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Recent and Planned Research

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My main interests are in the non-perturbative aspects of QCD and its implication to the phenomena in the nucleon structure, the nuclear structure, and relativistic heavy ion collisions.

1. QCD and Hadron Structure

(a) OZI Violation in Hadrons

T. Kunihiro (Ryukoku Univ.) and I have been working on the Nambu-Jona-Lasinio description of hadrons and the OZI violation in QCD on the basis of the instanton induced interaction.¹ This is an attempt to unify the constituent quark model and the collective picture of hadrons. The model can relate the OZI violation in baryons with that in mesons. By using the experimental information of the latter, we calculated the strangeness and charm contents of octet and decouplet baryons, which gives useful information to the nucleon structure.

(b) Twist-4 Matrix Elements of the Nucleon

Recent precession measurements of the lepton-hadron deep inelastic scattering at CERN (NMC and BCDMS group) and at SLAC have opened a possibility to extract the quark-quark and quark-gluon correlations inside the nucleon (twist-4 effect). S.H. Lee, Y. Koike (Michigan State), S. Choi (Yonsei Univ.) and I analyzed the recent data on the basis of the operator product expansion and have extracted model independent constraints on the nucleon matrix elements of the twist-4 operators.² We have also studied a parametrization of the data with extra theoretical constraints and found that (1) the twist-4 matrix elements have magnitude of $O(300 - 500\text{MeV})^2$ and (2) the quark-gluon mixed operator has negative value. Our results give a stringent test of the nucleon models and are also useful for the analyses of the other high energy processes. The twist-4 matrix elements of the nucleon determined here are also important for the study of the QCD sum rules in nuclear medium as was pointed out by Su. H. Lee and myself before.³

(c) H-particle in QCD Sum Rules

The H-particle is one of the most controversial particles in QCD. Originally, a stable H was proposed by using the MIT bag model and later lots of model calculations have been done without any definite conclusion. The result of the lattice QCD seems to favor the stable H-particle but it is not conclusive. M. Oka (Tokyo Institute of technology) and I have started to study the H-particle using the QCD sum rules.⁴ To get rid of the contamination of the 2Λ state, we constructed a flavor singlet 6 quark operator having a small overlap with 2Λ and carried out the operator product expansion. We are now analyzing the Borel sum rule obtained from the above procedure.

MASTER

107 12 1993

71

2. Hot and dense matter

(a) QCD Sum Rules in Medium

Y. Koike (Michigan State), S. H. Lee and I have completed our study of the ρ and ω mesons in the hot hadronic system on the basis of the QCD sum rules.⁵ We have developed a systematic method for generalizing the operator product expansion to finite temperature (T). By our method, the properties of ρ and ω at finite T were calculated by the information of the pion structure function in the deep inelastic processes. Although the vector-meson masses do not change at low T , there is a sizable decrease of their masses near T_c , which can be detectable by the lepton pair production from the hot hadronic plasma expected to be formed in the RHIC and LHC experiments. The similar formalism was also developed for the vector mesons in the dense/cold nuclear matter by S. H. Lee and myself.³ In this case, the structure function of the nucleon in the deep inelastic process controls the medium modification of the vector mesons. Creation of a zero-momentum vector meson inside the nucleus by the electron beam and subsequent detection of the lepton pairs from the decay of the vector meson will be a possible experiment to detect the medium modification of vector mesons.

(b) hadronic Screenings in Quark Gluon Plasma

There are several indications that the quark-gluon plasma is not just a free gas of quarks and gluons but has substantial correlations among the particles even at very high temperature. One of the measures of such correlation is the hadronic screening mass at high T . M. Ishii and are working on such screening masses based on the idea of the dimensional reduction of QCD at high T .⁶ In the high T limit, 4-dimensional QCD is known to become 3-dimensional Euclidian QCD (QCD₃) at $T = 0$. Then, the hadronic screening mass at high T is related to correlation functions in QCD₃ which can be analyzed by applying the method of QCD sum rules. We are currently calculating the Wilson coefficients of the operator product expansion in QCD₃.

2. Effect of the Isospin Breaking in QCD

The mass difference of u and d quarks gives various small isospin-breaking effects in hadrons. The mixing of light mesons such as the $\rho - \omega$ mixing and $\pi - \eta$ mixing is one of the typical examples of such effects. T. Meissner, E.M. Henley and I started to study the $\rho - \omega$ mixing by the QCD sum rule to determine the momentum dependence of the mixing angle in the spacelike region.⁷ Although the experimental mixing angle is determined on the mass shell of $\rho - \omega$, the space like region is more important from the point of view of the isospin-breaking nuclear force. In our approach, we can determine the momentum dependence of the mixing angle in terms of the quark condensates and the current quark masses; thus it is more reliable than the other approaches using effective theories. We are currently working on the quantitative estimate of the momentum dependence using the Borel sum rule.

