MASTER

THE UNIVERSITY OF TEXAS AT AUSTIN
PROGRESS REPORT
ON
"RESEARCH PROGRAM IN ELEMENTARY PARTICLE THEORY"
1979-1980

The Center for Particle Theory
THE UNIVERSITY OF TEXAS AT AUSTIN

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I. INTRODUCTION

This progress report of the Center for Particle Theory of the University of Texas at Austin covers the work done during the period of July 1, 1979 to June 30, 1980 and is to be treated as a continuation of our previous progress reports.

The senior academic staff of the Center for Particle Theory has essentially remained the same. Professor Chiu has returned from his extended visit to the Max-Planck Institute. Dr. E. Takasugi left in October for a period at the Institute for Theoretical Physics at the University of Oregon and has subsequently returned to a faculty position in Japan. Dr. Monowar Hossain has joined the staff of the Bell Laboratories. Dr. Changkeun Jue, Visiting Fellow from Korea has stayed on for a second year. Dr. K. Kraus from Wurzburg is a Visiting Scholar from West Germany. Professor C. C. Chiang from the Taiwan Normal University spent the past year at the Center. Dr. Peter Morley has joined the Center as a postdoctoral research associate. Professor W. Drechsler of the Max-Planck Institute is spending the Spring semester in Austin.

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 decaying 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 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 Fermi sea. This 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 system such as neutron star this kind of relativistic field theoretical treatment has been extensively investigated by Professor Gleeson and collaborators.

As we know, in the non relativistic treatment, the particle exchange mechanism can effectively be replaced by potentials. The non relativistic treatment of neutron star 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 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 Mr. P. Valanju have investigated the Zeno effect for superdense matter such as neutron star. It is found that if we take into account of the Zeno effect, the pressure due to boson exchange mechanism is increased and the pressure due to tadpole contribution is decreased as the density increased. 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 in preparation for publication

In those models of hadrons in which quarks are partially confined (e.g. the Pati-Salam model), one expects that, in the early high temperature stages of the standard model of the big bang, hadronic matter and antimatter exist in the form of free quarks. More generally, in any quark model, for sufficiently high cosmic temperatures hadron densities should be sufficiently large so that overlapping precludes identification of a quark as a constituent of any one hadron. As the universe cools and expands, however, a transition temperature is reached at which quark matter condenses into hadronic matter. In ORO-3992-371, Dr. Dicus, Dr. J. Pati of the University of Maryland, and Dr. V. Teplitz of Virginia Tech and the Arm Control Agency give a definite calculation of the temperature at which synthesis takes place. The relative quark-quark separation, $\bar{d}$, is roughly the inverse of the running momentum Q which is used to define the renormalized running mass, $\bar{m}(Q)$, and the running coupling constant, $\bar{\alpha}_s(Q)$, of quarks within the renormalization group approach,

since the average separation "defines" the average effective momentum of the exchanged gluon. The quark masses are small for large density and rise, as the density falls, toward their liberated quark values; this variation has been called the Archimedes effect. As the initially hot, dense universe expands, the falling density implies a rising quark mass. Elementary statistical mechanics arguments give a second relation between the quark density, $n \sim (\bar{d})^{-3}$, and the quark mass. This paper determines a self-consistent separation $\bar{d}(T)$ in the course of maximizing the entropy of a system of quarks, antiquarks, nucleons, and antinucleons. As $\bar{d}$ and $\bar{m}$ increase, hadrons become both non-overlapping and stable. The self-consistent $\bar{m}$ is relatively slowly varying with temperature above the synthesis temperature T_c , but that at T_c , it is almost always discontinuous.

The results for T_c and $\bar{m}(T)$ have two applications:

- (1) There has been considerable interest recently in computing the cosmic ratio of baryons to photons (10^{-9}) within models that enjoy nonconservation of both baryon number and CP. In these models, generation of excess baryons over antibaryons occur at some time after the rate for reactions involving B and CP violation becomes slower than the rate of expansion of the universe, but must be completed before the time when baryons are synthesized from quarks. This time is computed.
- (2) It has been argued by Okun and Zeldovitch that models involving heavy, free, unstable quarks in the early universe can be ruled out since the rapid decay of the quarks would essentially wipe out any excess of quarks over antiquarks prior to the formation of baryons. This comment was based on older estimates of quark lifetimes; better estimates arrive at longer lifetimes. Furthermore, the comment did not take into account the fact that, at high densities, through the Archimedes effect, the quarks have smaller mass and hence their decay rates are suppressed. The results of this work for the variation of $\bar{m}$ with temperature are that $\bar{m}$ goes from low values, at which quark decay is kinematically suppressed, to high values, at which the synthesis of baryons is accomplished, in most cases discontinuously and, in all cases considered, in too small a temperature (and hence time) interval to allow any appreciable amount of quark decays. Thus, the observation of Okun and Zeldovich is limited in applicability to those models which do not enjoy (temporary) asymptotic freedom.

Perhaps the most interesting result of this work was that at the transition temperature the equilibrium quark distribution changes abruptly from relatively low-mass, high-density quarks to high-mass, low-density quarks. This behavior corresponds to a phase transition from quark matter to hadronic matter. It is a result of the procedure of finding a self-consistent value for the quark mass. Analogous calculations for non-Archimedes phenomena do not show phase transitions; examples of such cases are nucleosynthesis at $T \approx 0.8 \times 10^9$ °K and "recombination" ($e+p \rightarrow H+\gamma$) around $T = 10^4$ °K. In addition extensive investigation has been carried out by many workers on QCD predictions for quark stars. These calculations have included in perturbation theory the contribution of the gluon field and of interactions to the energy density. They have also included a running renormalization point, Q , equated to the chemical potential μ ; they have not, however, included the Archimedes effect; i.e. a variation of quark mass with Q . Most of these workers have not found the hadronic matter - quark matter transition in stars to be a phase transition. This work cannot be easily generalized to calculations with the large chemical potentials needed in quark stars because the ideal gas approximation would then be suspect. If we ignore this problem, and if we assume that the Archimedes effect constitutes a valid approximation, then the qualitative conclusion is that quark matter should exist within stars of sufficiently high density and temperature. (The necessary temperature may be well in excess of anything likely in a realistic neutron star.) The transition from baryons to quarks would sometimes be a phase transition but, for other values of the input parameters, quarks and baryons could coexist over a range of temperatures. An example of a phenomena for which a phase transition may occur is the disappearance (or reappearance) of spontaneous symmetry breaking at high temperature.

In 1978 Weinberg and Wilczek introduced the possibility that there exists a new light (≤ 1 MeV) pseudoscalar boson, the axion. The existence of such a particle would explain the absence of CP nonconservation in the strong interactions. However, the existence of such a particle, coupling directly to hadrons and leptons, appears to be in conflict with experiment, particularly reactor experiments in which its production would be expected. In a recent letter Kim proposed a new type of axion that is not obviously ruled out by experiment. He did this by inventing a model in which the

particle appears with a very low mass ($\lesssim 1$ eV), and couples in lowest order only to a new heavy quark. In his model the absence of direct axion coupling to leptons and normal hadrons prevents conflict with experiment.

Any light particle has a potential for playing a major role in stellar energy loss. In a previous paper Dr. Dicus, Dr. E. Kolb of Cal Tech, Dr. Robert Wagner of Stanford and Dr. Teplitz investigated the implications of the Weinberg-Wilczek axion for stellar evolution. Such a particle would remove energy from the stellar thermal bath either directly or through the Primakoff process. They showed that the existence of helium-burning stars (red giants) implies a lower mass bound of about 0.3 MeV for the Weinberg-Wilczek axion and that, for this case, the direct process is more important than the Primakoff process. The effect of the light Kim axion on stellar energy loss rates has now been investigated by the same authors.

The previous paper gave a lower bound on the mass of the Weinberg-Wilczek axion. This is because helium burning occurs at temperatures of about $T = 10^8 \text{ } ^\circ\text{K} \approx 10^{-2} \text{ MeV}$ so that production of an MeV-range particle occurs from the high-energy tail of the photon distribution and grows exponentially with decreasing particle mass. The principal result of the present work will be upper bounds, from stellar energy loss, on the mass of the Kim axion. This is because in Kim's model, axion couplings decrease with decreasing axion mass so that, as pointed out by Kim, stellar evolution will not be affected by an axion of sufficiently small mass. In the present case the Primakoff process will be more important than the direct process since the axion considered here does not couple in lowest order to leptons or light quarks.

The principal result is that the axion in Kim's model must have a mass less than $6.3 \times 10^{-3} \text{ eV}$ for $e_Q = -1/3$ or less than $9.0 \times 10^{-2} \text{ eV}$ for $e_Q = 0$ in order that energy loss by axion emission not prevent Helium burning as observed in red giant stars.

It is also noted that a cosmic background of unstable long-lived axions would contribute to measured photon fluxes but that at the present level of such measurements, possible axion masses are not restricted by the data.

Also the present data on the gravitational constant does not provide a

lower bound on the axion mass and that future experiments will not correct this condition.

Recently Dover, Gaisser, and Steigman considered the astrophysical consequences that would follow from the existence of a new massive, neutral, stable, strongly-interacting baryon, H^0 . Such particles could appear, and are in some cases required, in certain models. Dover et al. point out that, even if the cosmic number difference between H^0 and its antiparticle $\bar{H}^0$ vanished, H^0 and $\bar{H}^0$ would both be present in small quantities ($H^0/p \approx 10^{-10}$, roughly independent of the H^0 mass) at the time of cosmic nucleosynthesis and that they would be incorporated into $Z > 1$ nuclei at that time. Middleton et al. subsequently searched for an isotope of oxygen with an anomalously heavy mass (4-38 GeV) and set a limit of 10^{-16} on its terrestrial abundance.

In OR0-3992-370 which was published in Physical Review Letters, Dr. Dicus and Dr. Teplitz calculate the abundances of anomalous isotopes that would be expected from the standard model of big bang nucleosynthesis. They apply the results of the detailed, coupled-channel computer calculations using nuclear reactions of normal nuclei that could be analogous to reactions of interest for anomalous nuclei.

They assume that the H^0 has $I = 0$, that the $N-H^0$ force is similar to the $N-\Lambda$ force, and that the pattern of stable H^0 -nuclei and their reactions is the same as that of Λ -hyperfragments. Because the H^0 can be distinguished from n , it will occupy the lowest nuclear shell; and, because it has $I = 0$, it does not feel the one pion exchange potential.

