interactions. Chiu and collaborators have reinvestigated the situation within solvable models. They have demonstrated the apparent equivalence and yet the subtle nonequivalence between these two types of theories.

RESEARCH HISTORY

Duane A. Dicus - Associate Professor of Physics

While a graduate student at U.C.L.A., Dr. Dicus collaborated with Dr. Ernest Abers and Dr. Richard Norton in calculating the electromagnetic corrections to the weak vector coupling constant of hadrons. This problem had intrigued particle physicists for ten years because of its bearing on the question of the universality of the muon and the hadron weak decay constants. These authors showed the radiative correction to hadron decay was independent of the strong interactions of the hadrons and thus could be calculated by known methods. In a second part of his thesis work, Dr. Dicus discussed the universality of nuclear weak vector coupling constants among themselves. An improved calculation of one of the Coulomb corrections was instrumental in bringing the various coupling constants closer together and resolving the so-called " A_2^{26} anomaly".

From 1969 to 1971 Dr. Dicus was a research associate at M.I.T. While there, he, Professor Roman Jackiw, and Professor Vigdor Teplitz showed that light cone commutators were the natural commutators to use to derive fixed mass sum rules on the structure functions of deep inelastic scattering. This method of deriving sum rules removed ambiguities that existed when equal time commutators were used and some of the old sum rules were corrected. Extending this method in a series of papers over the next several years Dr. Dicus, sometimes with Dr. Teplitz or Dr. David Palmer, derived new sum rules and relations among the structure functions.

Also while at M.I.T. Dr. Dicus, together with Dr. Teplitz and Dr. Daniel Freedman, wrote two papers on the Reggeization of field theories. This work has recently been useful to other investigators in their attempts to Reggeize unified gauge theories.

From 1971 to 1973 Dr. Dicus was a Research Associate and part-time Assistant Professor at the University of Rochester. Other than the light cone work mentioned above, he spent a large share of that time trying to find tests of unified gauge theories. This led him to calculate stellar energy loss rates, various lepton processes, and the radiative corrections to the process $e^+e^- \rightarrow \mu^+\mu^-$.

In 1973 Dr. Dicus anticipated that the spectrum of hadrons should be $SU(4)$ rather than $SU(3)$ and he and Vishnu Mathur initiated a program of studying the symmetry group chiral $SU(4) \otimes SU(4)$ and how it is broken. Later in 1973 Dr. Dicus joined the University of Texas as an Assistant Professor and he and Dr. N. G. Deshpande continued the work on $SU(4) \otimes SU(4)$. This work preceded by more than a year the interest in $SU(4)$ precipitated by the discovery of the $\psi(J)$ particles.

Attempts to find tests of weak interaction theories has been extended to models which are not gauge theories. Dr. Dicus, Dr. Teplitz of Virginia Polytechnic Institute, and Dr. Gino Segre of the University of Pennsylvania have discussed in detail tests of a model based on the exchange of heavy scalar bosons and have made interesting predictions for the processes $\nu_\mu + e \rightarrow \nu_\mu + e$ and $e^+e^- \rightarrow \mu^+\mu^-$. Also, Dr. Dicus has discussed again the use of stellar energy loss rates to test different theories, a method he first used in 1972 preceding by three years the current interest in such tests.

In addition to his work on finding tests of weak interaction models Dr. Dicus has also been active in constructing improved versions of gauge theories. In particular, Dr. Dicus, Dr. Teplitz, and Dr. J. E. Young of M.I.T. have their own unified gauge theory which uses the strong interaction technique of duality to incorporate the electron-muon universality in a natural way. This model also gives interesting predictions for $\nu_\mu + e \rightarrow \nu_\mu + e$ and $e^+e^- \rightarrow \mu^+\mu^-$.

The discovery of charmed mesons (D^0 , D^+ , D^{*0} , D^{*+}) and the realization that their branching ratios depend sensitively on the precise $D^+ - D^0$ and $D^{*+} - D^{*0}$ mass differences led to many attempts to calculate these mass differences. Dr. Dicus, together with Dr. Deshpande, Dr. Teplitz, and Dr. Ken Johnson of M.I.T., used the M.I.T. bag model to do the first fully dynamical and fully relativistic calculation of these mass differences as well as all other mass differences between particles with the same isospin in the lowest SU_4 multiplets of pseudoscalar, vector, spin 1/2 baryons, and spin 3/2 baryons. Later the same group used the bag model to calculate all the M1 radiative transitions between lowest SU_4 multiplets.