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7. T. Hatsuda, E.M. Henley and Th. Meissner, in progress.

T. Hatsuda

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E. M. Henley

My main areas of interest continue to be related to symmetries and the connection of the quark-gluon description of nucleons and nuclei with the nucleon-meson degrees of freedom. The motivations are to gain insight into QCD and to probe weak and electromagnetic interactions, particularly at short distances or high momentum transfers, or to use symmetries to discern nuclear and nucleon structure.

1. The Electroweak Theory; Parity Nonconservation

Parity nonconservation in semi-leptonic processes can be used to test the standard model and in non-leptonic processes can help elucidate the effective interaction and structure.^{21,32,37,50,51}

(a) The Anapole Moment

Semi-leptonic interactions are particularly useful to probe the electroweak theory.^{20,34,36,44} Among such reactions, measurement of the anapole is of interest, because it is a many-nucleon effect. Mike Musolf, Wick Haxton, and I are still working to complete the inclusion of the rho- and omega-meson exchanges to the anapole moment. Our work on pionic exchange contributions has been published.⁹

(b) Neutrino Interactions

A fundamental process of the weak interactions is the charged- and neutral-neutrino disintegration of the deuteron. W. Haxton, S. Ying, and I examined this process in connection with the proposed SNO detector.^{11,22,25}

2. Time Reversal Invariance

The intriguing question of the cause of CP- or T-violations is of continuing interest.^{37,39,50,51,52}

(a) There is an ongoing experiment at the Nuclear Physics Laboratory to test time reversal in positron- and electron-decays of mass 8 nuclei. Since the final state of the decay consists of two alpha particles, questions arise as to the role of the hadronic final state scattering effects. S. Ying, a student I supervised and I have examined this time reversal test in detail. We have also looked at the effects of the final state electromagnetic corrections due to the electron-nuclear interaction. This work is in the process of being written up for publication. [S. Ying, Thesis (unpublished)]

(b) By choosing a first forbidden beta decay, it is possible to enhance the sensitivity to time-reversal odd nuclear forces. I.B. Khriplovich and I have examined such tests in some detail and have concluded that the best examples are those in which mixing occurs in the initial state. If the admixed state is close in energy and of the opposite parity, the sensitivity and experimental practicality are both improved. This work has been published.²⁷

3. Chiral Symmetry and Charge Symmetry

In the past few years, the n - p system has been used experimentally to test charge symmetry. Tests have been carried out at TRIUMF^a and at the Indiana University cyclotron.^b In the latter case, theory suggests that the process is dominated by ρ - ω mixing.^c However, it was pointed out by Goldman, Henderson and Thomas^d that the on-shell matrix element, in the time-like region may be quite different from that in the space-like region, where it is needed for nuclear effects. T. Hatsuda, T. Meissner and I are investigating this effect by means of QCD sum rules and find an even more rapid change than that obtained in the perturbative treatment of ref. d. This work is presently being written up for publication. We intend to extend this calculation to nuclei and to π - η mixing.

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^b L.D. Knutson *et al.*, Phys. Rev. Lett. **66**, 1410 (1991)

^c G.A. Miller, A.W. Thomas, and A.G. Williams, Phys. Rev. Lett. **56**, 2567 (1986) and Phys. Rev. C **36**, 1956 (1987).

^d T. Goldman, J.A. Henderson and A.W. Thomas, Few Body Systems **12**, 123 (1992).

4. Aspects of the Quark-Gluon to Nucleon-Meson Transition; Quarks in Nuclei

(a) The $N\bar{N}$ System

Since the annihilation of a proton and antiproton only occurs when the two particles overlap appreciably, this system should be a good laboratory to examine the quark-gluon to meson-baryon transition. Mary Alber, Larry Wilets, Dale Kunz, and I have continued to examine the combination of the 3P_0 and 3S_1 models for exclusive annihilation channels.^{3,5,18,31,45,47} We have concentrated on strange baryonic final states because the decays of these baryons test the spin degrees of freedom in the process, and these are more sensitive to the reaction mechanism. We have written up our examination of the $\Lambda\bar{\Lambda}$ final states; it is for this reaction that the best data is available. Angular distributions, spin correlations, and polarizations have been examined. We have begun to examine the $\Lambda\bar{\Sigma}$ and $\Sigma\bar{\Lambda}$ final states, and the depolarization parameters in $\Lambda\bar{\Lambda}$ production.