Just as almost all neutrons end up in ${}^4\text{He}$ so will most H^0 's end up in ${}^5\text{He}^*$. (The * indicates an anomalous nucleus.)

In "normal" nucleosynthesis the absence of a stable, mass-5 helium isotope greatly reduces heavy element formation, since Li production then requires d or ${}^3\text{H}$ reactions instead of a proton reaction and these rates are suppressed by the small factors d/p and ${}^3\text{H}/p$. For anomalous nuclei the "gap" would occur at mass 6 but the existence of a stable, mass-6 hyperfragment, ${}^6_\Lambda\text{He}$, indicates the gap is filled by ${}^6\text{He}^*$. However, if the strong interaction ${}^6\text{He}^*(p,d){}^5\text{He}^*$ is exoergic, as indicated by the binding energies of the corresponding hyperfragments, then it will dominate and no significant amount of ${}^6\text{He}^*$ will be allowed to build up.

Production of Li^* requires ${}^6\text{He}^*$ or else it is forced to go through ${}^5\text{He}^*(\text{d},\lambda){}^7\text{Li}^*$ and ${}^5\text{He}^*({}^3\text{H},\lambda){}^8\text{Li}^*$ and thus is suppressed. The predictions are

$$\frac{{}^7\text{Li}^*}{\text{Li}} = 3 \times 10^{-14}$$

$$\frac{{}^8\text{Li}^*}{\text{Li}} = 3 \times 10^{-13}$$

which are just on the limit of what can be seen in the experiment of Middleton et al.

${}^8\text{Be}$ is unstable leaving the normal elements with a second mass gap at 8. ${}^9\text{Be}$ is stable, however, and nicely prevents the mass gap in anomalous nuclei at mass 9. Further, the strong reaction which depletes ${}^9\text{Be}^*$ requires the use of deuterium (${}^9\text{Be}^*(\text{p},{}^3\text{He}){}^7\text{Li}^*$ is endoergic) and is thus suppressed. The observed abundance of Be is about $10^{-10.7}$ and thus ${}^9\text{Be}^*/{}^5\text{He}^*$ is enhanced by a factor of $\sim 3 \times 10^4$ over ${}^9\text{Be}/{}^4\text{He}$. This means

$$\frac{{}^9\text{Be}^*}{\text{Be}} = 3 \times 10^{-6}$$

This would appear to make Be the best light element to check for possible existence of H^0 and H^0 . A calculation of boron gives

$$\frac{{}^{11}\text{B}^*}{\text{B}} = 6 \times 10^{-15}$$

since deuterium must be used to create it. (Hyperfragment binding energies imply that ${}^{10}\text{B}^*$ would β -decay to ${}^{10}\text{Be}^*$.) Based on these numbers it was recommended that further searches for H^0 's be directed to Beryllium and such an experiment, by Middleton et al., is currently underway.

During the past year Professor Gleeson and Mr. Raha have continued their investigation of the properties of superdense matter as they manifest themselves in heavy ion nuclear collisions. After studying and reporting (ORO-361) the formation of relativistic shock waves in infinite nuclear model, they concluded that this was a realistic model for the heating and compression of

nuclear matter in relativistic heavy ion collisions. This lead to an investigation of possible thermodynamic and hydrodynamic effects in the final states of these collisions. DOE-388 reports on a study of the partitioning among species (i.e. pions, deuterons, and nucleons) and spectra of moments observed in these collisions. These studies show that an expanding ball of compressed nuclear matter thermalized by two body strong interactions is consistant with the data. Gleeson and Raha are now preparing for publication a report on a crude two dimensional hydrodynamic calculation of the expansion and evaporation of the hot compressed matter developed by these collisions. For the light nuclei currently available as beams the calculations indicate that the expansion model must be modified to include evaporation and that in fact the final nuclei evaporate almost completely from the expanding matter.

Mr. Raha is completing a dissertation on this subject and will complete his Ph.D. by the end of summer 1980. He currently employed as a post doc at Phillips University of Marburg in Marburg, Germany, working on heavy ion collisions.

Professor Gleeson and Mr. Wheeler have continued their study of pion condensation at finite temperature. They have produced with the relativistic Hartree methods a realistic model which has pion condensation at $T = 0$ occurring at about two times nuclear density. The equation of state at higher temperature lose this condensate. The condensate predicted here does not appreciably affect the pressure energy density relationships and therefore does not affect the maximum mass calculations of neutron stars. This condensate is not present in equilibrium state nuclear matter which has no charge conservation constraints to drive the formations of the condensate.

In preparing the results of this study for publication, Wheeler and Gleeson have examined in some detail the alternative model of condensation based on the assumption of dominance of bubble diagrams in the thermodynamic Green's functions. They have found that the principal effect which produces the low density (approximately one half nuclear density) pion condensate is a nearby ghost pole in the pion's thermodynamic Green's functions. Using this observation they argue that all calculations based on this approach are unreliable and must be replaced by an alternative approximation such

as the Hartree approach discussed above.

This work is a part of the dissertation of Mr. Wheeler and is being prepared for publication.

Mr. Dykema, stationed at Lawrence Livermore Laboratories, and Professor Gleeson with Dr. J. Wilson (staff member at Lawrence Livermore Laboratories) have initiated the development of a fully general relativistic numerical analysis of the collapse of asymmetric distributions of energy. As a first phase of this program they have completed a two dimension numeric code which solves the strong field limits of the Einstein equations. This code is extremely stable and noise free and accepts any time symmetric initial gravitational field configuration. Initial value time symmetric Brill waves with sufficient energy to trap have been run and are observed to self bind. Lifetimes exceeding seven light diameters have been observed. This work is currently being prepared for publication. Mr. Dykema is using this material for a significant portion of his dissertation. He has been offered a post doctoral appointment at the Center for Relativity Studies at the University of Texas. He is expected to continue his collaboration with Wilson and Gleeson on the remainder of this program as described in the associated proposal.

While at Texas, Dr. Morley has studied the problem of quark confinement, using some ideas which were in his research notebook. It would have been anticipated, that the probability of coming up with any new insight into this well-trodden problem is low: but report ORO-386 reveals a physical picture of quark confinement that is new, original and pretty. Dr. Morley begins by devising the non-abelian London equation in broken non-abelian gauge theories and finding the solutions. The London equation, whether in abelian or non-abelian theories, is the principal equation describing gauge symmetry breakdown. Morley shows that color confinement on the quantum level results in exponential clumping of color currents on the macroscopic level. However, to prevent high energy gluons from tunneling through the vacuum, a necessary and sufficient condition is that they become infinitely massive away from the vacuum-matter boundary. Dr. Morley then gives a simple proof that color confinement is dynamical symmetry breakdown of $SU(3)$ with the gluons acquiring infinite mass. The exact mass generation is then studied and arguments are given that gluons bind

to form color glue balls, which have a vacuum expectation value. Dr. Morley argues that there should be 2-(8), 1-(10), 1-($\overline{10}$), 1-(27) colored scalars which cause the complete dynamical symmetry breakdown of SU(3) color. In the most important part of the report the mass of the gluons is derived and a localized vacuum expectation value hadron-bag emerges. The necessary condition that color confinement occurs is that the Callan-Symanzik function, $\beta(g)$, possesses an infrared stable fixed point

This research described below is being readied for publication by Dr. Morley. One of the interesting possibilities in electro-weak theories is the restoration of symmetry breaking at high temperature, first pointed out by Kirnitz and Linde (1972). Subsequently, Kislinger and Morley showed that in the limit ω fixed, $|\vec{k}| \rightarrow 0$ of the gauge propagator produced a mass $\sim g^2 T$, the so-called "plasma mass". However, it was argued that the reverse limits $|\vec{k}|$ fixed, $\omega \rightarrow 0$ was more appropriate for the early universe and that the gauge bosons have no mass, Linde, Ann. Phys. (N.Y.) 101, 195 (1976). It has been known for a long time by Morley and Kislinger that this is not true since a detailed calculation of $|\vec{k}| \rightarrow 0$, $\omega \rightarrow 0$ arill reveals a pole in the gauge propagator and the invalidation of gauge symmetry restoration. Dr. Morley has got so sick of reading the references to Linde's paper, he is publishing the result.

B. Phenomenology of Weak and Electromagnetic Interactions

The number of types of neutrinos is of interest to both astrophysics and particle physics. Particle physicists have a strong belief that each neutrino has associated with it a charged lepton and each of these pairs of leptons are matched by a pair of quarks. Thus the number of neutrinos tells the total number of different particles. Astrophysicists have a strong belief that the mechanism of nucleosynthesis of ^4He in the early universe is well understood. The amount of ^4He depends sensitively on the expansion rate of the universe which, in turn, depends sensitively on the number of relativistic particles. In particular, it has been recently argued that the present Helium abundance of less than 29% requires the number of types of neutrinos, N_ν , to be not more than seven. (Additional neutrinos cause the universe to expand faster, allowing less time for neutrons to convert to protons and essentially all the unconverted neutrons end up as ^4He .) There is some belief that the upper bound on the primordial ^4He abundance can be taken to be 25% which would require N_ν to be not greater than the three neutrinos presently known.

Ma and Okada have proposed that the colliding beam process $e^+e^- \rightarrow \gamma\nu\bar{\nu}$ can be used to determine N_ν . The dominant diagram for this reaction is where the e^+e^- pair form a neutral vector meson, Z , which can then couple to any neutrino type. They considered primarily the beam energies attainable at PEP or PETRA; E equal 15 to 18 GeV. At these energies the cross section is small, $\sigma \lesssim 10^{-38} \text{ cm}^2$, but if the background is also sufficiently small the experiment may be feasible. Gaemers et al., anticipating the next generation of machines, extended the calculation of the cross section to energies at and above the position of the Z pole. Dr. Dicus, in ORO-3992-364 showed that the background due to $e^+e^- \rightarrow 3\gamma$ is certainly not small at PEP or PETRA energies and that this experiment will have to wait for the higher energy machines.