In 1973 Dr. Dicus and Dr. Mathur established upper bounds on the masses of particles that occur in unified gauge theories (such as the Higgs mesons). This work was four years ahead of its time; in 1978 Ben Lee and collaborators repeated it and the importance of such bounds were realized.

Currently there is a lot of interest in the overlap between particle physics and astrophysics. Although Dr. Dicus has been doing such work since 1972 the current interest is at least partially due to his work in 1977 with Dr. Kolb and Dr. Teplitz on the cosmological implications of heavy leptons. They were able to limit the density, masses, and lifetimes of such particles and also the masses of axions and Higgs particles.

Dr. Dicus is part of a group that has analyzed low energy $\pi N \rightarrow \pi\pi N$ data. In particular they have compared the older bubble chamber data and the newer results from the single arm spectrometer experiment with current algebra and partial wave isobar model predictions. The most important of the many conclusions is a value for the symmetry breaking parameter of -0.2 ± 0.3 .

RESEARCH HISTORY

C. C. Chiang - Assistant Professor and
Research Scientist

As a graduate student at the University of Alberta, Dr. Chiang worked under Professor M. Razavy on the problem of nuclear matter. He received the M. Sc. degree in 1965. In 1965-1966 Dr. Chiang continued his graduate study at the University of Alberta and engaged in further investigations on the problem of nuclear matter.

In 1966, Dr. Chiang transferred to Syracuse University and joined the particle theory group as a research assistant in 1977. Under the supervision of Professor E. C. G. Sudarshan, he collaborated with Dr. M. Huq, Dr. R. P. Saxena and Mr. R. J. Gleiser in studying the universal theory of primary interactions proposed by Professor Sudarshan and nucleon-nucleon scattering. From the phase shift analysis of nucleon-nucleon scattering they found that the theory gave reasonable predictions.

In 1969, Dr. Chiang found himself interested in higher spin field theory and worked specifically on the Lagrangian formalism for neutral massive spin 3 fields. Based on this work, some further investigations on this problem have been carried out by other authors. To broaden his background in particle physics, Dr. Chiang studied the gauge invariant chiral Lagrangian and $\bar{P}P$ annihilation. He found that if p' is also included, a phenomenological gauge invariant chiral Lagrangian can be constructed.

In 1970, Dr. Chiang wrote his Ph.D. dissertation under the supervision of Professor Sudarshan on the infrared divergence problem in quantum electrodynamics. This work was published in collaboration with Professor Sudarshan. In this paper they pointed out some inconsistencies in the conventional treatment of infrared divergence problem from the physical point of view. This work has initiated some authors to reinvestigate the problem more closely.

From 1970 to 1973 Dr. Chiang was a research associate and later an assistant professor at the University of Texas at Austin. During this period he was very much interested in constructing quantum field theory without divergence. He reviewed the development of quantum field theory, especially in connection with the divergent problem. After studying all of the

attempts in formulating finite quantum field theory, such as space-time quantization, discrete space-time, non-local interaction, multilocal fields, etc., Dr. Chiang joined the research project on the theory of shadow states. He showed that with the introduction of shadow states the classical electron can be stable and the runaway modes in dipole electrodynamics can be avoided. In addition to his interest in particle physics and field theory, Dr. Chiang also investigated the irreversibility problem in non-equilibrium statistical mechanics. He found that the subdynamics proposed by the Brussels school does not lead to the irreversibility they claimed.

From 1973 to 1974 Dr. Chiang visited the Theoretical Physics Institute at Goteborg, Sweden as a visiting scientist. There he extended his investigation on the finite quantum field theory. He found that theory of shadow states in quantum field theory is consistent with the Bogolimbov boundary condition for a theory with indefinite metric. He also studied the renormalization and asymptotic behavior for a finite quantum field theory.