(b) Strangeness in Nucleons

The EMC measurements of the nucleon structure function together with earlier measurements of the σ -term in pion-nucleon scattering have led to the conclusion that the strangeness matrix elements of a nucleon might be large. Although there are numerous papers that attempt to show how this puzzling result can be understood without a large strangeness "content", there are only a few papers that suggest how to actually measure the strangeness matrix elements. G. Krein, A.G. Williams, S. Pollock, and I examined and suggested various ways of measuring these matrix elements.^{19,22,23,28,48,53} They include elastic scattering of electrons and neutrinos from light isospin zero nuclei, and ϕ production.

We examined electro- ϕ production from protons in detail as a method of measuring the vector strangeness matrix elements in the proton. Both magnitude and angular

distributions (or t and Q^2 dependences) of the cross section were calculated.²³ It is found that the magnitude is likely to be about the same as that due to vector meson dominance. A difference shows up in the angular (or t -) dependence, but it will be difficult for experimentalists to see this effect. It is likely that polarization studies will be required, but we are uncertain that even this distinction will be sufficient for a clean signal.

We also examined neutrino and antineutrino scattering from deuterium in detail.²² Here, the ratio of the difference between these cross sections to their sum is a direct measure of the strangeness axial matrix element of the nucleon. This ratio can be large, even approaching unity, for quite small values of the strangeness axial matrix elements. We included an examination of the best momentum transfer(s).

Lastly Werner Koepf, Steve Pollock, and I calculated the vector and axial-vector strangeness matrix elements to be expected in a simple (naive) model where, not only the pion, but all eight pseudoscalar bosons couple to quarks. We have used a point nucleon, a chiral bag and a constituent quark model to estimate the matrix elements. This calculation has been completed and published.²⁸ We are presently examining the full gauge invariance of our description.

Several talks on these and other proposed measurements of strangeness matrix elements were given. I was asked to write one of these talks up for publication and have submitted it, as requested.⁵³

5. Applications of QCD Sum Rules

QCD sum rules are a powerful technique, which goes beyond perturbative QCD. Together with some phenomenology, the method allows one to obtain meson and nucleon properties.

(a) The Axial Vector Nucleon Coupling Constants, g_A .

W-Y.P. Hwang, Leonard Kisslinger, and I used QCD sum rules to determine both the isovector and isoscalar axial-vector coupling constants. We find that the standard parameters give a value of 1.26 for the isovector g_A if diagrams up to dimension eight are included consistently. We also find that this coupling becomes 1.0 when chiral symmetry is restored. The value of the isoscalar coupling was also computed as well as its change when chiral symmetry is restored.^{26,49}

In the future, I intend to investigate the renormalization of g_A in nuclei.

(b) The n - p Mass Difference

W-Y.P. Hwang, L.S. Kisslinger and I have used QCD sum rules with finite quark masses to obtain the non-electromagnetic contribution to the n - p mass difference. This mass difference stems from the mass discrepancy of the up and down quark masses, the effects of which are kept to first order. A paper on this work has been accepted for publication.³⁰

(c) The Nucleon Mass in Nuclei

J. Pasupathy and I examined the changes of the nucleon mass which occur in a nucleus. We found that the results can be understood in terms of energy-dependent scalar and vector potentials. The sum of these potentials is small and leads to a shift of only a few MeV of the "effective mass", even though each term, by itself, is large and leads to larger "mass" shifts. This work has been written up and accepted for publication.²⁹

(d) ρ - ω Mixing Away from the Mass Shell.

T. Hatsuda, T. Meissner, and I have examined the momentum (q^2) dependence of ρ - ω mixing (see item 3 for details).

(e) The Weak $\pi - N$ Coupling Constants

Experiments on parity nonconservation, particularly in ^{18}F show that the weak π - N coupling is considerably smaller than expected.^a W-Y.P. Hwang, L.S. Kisslinger, and I are attempting to use QCD sum rules to obtain an estimate of the strength of this coupling. We believe that we have a technique which will allow us to calculate this desirable quantity.

^a E.G. Adelberger and W.C. Haxton, Ann. Rev. Nucl. Part. Sci. 35, 501 (1985).

6. Off-Mass Shell Electromagnetic Vertices

There has been considerable interest in recent years on the off-mass shell behavior of the electromagnetic interaction of nucleons. This interaction is required in pion electroproduction, nucleon Compton effect and nucleon polarizability. I intend to investigate these effects and to test the model against experiments.

E. M. Henley

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53. "Measuring Strangeness in the Nucleon," Proc. 35th National Physics Conference, Puebla, Mexico, December 1992, to be published in Rev. Mexicana de Física.