Assume that the photon detector covers a polar angle from θ_0 to $\pi - \theta_0$ and all 2π of the azimuthal angle and that some minimum photon energy, $E_{\min}$, is required to trigger it. The background is where one of the photons, say the one with k_2 , goes through the detector, $\pi - \theta_0 > \theta_2 > \theta_0$, with $\omega_2 \geq E_{\min}$ while the other two go out the ends, $\theta_1 < \theta_0$, $\theta_3 > \pi - \theta_0$. The only other region which must be included is where one of the other two photons goes

through the detector, $\pi - \theta_0 > \theta_3 > \theta_0$, but with $\omega_3 < E_{\min}$. The cross section for this combination of configurations is $\sim 10^{-35} \text{ cm}^2$ at E equal 20 GeV; this is 3 orders of magnitude above the $\gamma\nu\bar{\nu}$ cross section.

The leptonic decays,

$$\begin{aligned}\Omega &\rightarrow \Xi e\bar{\nu} \\ &\rightarrow \Xi \mu\bar{\nu} \\ &\rightarrow \Xi^* e\bar{\nu} \\ &\rightarrow \Xi^* \mu\bar{\nu},\end{aligned}$$

are rare but observable. The branching ratio for these modes is expected to be of the order of 10^{-2} . The CERN SPS charged hadron beam has been in operation for two years during which several thousand Ω^- decays have been detected. Thus, even though the branching ratio is small, the time seems right to attempt a careful calculation of the semi-leptonic modes listed above. This has been done by Dr. Dicus and a student, John Letaw, in ORO 3992-368. Several attempts at calculating the $\Xi\ell\nu$ modes were made shortly after the Ω^- was discovered. Those results are incomplete because of an ignorance of the axial vector current form factors. Only a rough estimate of the widths for the $\Xi^*\ell\nu$ modes has been made.

To attempt to improve on these previous calculations Dicus and Letaw work in a specific model designed for the decay of higher spin particles. The model is based on the idea that the weak interaction actually takes place between s-wave, spin 1/2 quarks. Thus if the hadronic matrix element of the weak current is expanded in multipole moments, those moments with $J > 1$ will be zero. Together with CVC or PCAC this will serve to determine most of the matrix element. In addition we now have models which allow accurate calculations of static quantities such as the axial vector coupling constant. They use the M.I.T. bag model for this purpose. Combining these things allows definite predictions for the vector and axial vector width of the $\Xi\ell\nu$ mode, the axial vector width for $\Xi^*\ell\nu$.

The lifetime of the Ω^- is not known exactly. The 1978 Review of Particle Properties lists $\tau = 1.1 \times 10^{-10}$ seconds while the recent experimental analysis of Gaillard finds $\tau = 0.82 \times 10^{-10}$ seconds. The accuracy of branching ratios is limited by the accuracy of the total lifetime

measurements. They find the branching ratios for the two cases are

	$\tau = 1.1 \times 10^{-10} \text{ sec}$	$\tau = 0.82 \times 10^{-10} \text{ sec}$
$\Omega^- \rightarrow \Xi^0 e \bar{\nu}$	$0.8 - 1.1 \times 10^{-2}$	$0.6 - 0.8 \times 10^{-2}$
$\Omega^- \rightarrow \Xi^0 \mu \bar{\nu}$	$0.6 - 0.8 \times 10^{-2}$	$0.4 - 0.6 \times 10^{-2}$
$\Omega^- \rightarrow \Xi^{0*} e \bar{\nu}$	$8.9 - 9.2 \times 10^{-5}$	$6.7 - 6.9 \times 10^{-5}$
$\Omega^- \rightarrow \Xi^{0*} \mu \bar{\nu}$	$4.7 - 5.1 \times 10^{-6}$	$3.5 - 3.8 \times 10^{-6}$

The Ξ^* branching ratios are for the axial vector contribution only. The vector contribution is comparable or smaller. In addition the lepton energy spectrum for $\Xi \ell \bar{\nu}$ was determined.

Dr. Morley has carried out the computation of the nucleon-nucleon potential from QCD. This work was initiated at AMES DOE Lab in collaboration with Stanley Williams and Derek Pursey there. The static potential involving the spin-orbit, spin-spin, tensor and scalar pieces has been computed. These look very similar to phenomenological potentials in the literature, thinly giving hope a complete description of the nucleon-nucleon potential is possible. However, the momentum-dependent pieces of the potential have not been finished so the work has not been written up for publication yet, but will be completed by the summer.

M1 transitions in particular $\rho \rightarrow \pi \gamma$ have been investigated using the spectrum generating group (SG) approach which has been developed by A. 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-Gordon 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 (1975); 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 (f. Lobkowicz 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. Even this value is still below the derived theoretical value of ~ 90 keV assuming unbroken SU(3) and the usual form of the current and no satisfactory fit of the radiative decays has been given in the usual theoretical framework. However, the idea of a purely magnetic term in the electromagnetic current operator or equivalent theoretical hypothesis have caught on and led to improved fits. A recent preliminary fit done by A. Bohm in collaboration with Dr. R. B. Teese (University of Mainz) give a satisfactory fit of all radiative decay rates.

The application of the S.G. 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 S.G. 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 $\Sigma^- \rightarrow n e \bar{\nu}$ (T.A. Romanowski et al) deviates again from the predictions of the Cabibbo model but is close to the value obtained in the S.G. approach.

C. Strong Interaction Physics and Quark-Parton Physics

The quark parton model has proved to be quite successful in explaining several features of hadronic reactions. A mechanism to explain large p_T hadron production by lepton hadron, hadron-hadron or e^+e^- collisions was suggested by Feynman and Field. They considered hadron production to be a result of a two-step process viz. a hard quark-quark scattering followed by the subsequent fragmentation of the (large p_T) scattered quarks into hadrons. The extrapolation of this idea to the small p_T regime resulted in a cross section about 50-100 times smaller than the one observed. This led Das and Hwa (Phys. Lett. 68B, 459 (1977)) to suggest that in addition to the above fragmentation mechanism, there was a competing mechanism by which a $q\bar{q}$ pair travelling in the same direction and with comparable momenta could directly recombine to produce the observed hadron. Since the interaction does not involve large momentum transfer at any stage, perturbative QCD methods are not applicable. It is also clear that for large p_T processes, the recombination mechanism contribution would be small. Das and Hwa chose a form for the recombination function (the probability density that quarks with specified momentum recombined into a hadron) and parameterized the two-quark structure function of the proton so as to reproduce the single $\pi^\pm, K^\pm$ inclusive production by pp collisions. Their approach, however, suffered from the fact that the calculation of multiparticle inclusive processes required introduction of ad hoc correlation effects to the multi-quark structure function (MWSF). Thus, their scheme although consistent in itself is devoid of any genuine predictions.

In previous work Dr. Takasugi, Mr. Tata, Prof. Chiu and Dr. Kaul (Phys. Rev. D20, 211 (1979)) have formulated a generalized Kuti-Weisskopf (KW) model for the multi-quark structure functions. The partons inside the hadron are treated as if they obey classical statistics; it is assumed that they are distributed statistically on the longitudinal momentum axis with no correlation among them other than the one that arises naturally on account of momentum conservation. The valence quarks are treated as distinguishable, but the sea quarks of the same species are considered indistinguishable. Single meson inclusive production by p-p collisions is used as an input to parameterize the "primitive" structure functions of the proton (i.e. the

structure functions in the absence of any correlation). The main advantage is that all the $MWSF^S$ can be unambiguously calculated. Inclusive multimeson production, for instance, is then a genuine prediction of the model. We also showed that the Das-Hwa recombination function corresponds to a Gaussian cut-off (of $\simeq 2$ units) on the rapidity gap of the recombining quarks. We found that the results were insensitive to the specific value of the cut-off used.

In a subsequent paper (Takasugi and Tata, Phys. Rev. D, in press) it is shown that the generalized KW model led to new power counting rules for inclusive multiparticle production. The parameter-free predictions for two pion inclusive production from the proton were in good agreement with the UCLA Saclay data.

The systematic method of generating all the $MQSF^S$ enabled Mr. Tata and Dr. Takasugi to bring baryon production within the scope of the recombination model. In a recent paper (Takasugi and Tata, ORO 378), they used the $MWSF^S$ of their earlier papers to extract the three body recombination function from $p \rightarrow \bar{p} X$ data obtained at Fermilab. Once again it is found that the results are rather independent of the details of the specific choice of the recombination function.

Mr. Tata and Dr. Takasugi have then used the pion structure function obtained from the preliminary analysis of single meson inclusive production data in the fragmentation domain of the pion together with the baryon recombination function to make parameter-free predictions for $\pi^\pm \rightarrow pX$ and $\pi^\pm \rightarrow \bar{p}X$. The results are in good agreement with the data. Mr. Tata and Dr. Takasugi have also obtained reasonable agreement for inclusive $\bar{\Lambda}^0$ production from the proton.

The success of the recombination model associated with generalized Kuti-Weisskopf structure functions, together with the fact that the results are relatively insensitive to the recombination function, the only dynamics introduced in the model, suggests that the gross features of low p_T hadronic reactions can be rather simply explained. Excluded from their analysis, of course, are reactions where the correlations between quarks cannot be neglected as in the KW mode, examples of such reactions are when two or more

valence quarks of the initial hadron combine to form the produced particles. In any event, the extent to which the observed multiparticle correlations deviate from our simple model may be regarded as a measure of how much the phenomenon is dependent on the dynamics.

There are also other fundamental limitations of the model. For instance, the invariant masses of the recombined hadrons are not specified within the model. An example would be that within the model, the π and ρ productions cannot be distinguished. Also there are several parameters involved in the $q\bar{q}$ sea structure functions and in the recombination function. It would be desirable, if these parameters can also be independently determined from other considerations. It turns out that the Dual-Topological Unitarization (DTU) scheme, as we shall come back later, does provide a way to estimate some of these parameters.

In the past year, the main research of Professor Chiu and Dr. Tow and their collaborators has been to understand high energy collision phenomena from the point of view of the constituent picture based on QCD. Their contributions in this area can naturally be grouped into the following topics: A QED-analog model for QCD- $q\bar{q}$ pair creation, QCD bremsstrahlung process based on the perturbation theory and its application to e^+e^- data, DTU-parton model for pA collisions, and its generalization to other processes.