From 1974 to 1976 Dr. Chiang joined the Max-Planck Institute for Physics at Munich as a senior visiting scientist. There he collaborated closely with Professor Durr on the problem of higher-order derivative quantum field theory. They studied especially the implication of the indefinite metric feature of theory in the Heisenberg's nonlinear spinor theory. In 1976 Dr. Chiang pointed out in a letter published in Physics Letters that the quark confinement models proposed by Schiff or Preparata can be formulated consistently in terms of multilocal fields. Professor A. Z. Capri from the University of Alberta found himself also interested in this problem and joined the investigation. In a series of papers they have constructed multilocal meson and baryon fields and constructed S-matrix for the multilocal fields. This work has initiated the new interest in the multilocal field theory originally proposed by Yukawa.

In 1977 Dr. Chiang was appointed a professor of physics at the Institute of Physics, the National Taiwan Normal University. Apart from his continuing interest in research work on particle physics and field theory, Dr. Chiang was also deeply involved in promoting research in physics in Taiwan. In 1979 the first workshop on High Energy Physics was

held in Taiwan, of which Dr. Chiang was one of the co-ordinators.

In 1979 Dr. Chiang took a leave of absence from the National Taiwan Normal University and joined the University of Texas at Austin as a visiting faculty. He is currently engaged in several research projects in collaboration with the members of the Center for Particle Theory. These projects include, e.g., investigations in the topics of Zeno effect and neutrino astrophysics, supersymmetry with internal symmetry, implication of dynamical symmetry breaking, quantization in curved space-time etc.

RESEARCH HISTORY

S. Nandi - Postdoctoral Research Associate

S. Nandi started his research career in 1972 as a graduate student at the University of Chicago, and also as a research assistant in the Enrico Fermi Institute. In 1973, together with Professor Peter G. O. Freund, he worked on the classic problem of the decay of neutral pion into two photons. The correct decay rate for $\pi^0 \rightarrow \gamma\gamma$ can be obtained by using Partially Conserved Axial Vector Current (PCAC) or by using Vector Meson Dominance (VMD). Freund and Nandi argued, by using duality that the two apparently unrelated pictures for the decay process are equivalent; and explored the consequences by equating the amplitudes obtained via PCAC and VMD. It was found that the strong coupling constant square, $g_{qq\pi}^2$ comes out to be inversely proportional to the number of color of the quarks. (The assumption $g_{\text{strong}}^2 N = \text{constant}$, has been the starting point in analyzing the large N behavior of SU(N) gauge theory, in perturbation theory, by 't Hooft et al). Then they argued that the strong interaction is strong because the quarks appear only in three colors. Using $SU(6)_W$ and also KSFR relation, it was further found that $g_{\rho\pi\pi}^2/4\pi \sim 2.8$, in excellent agreement with experiment.

In 1973-74, S. Nandi, together with Professor Peter G. O. Freund worked on the phenomenology of large transverse momentum exclusive processes. Following the scaling laws proposed by Brodsky and Farrar, and using the compatibility between the scaling and Regge description in the Kinematic region where both applied, they were able to determine the angular distribution of the exclusive hadronic processes. The calculated angular distributions are in good agreement with the available PP, $\overline{P}P$, πP and KP data.

S. Nandi obtained his Ph.D. degree in 1975 from the University of Chicago. His thesis work involved the study of supersymmetric quantum field theories. He made an effort to understand the supersymmetry, introduced by Wess and Zumino, dynamically using the requirement of renormalization compatibility. The Wess-Zumino Lagrangian for the fundamental supermultiplet containing a Majorana spinor field ψ , a scalar field ϕ and a pseudo-scalar field, ϕ' was derived dynamically, starting with the most general renormalizable Lagrangian for these fields, satisfying parity conservation.

The assumptions underlying the proof are: (i) the bare masses of the fields are equal, and remain so after renormalization; (ii) there exist relations among the bare coupling constants and these relations remain preserved after renormalization. This idea was applied by Drs. D. Wallace and R.K.P. Zia to other renormalizable field theories.

In 1975-76, Dr. Nandi worked at the Enrico Fermi Institute as a research associate, under the general guidance of Professor Y. Nambu. At this time, he got interested in the phenomenology of deep inelastic leptonic processes. Neutrino, electron and muon inclusive data were used by him to understand the structure of the weak currents and also the number of quark flavors.