G. A. Miller

My principal interest is the relation between nuclear physics and quantum chromodynamics (QCD). This theory makes predictions for high momentum transfer processes that can be tested with nuclear reactions. Furthermore, at low momentum transfer, the non-perturbative nature of the theory must be responsible for the existence and properties of nuclei. My general approach is to start by using high momentum transfer nuclear reactions to learn about perturbative and some non-perturbative aspects of QCD. I believe that the results of such studies will have implications for many areas of nuclear physics including: dense nuclear matter, nuclear modification of properties of bound hadrons and even the convergence of calculations of nucleon-nucleon potentials and effective nuclear interactions. Another aspect is that processes involving fundamental symmetries can provide relevant information about how QCD is manifest in nuclei, and are often of high intrinsic interest. I therefore plan investigations in four different areas: color transparency physics; fundamental symmetries; physics of confinement and hadronic form factors and, the EMC effect.

1. Background

Much of the proposed research is focused on using fundamental ideas about nuclear and nucleon structure to motivate new relevant experiments. Concern with stimulating experiments has been a long-standing interest, so I introduce the present proposal with a summary of past DOE work.

I began my career by studying processes in which pions interact with nuclei. One suggestion¹ was that short and medium ranged two-nucleon correlations could have an important effect on (π^+, π^-) nuclear double charge exchange reactions. Later I postulated² a more fundamental origin of such effects in terms of nuclear six quark bags. In response, experiments were performed at LAMPF and TRIUMF.³ The measured cross sections were not large enough to support the novel quark mechanism. However, the activity this stimulated other theorists³ to successfully explain the data using two-nucleon correlation effects. Moreover, our calculations⁴ on the related process of π^- absorption of a pair of protons bound in ^3He led to new experiments at TRIUMF.⁵ These confirmed that the absorption reaction was dominated by physics at small nucleon-nucleon separations, less than about a Fm.

Colleagues and I also suggested and explained⁶ the first experiments to detect charge symmetry breaking in a system which has no Coulomb force. We found that effects of charge symmetry breaking (CSB) of NN forces can be observed in spin-dependent measurements in neutron-proton scattering. Experiments which successfully observed the effect were then mounted at TRIUMF⁷ and the IUCF.⁸

Another area concerns the EMC observation that the structure function F_2 of a nucleon, bound in nuclei, is different from a free nucleon. This generated many different explanations. We showed⁹ that measurements of the production of high momentum $\mu^+\mu^-$ pairs in proton-nucleus reactions (nuclear Drell-Yan process) could disentangle explanations of the EMC effect. Diverse models of the EMC effect have rather similar predictions for the nuclear valence quark distribution functions (which dominate F_2) but very different nuclear anti-quark distributions. The kinematics of the Drell-Yan process

can be chosen so that the nuclear anti-quarks participate, so models with similar F_2 predict drastically different Drell-Yan cross sections. A Fermilab experiment to measure the predicted nuclear dependence was undertaken by LAMPF physicists.¹⁰ The results placed very severe limitations on the mesonic content of nuclei.¹¹

I also need to mention our treatment¹² of the baryon as three quarks in a bag, surrounded by a cloud of pions. This so-called Cloudy Bag Model became very popular. The crucial elements of asymptotic freedom and chiral symmetry are included in a manner which readily allows computation. Computations of many observables gave excellent agreement with experimental results, especially in providing a reasonable pionic cloud explanation of the charge radius of the neutron. Long ago, the model was applied to systems of heavy (s, c, or b) quarks bound to light (anti-) quarks and strong and electromagnetic decay rates were predicted.¹³ Those for the decays of the D^* mesons were confirmed by recent experiments.¹⁴

This concludes the discussion of the past work. The proposed work is described below. Much will be performed in collaboration with students, post-docs and with members of outside institutions. Many of these projects have their origins in INT workshops.

2. Physics of Color Transparency

Color transparency¹⁵ is the vanishing of initial and final state interactions in high momentum transfer (Q^2) nuclear reactions in which the resolution is good enough to ensure that no extra pions are created in the fundamental hadronic two-body reaction. Examples of such reactions are the $(e, e'p)$ (p, pp) and $(e, e'\Delta)$ processes involving nuclear targets. Experiments at SLAC(NE-18)¹⁶ and BNL¹⁷ searching for color transparency are underway. (The NE-18 experiment has not ruled out color transparency. Only a few very extreme models disagree with the present experimental results.)

The color transparency phenomenon may have many other implications. We have argued¹⁸ that measuring color transparency effects provides a promising new method to investigate nucleon and nuclear structure in the domain of non-perturbative QCD, construct a theory of super dense nuclear matter, and even to help disentangle the physics of heavy ion collisions.