In a Physical Review article (coauthored with S. Nussinov), Professor Chiu investigated the QED problem of pair creation in slowly varying and essentially constant fields using the momentum space Feynman diagrams for the pair production amplitude. When the production occurs via many interactions with small energy transfer, the problem can be viewed as an integration along different paths in energy space. An estimate via an integration over the optimal path given by Hamilton's principle, a Lagrange equation is introduced and discussed. Their new result relevant to e^+e^- phenomenology is that, in the C.M. frame of the pair, the magnitude of the momentum of each particle of the pair is limited. Now the QCD confinement model suggests that the singlet $q\bar{q}$ system with large invariant mass should form a flux tube. So it is suggestive that the $q\bar{q}$ pair created within the tube, which will lead to the subsequent breakup of the tube, should have limited transverse momentum (p_T), in turn the limited p_T for the broken up of the tubelets or the hadrons.

The parameter free p_T -dependence predicted by the QED-analog model has been compared with the available SLAC data. The model prediction agrees with the data reasonable well. (See Chiu, Proceedings of the Moriond Conference, 1979).

Professor Chiu and Dr. J. Szved have also attempted to understand the general description of the e^+e^- data from the point of view of perturbative QCD (PQCD). Among the results of their investigations, they found that the first gluon emission in e^+e^- collision takes a time $\sqrt{s}/s_1$, where s is the cm energy square of e^+e^- collision, and s_1 is the four momentum square of the off-shell quark. The same result has also independently been found by other authors. In view of the possibility of the long time involved, they argued that in principle QCD jets should consist of two components, the nonperturbative or the fixed- p_T component, and the perturbative or the conical component. (See Chiu, Proceedings of the Kazimierz Conference, 1979). Unfortunately at this point the two component prediction is not specific enough to warrant a careful analysis in this context.

Recently there has been some progress in understanding the small p_T physics from the point of view of the DTU model. In particular, making use of the specific parton model interpretation, Cohen-Tannoudji et al. and Capella et al. have found several predictions of the DTU model, which are in reasonable agreement with the data. For definiteness, we shall refer this specific parton picture - the implementation of the DTU scheme as the DTU-parton model. For instance Cohen-Tannoudji et al. have shown that the powers of x and $(1-x)$ in the structure functions and fragmentation functions of the parton model can be directly correlated to known Regge intercepts. Furthermore, DTU-parton model is applicable to the entire phase space region, which is to be in contrast to the recombination model, where its applicability is restricted only to the large- x domain.

Professor Chiu and Dr. Tow together with two Chinese collaborators have extended the DTU-parton model to proton-nucleus collisions. The qualitative idea of their work is as follows. First consider pp multiparticle production. An analysis of the asymptotic contribution to the topological pomeron reveals that the dominant contribution of multiparticle production is given by the two string contribution. One string is tied to the target nucleon and the other tied to the projectile nucleon. Now in general the breakup of the

string corresponds to a long time process. Thus when one considers hadron-nucleus collision, the projectile string will collide with the subsequent nucleons before the breakup occurs. So after ν -collisions, $\nu+1$ strings are obtained giving a multiplicity ratio for pA collision to pp collision: $(\nu+1)/2$, which is in reasonable agreement with the data. This work has been published in the Physical Review Letters.

Presently, Professor Chiu and Dr. Tow are extending their DTU-parton model to other hadron-nucleus collision processes. Their preliminary conclusion is that, they found an approximate ν -universality of the inclusive momentum distribution for different processes.

Since the last progress report, Professor Chiu has also completed some phenomenological analysis work in hadron-nucleus and heavy-ion collisions in collaboration with the Kiev group (a paper to appear in Physical Review C). Based on the general framework of a fireball model, they analyze the observed momentum spectra of protons and light nuclei produced in high energy hadron-nucleus and nucleus-nucleus collisions. The data including the phenomena of cumulative effect have been accounted for within this approach. In the context of analyzing the relative yield of the light fragments in heavy ion collisions, they have presented a thermodynamic description of highly excited nuclear matter.

Professor Chiu has also devoted some attention to matter wave interferometry in connection with the application of cold neutron physics. In a matter wave interferometry experiment, typically a particle beam is coherently split into two beams which are sent through some system of mirrors, media, fields or crystals and then recombined at a detector which measures an intensity depending on the phase difference of the two beams. In the process of exploring the possibility of constructing a gigantic neutron interferometer on earth making use of ballistic trajectories, Professor Chiu and Professor Stodolsky have found a theorem, which explains how various cancellations of small perturbations arising in matter wave interferometry can be understood by means of the action principle. In particular, they show that the phase difference for two paths which almost meet classically in space and time is not affected by first order variations of the beam. Similarly when some external influence, such as a potential is applied, the first order effect

arises only from the direct contribution of the influence and not from the changes in the path. Their work is to be published in the Physical Review D.

Dr. Morley has computed the decay $\frac{\bar{\mu} \rightarrow \bar{e} \gamma}{\bar{\mu} \rightarrow \bar{e} \nu \bar{\nu}}$ in SU(5) GUTS. It turns out to be 0 ($(\frac{M_W}{M_X})^4$) and therefore inaccessible to experiment. This low rate in SU(5) GUTS is characteristic of all GUTS for this reaction. However, though small, it may have some as yet unseen cosmological application.

There are at least three different sources of information on $\pi N \rightarrow \pi \pi N$:

- (1) Several groups have performed partial wave, isobar-model analyses of bubble chamber data in the region $W > 1300$ MeV.
- (2) A recent single-arm spectrometer experiment by Bjork et al., has measured the π^+ distribution (in $\pi^- p \rightarrow \pi^+ \pi^- n$) at several energies in the region $1240 < W < 1360$ MeV.
- (3) Current algebra calculations make a prediction for the threshold behavior of the process; this prediction depends on one parameter ξ , whose value ($\xi = 0$) is believed known from quark model considerations. The parameter ξ characterizes the chiral transformation properties of the chiral symmetry breaking term in the Lagrangian that must be present to give the pion its mass.

In OR0-3992-381, published in Physical Review Letters, Dr. Dicus, together with Dr. R. Aaron of Northeastern University, Dr. R. Arndt of Virginia Tech, Dr. J. B. Cammarata of Virginia Tech and N.S.F., and Dr. V. Teplitz investigate the consistency of the information from these three sources. All analyses of the bubble chamber data find a large imaginary part for the amplitude describing $PS11(\pi N)$ production for $W > 1300$ MeV. In the isobar model, this amplitude must dominate at threshold since it is the only one which describes all particles in relative s-waves. Furthermore, at threshold, current algebra is believed to predict this amplitude. Because of the large imaginary part of the amplitude for $W \approx 1300$ MeV, it is clear that unitarity must produce large corrections to the current algebra cross section predictions in the energy region from threshold to 1300 MeV.

In the region $1240 < W < 1300$ the cross sections deduced from the single-arm spectrometer experiment are two to five times larger than the $\xi = 0$ chiral symmetry prediction, although straightforward extrapolation to

threshold suggest $\xi \approx 0$! In this letter they analyze in detail the large corrections to the chiral symmetry contribution; in particular, they find that large $PS11(\pi N)$ production through the tail of the Roper (1470) resonance persists toward $\pi\pi N$ threshold. They are, however, able to separate isobar production from the chiral symmetry contribution, and show that $\xi \approx 0$ implies a contribution from the latter that is consistent with the data, while other proposed values such as $\xi = -2$ are ruled out. This result implies that the chiral invariance of the phenomenological Lagrangian is broken by a term which transforms according to the $(1/2, 1/2)$ representation of chiral $SU(2) \times SU(2)$. This result is consistent with the quark model, hard-pion current algebra, and the $I = 0$ $\pi\pi$ scattering length extracted from K_{e4} decay. The result of this analysis ($\xi = 0$) agrees with previous work in which the size of the $SPL1(\pi N)$ amplitude was used to determine ξ . The present analysis leads to the following picture of the $\pi^- p \rightarrow \pi^+ \pi^- n$ amplitude: Within a few MeV of threshold, the amplitude is well represented by the real contributions of tree diagrams evaluated with the phenomenological Lagrangian with $\xi = 0$. In this region the amplitude has only a $PS11$ wave. By 10 MeV above threshold, interference with dispersive corrections to the $PS11$ current algebra amplitude accounts for 30% of the cross section, and production of p-wave pions accounts for 1% of the cross section. By 50 MeV above threshold, the imaginary part of the $PS11(\pi N)$ amplitude and the dispersive correction to the (real) chiral symmetry contribution, are both as large as the chiral symmetry contribution itself. Furthermore, by this energy, p-wave πN production is of the same order and the $PP11(\pi\Delta)$ and $DS13(\pi\Delta)$ contributions are large enough to affect the π^+ angular distributions, although not the cross section.

In summary, the domain in which the corrections to the chiral symmetry cross section prediction are less than 10% extends to only a few MeV above threshold. Nevertheless, the low and high energy data are sufficiently correlated by unitarity that one can obtain the chiral symmetry breaking parameter ξ by fitting the known π -production data up to 1400 MeV in a parametrized K-Matrix formalism. The result is $\xi = -0.2 \pm 0.3$.

D. Quantum Mechanics, Quantum Field Theory and Fundamental Problems.

It is by now well understood that the equation of motion of a dynamical system may possess a larger group of symmetries than are captured in a Hamiltonian description with associated canonical structure. One can take the point of view that a system is fully defined by its equation of motion and the physical identification of the variables. It is in general possible to set up several inequivalent Poisson bracket structures or phase space each with an associated Hamiltonian all of which reproduce the same equations of motion. Depending upon which of these structures one chooses, a corresponding subgroup of the group of symmetries of the equation of motion is singled out as the one realized via canonical transformations. Professor Sudarshan, in collaboration with Professors Balachandran, Mukunda, Nilsson and Zaccaria has presented a different approach to this question which lays bare a radically new concept of symmetry breaking. Starting with a definite set of equations of motion, one can pick a specific subgroup of the symmetry group of the equations of motion and search for all possible definitions of the Poisson brackets on phase space with the property of being formally preserved under the chosen subgroup. Even for the simplest of systems one finds that this procedure of insisting that the Poisson brackets admit a given group as a group of automorphisms leads to a rich and varied set of results. An allowed bracket structure can be singular in the sense that one has non-trivial neutral elements so that the true number of canonical degrees of freedom is less than the dimension of the phase space with which one started. This leads to the breakdown of symmetries.