In 1976, Dr. Nandi joined the Department of Physics, the University of Bonn, West Germany as a visiting scientist. He continued his work on the phenomenology of deep inelastic lepton scattering. With Mr. H. R. Schneider, he estimated the multi-muon production in deep-inelastic muon-nucleus scattering. With Dr. G. C. Branco, he analyzed the available neutrino data to determine the structure of the weak neutral currents within the framework of $SU(2)_L \times U(1)$ gauge theory. V-A structure of the weak leptonic current was also analyzed in the light of then available multi-muon data in deep inelastic neutrino scattering (in collaboration with Dr. G. C. Branco, Mr. H. P. Nilles and Dr. V. Rittenberg). In Bonn (1976-78), Dr. Nandi also worked on the phenomenology of strong interaction. He (in collaboration with Mr. H. R. Schneider and Dr. V. Rittenberg) applied the quark-parton model to understand the general features of the inclusive low p_T hadronic processes. Quark and gluon fusion model was shown to give good fit to all the inclusive hadronic data. The gluon fusion mechanism was predicted to be the dominant one for ψ -production at Fermilab and ISR energies, and the ratio of the yield of ψ in P-P and $\bar{P}$ -P scattering was predicted as a function of energy. This was later confirmed by the Chicago-Princeton group at Fermilab. Also, the available data on ψ -production were used by Nandi and Schneider to extract the gluon distribution inside the proton. The gluon distribution was found to be, $G(x) \sim \frac{1}{(n+1)} \left(\frac{1-x}{x}\right)^n$ with $n = 5 \pm 1$; in good agreement with the data at this time.

While in Bonn, Dr. Nandi (in collaboration with Dr. W. C. Ng) worked the general problem of coupling constant relations in renormalizable field theories. Using renormalization group approach, they analyzed the con-

ditions in which several coupling constants, in a field theory, can be related to each other; the relations being independent of the choice of the renormalization point. In particular, they investigated the criteria for the feasibility of a power series relations among the various coupling constants, in various theories. It was shown that such a power series relation exists, order by order in perturbation theory, in spontaneously broken gauge theories (with Higgs scalars) when the gauge group is a simple one. Application to the Weinberg-Salam model (including Higgs scalars), gave, in lowest order, the Higgs mass to be ~ 240 GeV.

From 1978-80, Dr. Nandi was at the Ohio State University as a research associate. He worked in the area of SU(5) and SO(10) Grand Unified Theories, fermion masses and mixing angles in gauge theories, and also in the application of the QCD perturbation theories to the jet structure in e^+e^- annihilation, and in hadronic p-p scattering. The details of these works have been given in the accompanying progress report.

Starting September 1, 1980, Dr. Nandi has joined the Center for Particle Theory.

RESEARCH HISTORY

Allen Stern - Postdoctoral Research Associate

From 1975 to 1979 A. Stern was a Research Associate at Syracuse University under the guidance of Professor A. P. Balachandran. The topics which he investigated were charge monopole scattering, dynamical systems on group manifolds and dual string models and their interactions.

Regarding the first topic, charge monopole scattering, Stern (with A. P. Balachandran, S. Borchardt, S. S. Chang, R. Cahalan, R. Ramachandran and H. Rupertsberger) derived a semichlassical approximation (starting from the Feynman path integral) for the electric charge-magnetic monopole differential cross section. The problem was non-trivial because of the presence of many classical trajectories at large scattering angles. The analyticity of the exact quantum mechanical scattering amplitude was also investigated.

Concerning the second topic, Stern (with A. P. Balachandran and S. Borchardt) found a Lagrangian description for particles with internal spin in interaction with an arbitrary gauge field. The Lagrangian possessed the unique feature that it was defined on a group manifold. This feature was found to have application in three other problems. In the first problem, the dynamics of a spinning particle interacting with gravity could be formulated on the Poincare group manifold. Along these lines, Stern in collaboration with A. P. Balachandran, G. Marmo and B. Skagerstam developed an action principle leading to the Mathisson-Papapetron equations. The second problem was concerned with the dynamics of the charge monopole system. It was found that this system could be formulated on an $SU(2)$ group manifold. This treatment, unlike previous treatment, had the advantage that the action was globally defined and contained no "Dirac string" singularities. This investigation, along with a supersymmetric extension, was carried out in collaboration with Balachandran, Marmo and Skagerstam. In the third problem, the role of group manifolds in the description of non-linear field theories was shown (with Balachandran and G. Trahern).