The color transparency postulate is based on three main points: (a) small objects (ejected wave packets (ejectiles) which, if very small, are point-like configurations PLC) are produced in high Q^2 exclusive processes, (b) the interactions of such small color singlet objects are suppressed due to the effects of cancellation of gluonic emission (color screening or color neutrality) (c) if the small object remains small for long enough it can escape the nucleus without further interactions. For existing experiments the kinematics are such that expansion must take place. The observational evidence for (b) is mentioned in Ref. 18 and discussed in the references therein. But points (a) and (c) requires serious investigation.

A. Ejectile Propagation Through the Nucleus

B.K. Jennings (TRIUMF) and I developed the approach of treating the ejectile as a coherent superposition of baryonic states.¹⁹ In electron reactions the ejectile wave function depends on proton-baryon electromagnetic transition form factors, and the

ejectile-nucleon interaction depends on baryon-nucleon interactions. These inputs can be modeled or constrained by data. The expansion of the ejectile depends on the masses of its baryonic components, and determines the energy dependence of the reactions. Thus our approach allows us to show how the ordinary low momentum transfer nuclear black disk becomes transparent when the momentum transfer is increased.

The early work¹⁹ treated the ejectile as a point-like object or configuration (PLC), but we have lately studied²⁰ approaches in which the (p,pp) amplitude is described in terms of a wave packet which is a coherent sum of a PLC and a larger object (blob-like configuration BLC) which does interact with the nucleus. The previously proposed ideas regarding the BLC are the Landshoff term of Ralston and Pire²¹ and the ($c\bar{c}$) threshold enhancements of Brodsky and deTera mond.²² Including either of these effects improves the agreement between theory and the present experiment. In addition, the Landshoff term causes a huge enhancement at higher energies.

The earliest work¹⁹ was based on a simplified model of baryon-nucleon interactions and electromagnetic baryon transition form factors. We extended this by using measured proton diffractive dissociation and electron-proton deep inelastic scattering data to examine and severely constrain the relevant masses.²³ We find that significant color transparency effects are allowed. But the measured input data do not provide sufficient information to completely determine the ejectile-nucleon interaction, so there is a necessary uncertainty in the resulting ejectile-nucleon interaction.

Another aspect involves studying the nuclear time development of the PLC using a new class of exactly solvable models.^{18,24} These are derived by describing the baryon-nucleon interaction in terms of an n by n matrix, constrained to vanish when acting on a PLC. These models are rendered semi-realistic by requiring consistency with data for cross section fluctuations in proton-proton diffractive collisions. These models will be applied in future work, see parts C and D below. A related study²⁵ with student, W. Greenberg was an examination of the full multiple-scattering series required to compute the effects of wavepacket- nucleus interactions. Different approximations, each defined to be exact at either low or high energies, were developed. This allows us to be confident that we sum all the necessary terms and also to confirm the accuracy of earlier approximate treatments. This technique is used in future work on the spin-dependence of color transparency, see part E, below.

Another effect is the that the degree of color transparency depends strongly on the (Fermi) momentum of the initially bound nucleon.²⁶ Thus the proposed work is to extend our past studies of the high momentum transfer (p,pp) process¹⁷ by including all of the known effects e.g. (1) PLC expansion, (2) quantum interference between the PLC and the BLC and (3) momentum of the bound nucleon.

We also plan to test our models of the baryon-nucleon interaction by computing high energy neutron-nuclear total cross sections. This interaction enters through the effects of "inelastic shadowing"- the incident neutron can be excited in its interaction with a bound nucleon, propagate and, be de-excited by another.

B. Is the ejectile a small object?

L. Frankfurt (Tel Aviv), M. Strikman (PSU) and I developed a new method to study whether a small wavepacket or point-like configuration (PLC) is actually formed

in a high Q^2 process. The analysis starts by constructing an operator which measures the transverse size of a wave packet. Consider the nucleon form factor as the matrix element of a hard scattering operator T_H which acts on a nucleon to form a wave packet or ejectile. The ejectile-nucleon interaction is mainly controlled by nucleonic matrix elements of the operator $b^2 T_H$.^{18,28} Here $\vec{b}$ represents the transverse separation between any of the two quarks in the outgoing wavepacket. We define a term $b^2(Q^2)$ which is the ratio of the nucleonic matrix element of $b^2 T_H$ to that of T_H . Then $b^2(Q^2)$ is proportional to the ratio of the single-scattering and plane wave Born approximation terms. If the ejected wavepacket is a *PLC*, then the operator b^2 takes on small values and $b^2(Q^2)$ is small.