Professor Sudarshan and collaborators have studied one example in detail; the system chosen is a particle in three dimensions. $GL(3, R)$ which is an invariance group of the linear equation of motion for the nonrelativistic free particle as well as the isotropic harmonic oscillator is imposed as a group of automorphisms and the consequences are worked out in detail. The six independent variables of the classical system arrange themselves in each acceptable bracket into one canonical pair and four neutral elements. Among the consequences is the breakup of the states of motion into superselected subsets. This study shows the possibility of spontaneous breakdown of symmetry already at the classical level, not in terms of the symmetry being

broken in certain classical "ground states" configuration but rather in the canonical structure itself. This way of breaking symmetry is a promising one since it arises already at the classical level and is thus distinct from the Higgs mechanism.

A paper entitled "The Quantized Scalar Field in Rotating Coordinates" (ORO-3992-382) was written by John R. Letaw and Johathan D. Pfautsch. In this paper several different, but related, questions concerning the extension of quantum field theory to non-inertial coordinate systems in flat spacetime were explored. Previous work done in Rindler (accelerating) coordinates showed that (i) a detector of scalar or electromagnetic fields moving with constant linear acceleration through a vacuum would be excited as if it were in a thermal bath of particles and (ii) quantization of the scalar field using canonical procedure results in the definition of a vacuum different from the vacuum in inertial coordinates. The vacuum in Rindler coordinates appears to contain a thermal spectrum of particles.

Questions which arise from these results are:

- (i) Will the excitation of a detector be thermal regardless of its motion?
 - (ii) Does the detector excitation result from mechanical work done to keep it on its path?
 - (iii) What is the cause of the vacua differing in the Rindler and inertial coordinate systems? Is the difference related to the existence of the event horizon in Rindler coordinates?
 - (iv) Are the particles which the non-inertial detector registers related to the particles occupying the vacuum of the non-inertial coordinate system?
- In order to determine the answers to these questions we performed in rotating coordinates the two calculations previously done in Rindler coordinates. This is an ideal coordinate system for our purposes. It is stationary (time-independent) therefore allowing canonical quantization procedures to be used. There is no event horizon and no work need be done to maintain a detector in uniform circular motion.

Step one was to quantize the scalar field in rotating coordinates. The results were for the most part the same as in Minkowski coordinates. The difference was in the definition of positive frequency modes. Some particles in Minkowski coordinates appear to behave as antiparticles in rotating co-

ordinates. The number operators, however, were determined to be identical in the two coordinate systems. We therefore conclude that the vacua are equivalent. This is distinctly different from the results in Rindler coordinates where the vacua were not the same. This result strongly suggests that differences in the vacuum structure result from the existence of an event horizon in the coordinate system.

In the second part of our calculation the excitation of a detector moving in uniform circular motion was calculated. We found the detector to behave as if it was in a bath of particles which was not thermal. This result is clearly sufficient to answer questions (i) and (ii) above. Somewhat surprising though is the answer to question (iv). The vacua of rotating and Minkowski coordinates are identical yet a detector registers particles. Thus we may answer conclusively that the two sets of particles though seemingly identical in Rindler coordinates cannot be identical. This suggests to us that different vacuum structures in flat spacetime coordinate systems result from an inadequate mathematical treatment of the horizons rather than from any physical differences.

Several applications and generalizations of a new theory of radiative transfer recently proposed by Professor Sudarshan have been worked out by Mr. B. Kagali. This new theory takes into account essential quantum mechanical aspects of radiation that are missing in the usual phenomenological theory and obtains the latter as a limiting case valid for statistically stationary and homogeneous fields. Various optical phenomena are also discussed with the help of a set of generalized, partially coherent, polarized, non-geometric rays derived from the new theory.

One of the most fundamental, yet most tantalizing ingredient of orthodox quantum theory is the von Neumann postulate of state reduction by measurement. To go beyond word pictures and produce a picture of the measurement process in which one could compute the effect of measurement and display the state reduction has been one of Professor Sudarshan's goals. This problem, of course, is intimately related to the problem of irreversibility and stochastic evolution in statistical physics. Using the general theory of dynamical mappings which he outlined two decades ago and which has been extended and applied by Sudarshan and Gorini to a number of systems, Prof-

essor Sudarshan has developed a model of state reduction of arbitrary many level systems. This work is being written up for publication.

Some years ago Professors Sudarshan and Misra had shown that repeated observation of a decaying system led to a Zeno effect. (Elsewhere in this Progress Report we have reported on the application of the Zeno effect to astrophysics; see also, the Archimedes effect).

In his study of decaying quantum systems Dr. K. Kraus, who, while visiting the Center for Particle Theory, investigated the effect of the measurement upon the decay process. He showed (DOE-ER-03992-387) that "Zeno's paradox" is not overcome by taking into account the very large energy uncertainty resulting from measurements performed in very short time intervals as it was suggested recently by Ghirardi et al.

In another paper Dr. K. Kraus (DOE-ER-03992-390) investigates the behavior of decaying systems under continuous observations achieved by a coupling of the decaying system to a counter. He shows that the observation modifies the decay law and similar to the "Zeno's paradox", prevents the decay completely in the limit of a perfect infinitely sensitive counter. However, under practically realizable conditions this effect is not very likely to be observed and leads only to a small and hardly detectable modification of the usual decay law.

Since the publication of the papers by Nambu and Jona-Lasino, and Goldstone, dynamical breakdown of symmetries in quantum field theory plays a very important role in particle physics. A way to understand the mechanism of dynamical breakdown of symmetries is to view it as some kind of "rearrangement" of invariance properties taking place in the dynamical process of going from the bare particles to physical particles given by the theory. By making use of the idea of dynamical rearrangement, Dürr and Saller have claimed that it is possible to construct a theory such that for large distance the dynamical rearrangement induces new degree of freedom and for short distance these new degrees of freedom disappear. Following this line of thinking they have constructed a model in which the hypercharge is an induced quantum number due to the spontaneous symmetry breakdown induced by condensation of fermion pairs. Whether the hypercharge is a fundamental quantum number or only a phenomenological quantum number in the sense that

it is induced by dynamical rearrangement and can only be observed asymptotically is an important fundamental question in particle physics. Professor C. C. Chiang, C. B. Chiu and E. C. G. Sudarshan and Mr. X. Tata have investigated the mathematical structure of the model proposed by Durr and Saller carefully. They find that the hypercharge generator constructed by these authors is not a well defined operator and therefore the model is not mathematically justified. However, this investigation, only finds that the scheme for inducing hypercharge proposed by Durr and Saller is not appropriate. This still does not exclude the possibility that hypercharge cannot be induced through dynamical rearrangement, since in some models studied, symmetry associated with the asymptotic fields can be different from the original symmetry. For example in the spontaneous breakdown of a non-Abelian $SU(2)$ symmetry group, the symmetry associated with the asymptotic fields is not $SU(2)$ but $E(2)$.

To have a better understanding of the mechanism of spontaneous breakdown through dynamical rearrangement, they have started to investigate the symmetry properties of the massive boson bound state in the Nambu-Heisenberg model. It has been demonstrated by Umezawa that through the dynamical rearrangement the physical fermion field becomes frozen and the original invariance turns itself into gauge invariance of a massless physical particle, the Goldstone particle. It seems that one would expect the massive Boson particles also to be frozen. Explicit demonstration of this point is under way.

The question whether the equations of motion determine the commutation relations of quantum mechanics leads to the problem of para-Bose oscillators. The Schrodinger description of para-Bose system with one degree of freedom was examined by Yang in 1951 and more recently a thorough analysis of this problem has been made by Ohnuki and Kamefuchi. Professor Sudarshan and collaborators have studied this problem by making use of matrix representations of the para-Bose oscillators. It is found that the results of Ohnuki and Kamefuchi can be understood at a much more elementary level. The para-Bose problem of two degrees of freedom is much more complicated. Nevertheless, it is still not difficult to obtain the matrix representation for the para-Bose system with two degrees of freedom. Professors C. C. Chiang and E. C. G. Sudarshan have studied the irreducible representation of this para-Bose

system. It can easily be formulated in the language of the group $SO(3,2)$. The irreducible representation of the para-Bose system is obtained as the representation of $SO(3,2)$ reduced with respect to the maximal subgroup $SO(3) \times SO(2)$. The matrix elements of the annihilation and creation operators of the $SO(3,2)$ generators constructed from these operators are given. The values for the Casimir operators are also computed.

In 1976 Dr. Chiang pointed out in a letter published in Physics Letters that quark confinement models proposed by Schiff, Preparata and other authors can be formulated consistently in terms of multilocal fields. In collaboration with Dr. A. Z. Capri, Dr. Chiang has constructed multilocal fields similar to that proposed by Yukawa. They have also constructed S-matrix for the multilocal fields. While QCD is generally believed to be a possible correct theory for hadrons, due to the complicated dynamical structure, the multilocal fields might be viewed as an effective representation for hadrons. For example the two jets phenomena can be described in terms of the multilocal fields. From the experience in the theory with non-local interaction, we know that a formally unitary S-matrix might lead to violation of unitarity in the higher order perturbation calculation. For example it has been demonstrated that in explicit calculation, the fourth order S-matrix for a theory with non-local interaction violates unitarity. For the S-matrix constructed by Dr. Chiang and Dr. Capri, Dr. Chiang has explicitly computed the S-matrix up to the 4th order and showed that the unitarity is satisfied.

The physics of unstable particles and the problem of irreversibility in quantum systems has been of longstanding interest to Professor Sudarshan. 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 of the semigroup law for the evolution of the density matrix representing the unstable state, thereby obtaining for the survival probability an exponential behavior at all times in agreement with the classical prediction. This derivation is 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 semi-group 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, the treatment of unstable states and resonances has been based on the association of such states to second sheet poles of the analytic continuation of the S-matrix in the lower half plane across the cut determined by the absolutely continuous spectrum of the Hamiltonian. Sudarshan et al. conform to this point of view as a working hypothesis, even though there is no logical reason for its general validity. For example, it is possible to construct models in which a resonance appears, whereas the analytically continued S matrix has no poles in the unphysical sheet. Conversely, the Friedrichs model with a non-analytic potential provides an example of a resonance model in which the S matrix is not even analytically continuable. 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. On the one hand, one can consider the system from the point of view of a typical scattering problem. 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, which are interpreted as quasibound states. The mean life of these resonant states is given by $1/\Gamma_0$, if Γ_0 denotes the full width at half maximum. This behaviour of the cross section is 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 been proposed some time ago by Horowitz and Marchand, based on the notion of decay-scattering system. The problem of eigenvalues embedded in the continuum which may dissolve under the action of a perturbation was first considered by Weisskopf and Wigner in connection with the study of the width of spectral lines. Its first mathematically rigorous treatment was given by Friedrichs in a particular model and subsequently developed in a general context, in connection with the theory of spectral concentration. The Friedrichs model is equivalent to the Lee model in the first nontrivial sector, with an unstable V -particle. The theory of dilation analytical potentials, has allowed to interpret 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. As we shall see, a physically motivated selection of the matrix elements of the resolvent which are to be continued is of crucial importance.