Concerning the third topic, A. Stern (with Balachandran and Skagerstam) generalized the previous work on particle interactions to include dual string interactions. Upon coupling strings to gauge theories, the strings were found to have properties similar to superconductors. Similar results were found for the coupling of higher dimensional objects (shells and bags). The dynamical system developed above was employed in studies of the QCD vacuum. In collaboration with Skagerstam, Stern demonstrated that the dynamics of a "hole" in a (dual) superconducting 4-volume was identical to the dynamics of gluons in an MIT bag. They also showed that glue bound states can occur in the (Copenhagen) vacuum, although they are highly unstable.

RESEARCH HISTORY

Prashant M. Valanju - Instructor and Postdoctoral Research Associate

Dr. Valanju joined the Center for Particle Theory, Physics Department, the University of Texas in mid-January 1976, as a research assistant, to work under the supervision of Professor Sudarshan.

He reviewed experimental data on possible CP-violation in K-decay to check for alternative explanations. This problem is also connected with the general problem of description of decaying particles in field theory.

He examined, with Dr. Mahajan and Dr. Quadir, the forces acting on a charged test particle approaching a charged, rotating spacetime singularity. They found that a short range, strong repulsive force acts on the test particle, never allowing it to come too close to the singularity. They also examined a possible way to modify quantum mechanics at very short distances to explain confinement and asymptotic freedom.

He worked with Dr. Sudarshan and Dr. Chiu on the application of Zeno effect to high energy hadron nucleus collisions. They found that the reduction in pion production in these interactions is very well explained by the simple quantum mechanical Zeno effect.

He worked with Dr. E.C.G. Sudarshan, Dr. A. Gleeson and Dr. C.C. Chiang on the formulation of Zeno effect in relativistic many body theory and its application to superdense matter in astrophysics. The results of this investigation are in process of publication.

He was awarded a Ph.D. degree based on the results of his investigations of Zeno Effect in 1980.

He is currently working with Dr. Gleeson on a new formulation of Fermion transport in superdense matter which will take into account the wave-nature of the Fermions.

RESEARCH HISTORY

Manuel Gadella - Visiting Research Associate

From 1971-1976, while a teaching assistant in Facultad de Ciencias, Universidad de Valladolid, Manuel Gadella wrote his "Tesis de Licenciatura" on "Exact Mass Renormalization in non-relativistic quantum electrodynamics", under Prof. E. Santos. A calculation of Lamb's effect to all orders was also done. Later on, and also with E. Santos, he tried to perform the same calculations by using some special kinds of diagrams. With Dr. Y. Carinena and Prof. E. Santos, he studied the algebra of functions of a random variable, and its consequences in the description of states and observables in classical and quantum mechanics.

From 1977-1979, M. Gadella was a Lecturer at Universidad de Santander. During this time he worked with Prof. E. Santos on a model of "Generalized Weyl's transformations". In this model they considered correspondence rules between quantum observables and states, and general sample spaces and random variables. After some very general results, they were able to represent non-relativistic quantum states as a class of probability measures in some sample space. They also studied the correspondence between states in stochastic and quantum electrodynamics (non-relativistic), and they found out that at least some coherent states overlap both theories.

In the fall of 1979 and the spring of 1980, M. Gadella visited Princeton University. In this period, he wrote a paper about a classical stochastic description of the quantum Ising model. The most striking result coming in this paper is that quantum mixture states are irrelevant in this model (for a finite number of sites).

RESEARCH HISTORY

Patrick J. Moylan - Research Assistant

As a student at the University of Texas at Austin, Patrick Moylan became interested in the Mossbauer effect. He applied this effect to the study of the structure of the chemical compounds $\text{Fe}(\text{8-QS})_2 \times 1\frac{1}{2}\text{H}_2\text{O}$ where X is an appropriate halogen-like compound (Cl, Br, I, NCS). His experimental results provide further verification for the magnetic moment versus spin of the metal ion law of chemical compounds.