Consider first non-relativistic constituent quark models. For two-quark systems confinement via the harmonic oscillator potential does not allow a *PLC*, but including a small residual $1/r$ force causes a *PLC*. For systems of three quarks, mean field models leads to no *PLC* formation, but if inter-quark correlations²⁹ are present, a *PLC* is obtained.

Models with pion clouds are relevant. The cloudy bag model admits a *PLC*. The pion cloud accounts for the large distance nucleon wave function and becomes less important as the momentum transfer increases. One may say that the high momentum probe blows the pion cloud away. Moreover, the remaining three-quark core will also be decreased in size if the effects of quark-quark correlations are important. The possible consequences of this will be studied, see part D below.

The results for relativistic quark models are similar to those of non-relativistic one. Harmonic oscillator gaussian-like wave functions have no *PLC*. Indeed the transverse size increases with momentum transfer. But hydrogenic wavefunctions do have a *PLC*.

We also considered a model based on perturbative QCD as extended by Sudakov effects, see e.g. Ref. 30. The Sudakov effects increase the importance of short distances and a *PLC* is obtained. Further studies and extensions of this model are planned, see Sect. 4.

The net result is that for the most realistic models, we find that point-like configurations occur at relatively low $Q^2 \approx 1 \text{ GeV}^2$. Options for measuring these difficult to find low Q^2 effects are discussed in parts C and D below.

C. Double Scattering Processes and Intermediate Q^2 Color Transparency

This project is a collaboration between K. Egiyan (Erevan PI), W. R. Greenberg, L. Frankfurt (Tel Aviv), M. Sargsyan (Erevan PI), M. Strikman (PSU) and myself. This study defines and supports an experiment proposed for CEBAF.

The practical problem in looking for CT effects in experiments at Q^2 from about one to a few GeV^2 is that the *PLC* expands rapidly while propagating through the nucleus. This is true even if it is assumed that a small-sized configuration is produced at the point of the hard interaction. This expansion of the wavepacket dominates up to rather large values of Q^2 because of the relatively small Lorentz γ factor of the struck nucleon.

To observe CT at intermediate values of Q^2 it is necessary to suppress the effects of wavepacket expansion. This can be achieved by using the lightest nuclear targets,

where the propagation distances are small. In this case, the transparency is close to unity, so the effects of CT in $(e, e'p)$ reactions are small. However, if we select a process where the produced system can **only** be produced by an interaction in the final state, a double scattering event, then the color coherent effects would manifest themselves as a decrease of the probability for final-state interactions with increasing Q^2 . An advantage of looking for the processes with rescattering is that it is possible to observe an effect decreasing from the value expected without CT (Glauber-value) to zero. Thus, the measured cross section is to be compared with a vanishing quantity so that the relevant ratio of cross sections runs from 1 to infinity.

Therefore, we study the reaction ${}^3\text{He}(e, e'pp)$. The experiment involves triggering on a fast proton which carries almost all of the virtual photon's three-momentum, and also detecting another proton of momentum about 400 MeV/c. This value is small compared with the fast proton's momentum and large compared with a proton's Fermi motion inside ${}^3\text{He}$ nucleus. If such a proton is detected, we can be almost certain that this relatively large value of the momentum was the result of a final state interaction. In the limit of full CT, there will be no final-state interactions and the fast proton will leave the ${}^3\text{He}$ nucleus without interacting to produce a 400 MeV/c proton.

The three-state model of Ref. 24 is employed to calculate the cross section for such a process. Our first calculation³¹ used a very simple ${}^3\text{He}$ wave function, a first order evaluation of the final state interactions, and included only effects of CT. The results of this first calculation are promising: we find significant reductions of the cross section, as large as an order of magnitude, for values of Q^2 as low as $Q^2 \approx 6 \text{ GeV}^2$.

The planned future work would use a better ${}^3\text{He}$ wave function, include higher order effects and assess the influence of conventional two-step mechanisms such as meson exchange currents.

D. Chiral transparency

We have discussed above that probing a nucleon at intermediate momentum transfers (Q^2 about a few GeV^2) may produce a small system without a pion cloud. We (L. Frankfurt, M. Strikman and I) hope to investigate this cloud-stripping effect by considering processes that require a pion exchange to proceed. An example is the quasielastic production of the Δ^{++} in electron scattering - the $(e, e'\Delta^{++})$ reaction. The initial singly charged object is knocked out of the nucleus by the virtual photon and converts to a Δ^{++} by emitting or absorbing a charged pion. But pionic coupling to small-sized systems is suppressed^{32,33} so this cross section for quasielastic production of Δ^{++} 's should fall faster with increasing Q^2 than the predictions of conventional theories. The first step planned is to estimate the size of this effect. This could be a new kind of transparency that involves pions, so we invoke the name "chiral transparency".