In the analysis of the behaviour of an unstable system described by a normalized state vector ϕ prepared at the time $t = 0$, the main object of study is the survival amplitude

$$A(t) = (\phi, \exp(-iHt)\phi), \quad t \geq 0, \quad (1)$$

where H is the total Hamiltonian of the system. In two preceding papers, have been carried out a detailed study of the structure of (1) 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 $(H - z)^{-1}$ and deforming the integration contour, one ex-

presses the survival amplitude as a sum of two contributions:

$$A(t) = A_0(t) + A_\Gamma(t). \quad (2)$$

They have respectively the following forms:

$$A_0(t) = b_0 \exp(-iE_0 t) \exp[-i(\Gamma_0/2)t] \quad (3)$$

and

$$A_\Gamma(t) = \int_\Gamma \exp(-izt) b(z) dz. \quad (4)$$

The purely exponential term (3) arises from the residue of the S matrix at the pole z_0 and, if the resonance is sufficiently narrow, it dominates the survival amplitude over a long range of intermediate times $\tau_1 < t < \tau_2$, with τ_1 and τ_2 being respectively very short and very long as compared to the mean life $1/\Gamma_0$ of the unstable state. On the other hand, the background integral (3), which is performed along a complex contour Γ running below the location of the pole, is responsible for the deviations of the decay law from the pure exponential at short ($t < \tau_1$) and long ($t > \tau_2$) times (estimates of the time parameters τ_1 and τ_2 have been calculated in various models. In the special case of the Friedrichs model, 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 (2)-(4) 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, it is natural to associate the unstable particle to the pole $z_0 = E_0 - i(\Gamma_0/2)$, 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 interpreta-

tion 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. Later, Baumgärtel showed explicitly how, within the rigged Hilbert space formalism, one can associate resonances to eigenvectors of the Hamiltonian, with complex eigenvalues, for a large class of perturbations. Professor Sudarshan's approach is close to his. The main difference is that this author is not interested in the solution of the eigenvalue equation outside the position of the resonances, whereas in our approach such solutions are of relevant importance.

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 H and a suitable nuclear space Φ densely and continuously embedded into 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. Therefore, they can be interpreted as describing the decaying state, much in the same way as the stationary scattering states can be viewed as representing an incoming or outgoing particle in the idealized limiting situation of a well defined value of the magnitude of the momentum.

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. The theory can also be applied to other interesting models.

To recapitulate:

It is well known from the work of Maurin, Gel'fand and collaborators that given a self-adjoint operator A in a Hilbert space H , there exists a (now unique) rigged Hilbert space $\Phi \subset H \subset \Phi'$ such that the dual A' of A in Φ' has a complete set of eigenvectors with at least the points of the spectrum of A as eigenvalues. In general the eigenvalue equation for A' in Φ' has also solutions outside the spectrum. This feature has often been considered to be a nuisance (from a mathematical point of view) and conditions have been given in order that the eigenvalue equation in Φ' has solutions corresponding to the points in the spectrum only. However, there are cases when it is desirable to have eigenvalues outside the spectrum. A first example of this fact was met by physicists in connection with the reduction of self-adjoint representations of a non-compact Lie algebra with respect to a non-compact Abelian subalgebra. As shown for example by Mukunda and collaborators, this problem can be solved strictly within the framework of Hilbert spaces; essentially, the solution amounts to the fact that the direct integral decomposition of the carrier space of the representation with respect to the non-compact generators is such that vectors belonging to the common domain of all the relevant operators are represented by functions which are analytically continuable. Of course, in a Hilbert space setting eigenvectors are envisaged in a formal sense only. In order to solve the problem, while at the same time giving a rigorous meaning to eigenvectors, one has to use rigged Hilbert space techniques. This was first done explicitly by Iverson and later independently by Lindblad and Nagel.

Also, for the description of resonances it is desirable

to have solutions of the eigenvalue equation outside the spectrum. In the approach of Sudarshan and collaborators, which stems from earlier work of some of us about analytic continuation in the Lee-Friedrichs model, rigged Hilbert spaces $\Phi \subset H \subset \Phi'$ such that both the unperturbed Hamiltonian H_0 and the perturbed one H have eigenvalues in regions of the complex plane is considered. Here we wish to point out that the eigenvectors with eigenvalues outside the spectrum of the Hamiltonian have the same physical concreteness as stationary scattering states or plane waves. Indeed, if $G(z_0)$ is such an eigenvector in Φ' with z_0 as eigenvalue, it can be approximated, in a weak sense, by vectors in Φ , i.e., physical wave packets, and the eigenvalue equation can be approximated analogously. To wit, $\forall \epsilon > 0$ and $\forall \phi \in \Phi$, $\exists \psi \in \Phi$ such that $|\langle G(z_0) | \phi \rangle - \langle \psi | \phi \rangle| < \epsilon$ and $|z_0 \langle \psi | \phi \rangle - \langle \psi | H \phi \rangle| < \epsilon$. The families of eigenvectors that are dealt with are also required to be analytic with respect to the eigenvalue, considered as a parameter, in some regions of the complex plane. Once one assumes that resonances are given by poles of the S matrix continued into the unphysical sheet, if one is able to connect the analytic structure of the eigenvector family of the perturbed Hamiltonian to that of the S matrix, resonances appear as poles of the eigenvector family. The interesting fact is that the coefficient of the most singular term in the Laurent expansion of the eigenvector family about the pole z_0 is also an eigenvector with z_0 as eigenvalue. In this way, resonances appear as eigenvectors of H with complex eigenvalues. The family of eigenvectors of H whose analytic structure is linked to that of the S matrix turns out to be the one associated to the "out state" representation of the Hilbert space. In this framework, a rigorous ground is given to the interpretation of the analytic continuation techniques of their previous work in terms of expansions over eigenvectors with complex eigenvalues of the Hamiltonian. As we have eigenvector families which are analytic in some region, we can apply Cauchy techniques to scalar products

between elements in Φ . Such scalar products can be expanded in terms of complete systems of eigenvectors with complex eigenvalues of either H_0 or H . There appears an integral along a contour in the complex plane, plus discrete contributions due to the poles of the eigenvector family. The expansion of the survival amplitude of a state in Φ in terms of eigenvectors with complex eigenvalues breaks down into a sum of terms with exponential (or polynomial times exponential) behaviour in time in correspondence to the singularities of the eigenvector family, plus a background integral, a fact which stresses again the connection between unstable states and resonances. It can be seen also how the resolvents of H_0 and H , reduced to Φ , can be continued across the absolutely continuous spectrum (provided the singular spectrum has good behaviour) into the unphysical sheet. The continuation of the resolvent of H has the same singularities as the continuation of the S matrix; in contrast, the continuation of the resolvent of H_0 is regular at these points.

There is a criticism that could be made about the fact that use is made of a perturbed and an unperturbed Hamiltonian: namely that since nature ignores the unperturbed Hamiltonian, resonances should be entirely characterized in terms of the total Hamiltonian alone. However, it must be maintained that this cannot be the case: in addition to the total Hamiltonian, one needs some further input from physics. This reflects itself upon the mentioned arbitrariness in the choice of Φ and on the fact that the analytic structure of the eigenvector family depends critically upon such choice. This feature can be easily shown again in the example of the Friedrichs model. Let us consider a Hamiltonian H whose absolutely continuous spectrum is $[0, \infty)$ and Lebesgue; it can be assumed to be simple. Then, the restriction of H to the subspace of absolute continuity is given by the operator of multiplication by x in $L^2(0, \infty)$. Let us consider the operator H_0 given by:

$$\begin{aligned}
(H_0 h)(\lambda) = & M\epsilon^2 \frac{f(\lambda)}{\alpha(\lambda + i0)} \int_0^\infty \frac{\overline{f(x)}h(x)}{\alpha(x - i0)} dx \\
& + \lambda h(\lambda) - \epsilon^2 \lambda f(\lambda) \int_0^\infty \frac{\overline{f(x)}h(x)}{\alpha(x - i0)(\lambda + i0 - x)} dx \\
& + \epsilon^2 \frac{f(\lambda)}{\alpha(\lambda - i0)} \int_0^\infty \frac{\overline{f(x)}}{\lambda + i0 - x} \\
& \times \{xh(x) - \epsilon^2 xf(x) \int_0^\infty \frac{f(x')h(x')}{\alpha(x' - i0)(x + i0 - x')} dx'\} dx,
\end{aligned} \tag{5}$$

where ϵ , M , f are arbitrary provided they satisfy certain general conditions. H_0 and H are then immediately recognized to be the Friedrichs' unperturbed and perturbed Hamiltonians, respectively, in the "out state" representation. By means of a unitary transformation, one can obtain poles of the continued resolvent of H , exponential time behaviour, etc., at the zeros of the function $\alpha_{II}(z)$. However, this function depends on the parameters ϵ , M and on the function f , which can be arranged in such a way as to have a zero of $\alpha_{II}(z)$ at any arbitrarily given point of the fourth quadrant. Therefore, given H , one can choose Φ which will depend on the parameters ϵ , M and on the function f , in such a way that the resolvent, as an operator in $L(\Phi, \Phi')$, can be continued across the spectrum into the unphysical sheet with a pole at any given point of the fourth quadrant; to such a pole are associated all the mathematical features of an unstable state or a resonance and, of course, if the imaginary part of the pole is not too large, the physical features too. However, resonances are not seen with any energy and life-time. This suggests that, for a given Hamiltonian system, not all the states in the corresponding Hilbert space are realizable in principle, but that there is a mechanism that selects the

physical states; and this mechanism does not depend on the Hamiltonian alone. Such a mechanism could possibly be the following: the "natural" states for the system are those in the domain of the Hamiltonian; on the other hand, the observer has in the same Hilbert space a "natural" set of states of his own, depending on the structure of the preparing and measuring devices, and at least in many instances, these can probably be described as states in the domain of a fictitious, unperturbed, Hamiltonian H_0 . The observable states should then belong at most to the intersection of such two sets, the system's natural set and the observer's natural set of states, which perhaps could explain why resonances are not found everywhere in the complex energy plane. These considerations reflect themselves upon the arbitrariness of the choice of ϕ in the rigged Hilbert space, and on the dependence of the analytic structure of the eigenvector families upon such choice. In their paper in course of publication in Journal of Math. Phys. (ORO 358), to overcome such arbitrariness. Sudarshan and collaborators have considered the fictitious Hamiltonian as given, and adhered to the point of view that resonances are associated with poles of the S matrix, being well aware that this is not always the case.