While working on his masters thesis, he became interested in the SU(3) and SU(4) scheme of particle classification. Working with A. Bohm and others at Texas he applied a phenomenological theory, based on SU(n) as a spectrum generating group for the hadrons, to the calculation of the radiative decays of the vector mesons. Recently, this theory has obtained amazing success through the work of J. Werle, A. Bohm, A. Garcia, R. B. Teese and P. Kielanowski.

Since the spring of 1978 P. Moylan has taken up a study of gauge theories. He is interested in applying a gauge theory to the strong interactions. One such proposal he is currently working on is that of the SO(4,1) gauge theory of strong interactions first proposed by W. Drechsler (Munich).

After obtaining his masters in summer of 1978, Moylan took up a theoretical problem which he worked on for one year: to describe the bound and scattering states of the hydrogen atom by a fiber bundle over the configuration space of the center of mass. It is a model for an elementary system (a hydrogen atom), which avoids the use of constituents. Forts. Phys. 28, 251 (1980). The model has many uses from a practical point of view, such as the calculation of the matrix elements of the position operator $\langle nlm | Q_\mu | n'l'm' \rangle$ between states of the hydrogen atom.

RESEARCH HISTORY

Hamad Abdulla Alhendi - Graduate Student

With R. Delbourgo we have taken $SU(3) \times SU(3)$ proposed by Han-Nambu as a symmetry group that would explain the decay width of ψ -particles. Thereafter with A. Bohm $SU(4)$ -group has been taken as a spectrum generating group rather than a symmetry group. Later on the de Sitter-group has been suggested as a structure group of de Sitter fiber erected over the space-time manifold that would describe hadrons as extended objects.

At the present time he is working under the direction of Dr. E.C.G. Sudarshan on Quantum field and Gauge theory.

RESEARCH HISTORY

Xerxes R. Tata - Graduate Student

Mr. Tata joined the Center for Particle Theory, Physics Department, University of Texas at Austin in midsummer 1978 as a student working under the supervision of Dr. Charles Chiu.

Drs. C. Chiu, E. Takasugi, R. Kaul and Mr. Tata have developed a formalism to describe (within the framework of the quark parton model) small p_T particle production in high energy hadron collisions. Dr. Takasugi and Mr. Tata have applied this formalism, the basis of which is the recombination mechanism of Das and Hwa together with momentum-correlated structure functions, to single and multimeson, and to baryon production by pp and πp collisions. The study of kp collisions is in progress. Mr Tata is also studying, with Drs. Chiu, Chiang and Sudarshan, the dynamical breakdown of symmetries in Lagrangian field theoretic models.

RESEARCH HISTORY

James Wheeler - Graduate Student

Neutron star matter provides a problem of interest not only to the astrophysicist but also to those interested in many-body theory and elementary particles. During the year 1978, Mr. Wheeler has been investigating two modifications of previous work done with Dr. Bowers and Professor Gleeson.

Their model is based upon mean field theory using phenomenological scalar and vector interactions. One way of modifying this is to add a spin-two interaction. This attractive interaction will lower the bulk-modulus, improving the fit of their model to nuclear matter. An interaction strong enough to bring the bulk modulus down to the accepted value was found to break down (the pressure must be negative at high density) at too low a density, only about 3 to 5 times nuclear density, for the model to be acceptable. If the model is modified by coupling the vector field via a covariant derivative, the high density limit is better behaved, but the bulk modulus is insufficiently lowered. A simpler way to lower the bulk modulus has been found to be the addition of a four-scalar interaction.

A second way of modifying the model is to add charges. In particular there is considerable interest in the possibility of a pion condensate. They have calculated at finite temperature a model based on a 2-pion, 2-nucleon vertex, gauge inclusion of the ρ -meson and a 4-pion vertex fit to the appropriate low energy. In this model pion condensation occurs slightly above nuclear density. A second method of computing the pion threshold is to compute in otherwise non-interacting matter, the first Quantum correction, vacuum polarization, to the pion propagator. For a pseudoscalar coupling this effect is found to inhibit the formation of a condensate, and for the case of an Axial vector coupling initial calculations of the condensate imply a breakdown of the theory for both charged and neutral pions below nuclear density. Wheeler's current research is engaged in a more sophisticated approach to the axial vector coupling problem using a full axial vector propagator.