E. Spin dependence of color transparency

So far all calculations of color transparency effects in electron scattering have used scalar photons. Student W. Greenberg (his thesis) and I perform and plan to perform calculations in which the vector nature of the photon is taken into account. Thus both the γ_μ and $\sigma_{\mu\nu}$ forms of photon-baryon coupling are included. The **phenomenological** properties of the bound and scattering proton wave functions can be represented

by Dirac Hartree-Fock wave functions³⁴ and the Dirac optical potential.³⁵ The latter is generalized to include the effects of color screening or color neutrality. This optical potential is obtained from high energy proton-nucleon scattering data. The resulting treatment incorporates a wide variety of low momentum transfer information in a **phenomenological** fashion. Our approach allows us to calculate the spin dependence of color transparency in (e, e', p) reactions which could occur at CEBAF or at a future European electron accelerator. In particular, the polarization of the outgoing proton is caused by the final state spin orbit interaction. This vanishes if color transparency occurs.^{36,37} We plan to study all of the observables, and the project includes a fairly complete account of the important conventional effects.

F. Coherent Pion Diffraction into Minijets

L. Frankfurt (Tel Aviv), M. Strikman (PSU) and I examine³⁸ the cross section for coherent processes in which an incident meson or photon dissociates diffractively into two jets of high transverse momentum off a nucleon or nuclear target. We extend an early paper of Bertsch et al.³⁹ by demonstrating that at large transverse momenta this cross section is controlled by perturbative QCD and is calculated through the light-cone meson $q\bar{q}$ wave function $\phi(x)$ and gluon parton density in a nucleon (nucleus). We estimate the relevant cross section and the kinematic region where leading twist effects may dominate by developing a model of the amplitude $\mathcal{M}(N)$ for high κ_t diffractive jets produced by a nucleon target. This model depends on a $q\bar{q}$ -target nucleon interaction⁴⁰ ($\sigma(b^2)$ where b is the transverse spatial separation between the quark and anti-quark) with $\sigma(b^2) \propto b^2 \alpha_S(1/b^2) G_N$ for small values of b^2 . The necessary model of the pion $q\bar{q}$ component is restricted by imposing the condition of approximate scale invariance of QCD and reproducing some experimental information. The resulting amplitude $\mathcal{M}(N)$ may be computed numerically or approximated as a ("higher twist") expansion in powers of $\frac{1}{\kappa_t^2}$: $\mathcal{M}(N) \propto c_1/\kappa_t^4 + c_2/\kappa_t^6$. The c_1/κ_t^4 behavior appears because the interaction times the π wave function acts as $b^2 1/\kappa_t^2 = -\nabla_{\kappa_t}^2 \frac{1}{\kappa_t^2} \propto \frac{1}{\kappa_t^4}$ for large κ_t . Thus b^2 acts as $1/\kappa_t^2$, so b^2 is small and the $\bar{q}q$ -nuclear interaction is suppressed when κ_t is large. At large κ_t^2 it may be possible to discriminate between asymptotic^{41a} and Chernyak-Zhitnitski^{41b} type predictions for $\phi(x)$.

Since this process is dominated by small interquark distances in the pion, its cross section should behave as A^2 for coherent nuclear production. This is a new kind of color transparency phenomenon. We obtain the nuclear amplitude $\mathcal{M}(A)$ from $\mathcal{M}(N)$ and standard multiple scattering theory. The suppression of the $\bar{q}q$ -nuclear interaction at large κ_t leads to the result: $\mathcal{M}(A)/\mathcal{M}(N) \approx A(1 + c A^{1/3}/\kappa_t^2)$ where c is a significant positive term which can be calculated more reliably than both amplitudes.

This process will be studied using 500 GeV pions at Fermilab.^{42,43} The proposed work is to study the influence of non-coherent nuclear and nucleon excitations which could be erroneously included due to imperfect detector resolution. The first work³⁸ included only estimates of such effects. Furthermore, we and B. Jennings (TRIUMF) plan to study the influence of the orthogonalization between the initial pion and final two-jet state.