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 as a pole and the usual description of states by vectors in a linear space. In a paper that will appear in Journ. 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.

E. Groups, Gauges and Grand Unified Theories

During a recent visiting appointment at the Max Planck Institute in Munich, Professor Bohm has 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 fibre 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 $(4+1)$ -deSitter constraint. A preliminary comparison of the predictions from the deSitter constraint (using variable deSitter radius) with the experimental data for $I = 0$ and $I = 1$ mesons has been performed. This deSitter 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.

The description of known quantum mechanical systems by a fiber bundle has been considered by Mr. P. Moylan (Fortsch Phys. 1980, ORO 3992-375) as a preparatory study for the application of these methods in particle physics.

A fiber bundle description of the Kepler problem and the non-relativistic rotator was discussed.

Professor 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, 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.

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.

Professor Ne'eman has completed the construction of "world spinors". These appear only in the discrete series of irreducible representations of $\overline{GL}(4,R)$ (see articles with Dj. Sijacki in PNAS and Annals of Physics and errata), as in $\overline{SL}(3,R)$, and not in the Principal and Supplementary series as they first thought.

In the search for a generalization of the string algebra to membranes and lumps, Professor Ne'eman has constructed membrane-algebras with a center, as in the dual model (see article with Dj. Sijacki in Jour. Math Phys.) without noticing the need for appropriate conditions, which were recognized by later workers.

The $SU(2/1)$ model for a highly restricted Weak-Electromagnetic unified interaction was further developed by Professor Ne'eman. 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.

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 they have found an extremely satisfactory answer. Together with S. Sternberg (see article to be published

in the Proceedings of the National Academy of Sciences, USA) Professor Ne'eman found representations of $SL(5+k/1)$ of dimensionality 2^{5+k} , containing precisely 2^k "families" (16 fundamental fermions and 16 ghosts). They have also shown that $SU(3)_{\text{color}}$ is selected by the representation structure for the color group uniquely.

Experimentally, Professor Ne'eman predicts that the Higgs meson mass will be found around 240 GeV. The heaviest families will be right-handed.

Professor Ne'eman has also generalized the use of an internal supergroup to deal with other case of spontaneous symmetry breakdown. One such case is that of non-linear chiral $SU(3)$, which we have shown to be equivalent to a linear $Q(3)$ supergroup theory (see article with J. Thierry-Mieg in PNAS)

A project which Professor Ne'eman developed at the Center in 1969-72 with Y. Achima 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, Wilczek and Zee, Weinberg, Susskind and others have now used grand-unification gauge theories, to explain the asymmetry in baryon numbers in the universe, and the ratio of baryons to photons. In doing these calculations, their 1970 results have proved important. Some of the new work was done at the Center

Dr. C. K. Jue and Professor 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. Three papers based on this work are in preparation for publication. Part of the results will be 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 called 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 remain 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 has 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 non-standard 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 study 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-03992-391) is in course of publication in Pramana.

APPENDIX A
TITLES OF DOE REPORTS
SINCE ORO-362

-
- ORO 3992-374 Geometrical Theory of Ghost and Higgs Fields and $SU(2/1)$, Y. Ne'eman and J. Thierry-Mieg
-
- ORO 3992-375 Fiber Bundles in Non-Relativistic Quantum Mechanics, P. Moylan
-
- ORO 3992-376 A Simple Spacetime Description of High Energy Hadron-Nucleus Collisions, Chao, Chiu, He, and Tow
-
- ORO 3992-378 The Recombination Model and Baryon Production by pp and πp Collisions, E. Takasugi and X. Tata
-
- ORO 3992-379 Gamow State Vectors as Functionals Over Subspace of the Nuclear Space, A. Bohm
-
- ORO 3992-380 Four Lectures on Poincare Gauge Field Theory, F. Hehl
-
- ORO 3992-381 Analysis of $\pi^- p \rightarrow \pi^+ \pi^- n$ below 1400 MeV and Chiral Symmetry Breaking, Aaron, Dicus, et al.
-
- ORO 3992-382 The Quantized Scalar Field in Rotating Coordinates, J. Letaw and J. Pfautsch
-
- ORO 3992-383 What Can We Learn from High Energy Hadron-Nucleus Interactions?, D. Tow
-
- ORO 3992-384 Superalgebras, Supergroups and Geometric Gauging, Y. Ne'eman
-
- ORO 3992-385 $SO(4,1)$ as a Structure Group of a Fibre Bundle and $SO(3,2)$ as a Relativistic Spectrum-Generating Group, A. Bohm
-
- ORO 3992-386 A Physical Picture of Color Confinement, P. Morley
-
- DOE 3992-387 A Note on Zeno's Paradox in Quantum Theory, K. Kraus
-

-
- ORO 3992-362 The University of Texas at Austin
Progress Report "Research Program
in Elementary Particle Theory" by
E. C. G. Sudarshan and Y. Ne'eman
-
- ORO 3992-363 The University of Texas at Austin
Research Proposal "Research Program
in Elementary Particle Theory" by
E. C. G. Sudarshan and Y. Ne'eman
-
- ORO 3992-364 Background to Neutrino Counting in
 e^+e^- Collisions, D. Dicus
-
- ORO 3992-365 Spatio Temporal Development of
Hadron-Nucleus Collisions, P.
Valanju, E.C.G. Sudarshan and C.
Chiu
-
- ORO 3992-366 Modification of Quantum Mechanics at
Short Distances-A Simple Approach to
Confinement and Asymptotic Freedom,
S. Mahajan, A. Qadir, and P. Valanju
-
- ORO 3992-367 Reintroducing the Concept of 'Force'
into Relativity Theory, S. Mahajan,
A. Qadir, and P. Valanju
-
- ORO 3992-368 Leptonic Decays of the Ω^- , D. Dicus
and J. Letaw
-
- ORO 3992-369 Discrete States Buried in the
Continuum, E.C.G. Sudarshan
-
- ORO 3992-370 Primordial Synthesis of Anomalous
Nuclei, D. Dicus and V. Teplitz
-
- ORO 3992-371 Synthesis of Baryons from Unconfined
Quarks, D. Dicus, J. Pati, and V.
Teplitz
-
- ORO 3992-372 de Sitter Fibers and $SO(3,2)$ Spectrum
Generating Group for Hadrons, A. Bohm
-
- ORO 3992-373 Isobar production in $\pi^-p \rightarrow \pi^+\pi^-\bar{n}$, R.
Arndt, J. Cammarata, D. Dicus, et al
-

DOE 3992-388 A Thermodynamic Interpretation of
Multiparticle Emission in Relati-
vistic Heavy Ion Collisions, A.
Gleeson and S. Raha

DOE 3992-389 Classification: Physics -
Internal Supersymmetry and
Unification, Y. Ne'eman and
S. Sternberg

APPENDIX B
RESEARCH HISTORIES OF THE SCIENTIFIC STAFF
OF
THE CENTER FOR PARTICLE THEORY
SINCE ORO-362

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 has 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.

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 precise 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 B. 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.

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 $V \rightarrow \gamma$ 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 preceded 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 which 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

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

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 zero 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.

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 " $A\ell^{26}$ 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 preceeding 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

Don M. Tow - Assistant Professor and
Research Scientist (Faculty)

From 1968 to 1971, while a research assistant under Professor Geoffrey F. Chew at the University of California at Berkeley, Don Tow was one of the first people who revived interest in the ABFST multiperipheral model (MPM) as a viable model for high energy multiparticle production. He calculated the quantitative predictions of the model and pointed out its agreements and shortcomings. With Dr. D. R. Snider, he formulated this MPM including interference terms and also calculated the contribution of an important class of interference terms. Then with Dr. S.-S. Shei, he showed that a simple modification of this MPM can also account for certain general features, e.g., Bjorken scaling, of deep inelastic electron-nucleon scattering. In a paper with Drs. D. E. Lyon and C. Risk, he pointed out that the usual relativistic approximation for transforming single particle inclusive angular distributions from the laboratory to the center of mass is incorrect and worked out the correct transformation.

From 1971 to 1973, Dr. Tow was a member of the Institute for Advanced Study in Princeton. There he extended his investigation of the modified MPM to the study of deep inelastic neutrino-nucleon scattering. He also derived the average multiplicity formula in the Mueller-Regge model containing a secondary trajectory and considered its phenomenological implications.

From 1973 to 1975, Dr. Tow was an Assistant Professor (Research) at Brown University. In collaboration with Dr. C.-I. Tan, he pursued the hypothesis that dynamical production of high mass clusters, such as $N\bar{N}$ clusters, is the major reason for the rise of total cross sections at high energies; some preliminary implications for pion inclusive cross sections were pointed out. They also showed that in multiperipheral cluster models, pions cannot be the dominant exchanges, a result which was later confirmed and used by several other authors. They together with Drs. T. K. Gaisser and H. I. Miettinen, proposed several experimental tests to distinguish a peripheral mechanism or a central mechanism for the production of $\bar{p}$'s. Dr. Tow, together with Drs. H. M. Fried, K. Kang, and C.-I. Tan, also suggested the possible existence of $\Omega\bar{\Omega}$ and other $B\bar{B}$ bound states and resonances.

Dr. Tow joined the University of Texas' Center for Particle Theory research staff in 1975. Together with Dr. C. B. Chiu and Mr. M. Hossain, he formulated the topological dual bootstrap model with symmetry breaking and with unequal cylinder and planar couplings. They showed that this Pomeron-f Identity model can explain all meson-nucleon total cross sections for P_{Lab} from 10 GeV/c to 50 GeV/c. In a subsequent paper, they extended the topological dual bootstrap model to include the investigation of its t -dependence and of cut cancellation. They showed that the question of cut cancellation is related to the type of production mechanism and found that even when cuts exist, their discontinuities are always small compared with the corresponding pole residues. They also provided further evidence for the exciting property of precocious asymptotic planarity.

Dr. Tow and Dr. Chiu also showed that the Pomeron-f Identity model is compatible with certain cross section differences as well as the ratios of the real over imaginary parts of the forward π and K amplitudes. This refuted an objection of Freund and Romao to the Pomeron-f Identity model.

Elaborating on the earlier work of Tan and Tow, Dr. Tow and Dr. Chiu made a systematic investigation of the effects of $N\bar{N}$ cluster production on pion and kaon inclusive cross sections. They concluded that the recently observed 30%-40% rise of these cross sections over ISR energies is compatible with the explanation of the opening up of the high dynamical thresholds of producing $N\bar{N}$ clusters.

Together with Dr. Chiu and Dr. G Bialkowski of the University of Warsaw, Dr. Tow formulated a new space-time model (the Modified Cascade Model) for high energy hadron-nucleus collisions. They proposed that particles at the moment of creation are bare or immature, that there is a certain characteristic time (in the particle's own rest frame) after which they become dressed or mature, and the dressing up process is enhanced in the presence of other hadronic matter. They formulated this one-parameter model and showed that it can explain a surprisingly large amount of experimental data: dependences of the multiplicity on incident particle, nucleus, rapidity, and energy, as well as the A dependences of the total inelastic cross sections. They also showed that two popular models, the so-called cut-tupe model and the fan-plus-cut-type model, do not quantitatively agree with the data.

During 1977-1978, Dr. Tow was on a one-year leave of absence to the University of Paris VI in Paris and the University of Paris XI in Orsay, France. Together with Drs. C.-I Tan and Tran Thanh Van, he showed that even though the Pomeron-f Identity model has many nice phenomenological properties, the model in its present versions cannot simultaneously explain total cross sections and vector meson production data. They, however, suggest possible ways out of this difficulty.

In a collaboration with Drs. B. Nicolescu and J.-M Richard, Dr. Tow investigated the physics of multiquark systems to search for a phenomenological manifestation of the concept of hidden color. In particular, they studied the class of $(q\bar{q}q\bar{q})$ states in which each $(q\bar{q})$ pair is in a color-octet representation and the two $(q\bar{q})$ pairs are separated by some angular momentum. They discussed its spectroscopy, production, and decay properties with some emphasis on those states which can appear in e^+e^- and in photo-production experiments.

Dr. Tow in the fall of 1978 returned to the University of Texas as an Assistant Professor and Research Scientist (Faculty). There he continued his research in the area of high energy hadron-nucleus interactions. Together with Dr. Hossain, he extended the Modified Cascade Model of Bialkowski-Chiu-Tow for hadron nucleus collisions to photon nucleus and lepton nucleus collisions. They showed that the model successfully passed several more experimental tests. They also presented several representative predictions of the model for future experiments to test.

Then together with Dr. Chiu and Drs. Chao and He of the Institute of Theoretical Physics of the Academia Sinica in Beijing, China, Dr. Tow proposed an alternative and even simpler spacetime description of high energy hadron-nucleus interactions. The model motivated by recent developments in Dual Topological Unitarization but can also be phrased in the parton model language, showed that the energetic secondaries are never produced until the incident particle has passed through the nucleus. This zero-parameter model agrees well with the general features of the data. Because of the model's underlying basis in recent developments in hadron-hadron interaction, it shows that hadron-nucleus interactions can shed light on the correct theory of hadron-hadron interaction.

Recently Dr. Tow finished a review paper on high energy hadron-nucleus interactions.

RESEARCH HISTORY

Changkeum Jue - Visiting Fellow

Dr. C. K. Jue and Professor 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 variation of superfields under supersymmetry transformation has also 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 investigations by other authors, for the case of $SU(2)$ internal symmetry we 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 with internal spin fields which are equivalent to Bargmann-Wigner equations. Three papers based on this work is in preparation for publication. Part of the results will be presented at the ninth international colloquium on the group theoretical methods in physics, Cocoyoc, Mexico (June 23-27, 1980).

RESEARCH HISTORY

Peter D. Morley - Postdoctoral Associate

During his graduate studies at the University of Chicago, Morley collaborated with his advisor, Mark Kislinger, on the formulation of the statistical mechanics of quantum chromodynamics (QCD). This resulted in the proof of the fundamental theorem of relativistic statistical mechanics, that of the renormalization of the thermodynamic potential, Ω , in quantum field theory. The statement and proof of the theorem was Morley's dissertation (P.R. D17, 598 (1978)). In all, the collaboration between professor and pupil was extremely fruitful (probably because of a good match up in personalities and diverse abilities) resulting in seven papers. P.R. D13, 2771 (1976) showed the cancelization of information to all orders of perturbation theory, in finite temperature field theory. P.R. D13, 2765 (1976) demonstrated the plasma effect for QCD. Phy. Lett. 67B, 371 (1977) proved that the strong force (QCD) becomes weak at high temperatures and/or high densities. Ap. J. 219, 1017 (1978) then used this complete formal program and applied it to neutron stars to compute the equation of state for cold dense baryonic matter above nuclear densities. There emerged two distinct supernova mechanics, that of hydrodynamic bounce and hyperionization. Finally, the temperature effects were computed in Nuov. Cim. 50A, 515, (1979). A formal monograph on these three years of work appeared in Phys. Rep. 51, 64 (1979). This collaboration resulted in the creation of a new field of research which has yet to see its apex. For the last two years Morley has been involved in the calculation of the nucleon-nucleon potential from QCD. This has been in collaboration with the nuclear theorist Stanley Williams and the mathematical physicist Derek Pursey, both of Ames DOE Lab. The research is almost completed. Preliminary results indicate that the QCD derived potential has the correct scalar spin-orbit and tensor pieces, but whether or not the deuteron is bound is not known yet. The uncertainty is due to the unfinished computation of the momentum dysentent pieces of the nucleon-nucleon force. If it turns out that the derived potential from QCD binds the deuteron, along with the correct prediction of its magnetic dipole and electric quadrupole moments, then a new field of research will be opened. In between research in the nucleon force, Morley worked on his model of color confinement, described earlier. At the end of August, Morley will leave the Center in order to take an awarded NATO Science fellowship.

RESEARCH HISTORY

Basavaraj A. Kagali - Research Assistant

In collaboration with Dr. E.C.G. Sudarshan it was observed that regularization of Feynman integrals is necessary to obtain neutral neutrons in gauge field theories and that this result is independent of the method of regularization employed.

In collaboration with Dr. Bohm and others Mr. Kagali worked on the radiative decay of vector mesons.

In collaboration with Dr. J. Wheeler, Mr. Kagali worked on the discussion of the EPR paradox of quantum mechanics in terms of Stokes' parameters.

Currently, Mr. Kagali is working on generalizations and applications of a new theory of radiative transfer recently proposed by Dr. E.C.G. Sudarshan.

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 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. Boh, 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). Moylan is investigating maximally symmetric solutions of the field equations of this non-abelian gauge theory. Using these solutions he hopes to obtain a relation between the mass and spin of the mesons. Preliminary results seem encouraging.

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 $\langle n'l'm | Q_\mu | n'l'm \rangle$ between states of the hydrogen atom.

From 1979 up to the present, along with his work on gauge theories, he has investigated the relativistic rigid body in quantum mechanics. As is well known, the position of the center of mass of a system in relativistic quantum mechanics is not equal to the instantaneous position. Applying this fact to the relativistic rotator, which is a system having a certain Hamiltonian, he hopes to obtain a mass spin relationship which agrees with experiment. Preliminary results are very encouraging.

RESEARCH HISTORY

Sibaji Raha - Research Assistant

In the last twelve months, Mr. Raha has extended his work on successive canonical transformation in action-at-a-distance electrodynamics to the case of a model two-body problem. Starting with the field theoretic hamiltonian, he solved for the field variables in terms of the particle variables only, thereby paving the way to write an action-at-a-distance hamiltonian for the problem. With suitable canonical transformations, the particle-field coupling was shown to be removable up to order e^2 and thereby a scheme for bypassing the no-interaction theorem of Currie, Jordan and Sudarshan for direct action Lagrangians was pointed out. This work was carried out in the non-relativistic domain (for particles executing straight line motion).

With Professor A. M. Gleeson, Mr. Raha has been investigating a model for superdense hadronic matter and its applications to heavy ion collision. With increased capabilities of heavy ion accelerators, the uses of relativistic kinematics and realistic equations of state to explain heavy ion phenomena are becoming manifest. Professor Gleeson and Mr. Raha developed the relativistic equations of hydrodynamic shock formation relevant to heavy ion collisions and used them to investigate the effects of kinematics and the interactions on the thermodynamic state of the fireball.

In the same context, Professor Gleeson and Mr. Raha have also investigated the limits on pionization in heavy ion collision. They have also calculated the possible dissociation modes of the unstable fireball. The angular distributions of the fragments are calculable in this framework. All these results also are dependent on kinematics and the equations of state.

Data for deuteron fragments are available for the collisions of relativistic ions. Professor Gleeson and Mr. Raha advanced a consistent thermodynamical and hydrodynamical picture of multiparticle emission in such cases. They are the first to point out the importance of using realistic interactions in analyzing such processes. These results were reported in DOE-ER-03992-388 (1980) and is to be published.

Under the guidance of Professor Gleeson, Mr. Raha has also initiated an investigation of the bound states of vector gluons. It has been proved that there are no classical bound states of gluons. However, the case in quantum theory is totally different and the existence of bound states of vector gluons will lend more credibility to the non-abelian structure of QCD. Professor Gleeson and Mr. Raha have already discovered that a scale invariant Bethe-Salpeter equation admit no bound states of gluons. One loop corrections are expected to introduce scale violations to the zeroth order bound state equation and may possibly then allow a glueball. This problem and other aspects of a finite density many body formalism are being investigated now.

RESEARCH HISTORY

Prashant M. Valanju - Research Assistant

Mr. 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.

Currently he is working with Dr. Sudarshan, Dr. Gleeson and Dr. Chiang on the formulation of Zeno effect in relativistic many body theory and its application to superdense matter in astrophysics.

RESEARCH HISTORY

James Wheeler - Research Assistant

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.

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 Λ -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.

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.