3. Fundamental Symmetries

A. Charge Symmetry Breaking

Slaus (Zagreb), Nefkens (UCLA) and I published a Physics Report on Charge Symmetry Breaking (CSB).⁴⁴ CSB in systems ranging from mesons to heavy nuclei was studied. We found that ALL observed CSB can be explained in terms of quark mass differences and electromagnetic interactions between quarks. The down quark is more massive than the up quark at momentum scales corresponding to confined systems. Thus CSB in nuclear and particle physics is due to the difference between the down and up quark masses δm and the non-equality of their electromagnetic interactions. The large body of data that support this conclusion was reviewed, and a value of δm of about 3 MeV (at a scale of 1 (GeV/c)²) extracted.⁴⁵

The influence of the quark mass difference on nuclear physics was discussed in Ref. 46. It has long been known that δm accounts for the observed value of the isospin mixing between the ρ^0 and ω mesons. Furthermore, one can compute the CSB-potential between two nucleons arising from the exchange of a mixed ρ^0 - ω meson. The resulting CSB potential is large enough to explain the Nolen Schiffer anomaly and also provides a spin-dependent potential which makes a significant contribution to the IUCF experiment.

However, Goldman, Henderson and Thomas⁴⁷ (GHT) have claimed that the $\rho^0 - \omega$ mixing matrix element has a significant off-mass shell dependence which renders its effects negligible in nucleon-nucleon scattering. A simple $q\bar{q}$ model of the vector meson was used. Williams and Pickarewicz⁴⁸ find the same result using a model in which the vector mesons mixing is described in terms of the mass difference between nucleon-anti-nucleon pairs. Hatsuda, Meissner and Henley⁴⁹ have used QCD sum rules to obtain a similar result.

I also plan to study this off-mass shell effect. Student Yan Zhang and I found that the importance of GHT effect decreases strongly as the value of the quark mass used in the calculation decreases. But quark masses vary strongly with kinematics. For on-mass shell kinematics at zero momentum transfer, the quarks in the vector mesons should be constituent ones. But suppose the four-momentum squared of the vector meson is small and spacelike as in NN potentials. What is the appropriate value of the quark mass? We plan to investigate this question. For such highly virtual mesons, the quarks may have the values of current quark masses. If this is the case, the GHT effect will vanish.

In any case, with the ultimate origin of important CSB effects presently in doubt, it is worthwhile to examine other sources. One old, but often forgotten, effect is that due to the two-boson gamma-pion exchange potential. Indeed a definitive calculation of this computationally difficult term has not yet been done. I encouraged U. van Kolck (Texas) to evaluate this potential as part of his chiral perturbation theory plus phenomenology treatment of the nucleon-nucleon potential. After his arrival, we hope to examine the consequences of this potential for a wide variety of CSB phenomena, including the recent IUCF and TRIUMF and ongoing TRIUMF experiment.

B. CP Violation (CPV) and Time Reversal Violation

The existence of CPV effects has important implications for many areas of physics. But so far, has been observed only in the neutral kaon system. Future progress in

understanding the origins of CPV depends on a new experimental observation. Therefore, I investigated⁵⁰ possible CPV violations in processes involving baryons. This work used a new technique in which CPV was evaluated in terms of hadronic CPV matrix elements measured in the neutral kaon system. Thus the calculation was strongly constrained by experimental measurements. The neutron electric dipole moment and the CPV meson-nucleon coupling constants G_{CPV} were computed. The nuclear consequences of the CPV pion-nucleon coupling constant seem very small. However we found, as had Ref. 51, that CPV may be observable in the decays of hyperons because the CPV coupling constant for the decay of the lambda hyperon to the pion and nucleon is about six orders of magnitude larger than G_{CPV} . Experimentalists⁵² are interested in pursuing this by comparing the decays of hyperons and anti-hyperons produced in proton-antiproton collisions, so it is worthwhile to try to improve the calculation.

Our early work did not take the effects of chiral symmetry into account. This can now be done with the techniques of chiral perturbation theory. In addition, we plan to calculate some higher order diagrams. The result could be a more reliable prediction of the size of the CPV effects.

4. Physics of Confinement and Hadronic Form Factors

The issues of color transparency are closely related to those involved in computing hadron factors, so our attention has been drawn to this area. Our studies will be simplified by concentrating, at first, on the pion.

The earliest QCD calculations^{41,53} used asymptotic perturbative techniques and predicted values of the pion form factor that are much smaller than the observations⁵⁴, which are difficult.⁵⁵ See also Ref. 56. The early computations did not include the effects of the $q\bar{q}$ transverse relative momentum. We work in coordinate space and consider the dependence of the pion wave function on the transverse separation $\vec{b}$ between the quark and the anti-quark. Those transverse effects accounted for by Sudakov form factors have been included.³⁰ But this is not complete, non-leading twist effects and confinement should also lead to significant effects.

We plan to attack the problem of the pion wave function using four different approaches.

A. Higher twist effects and other non-perturbative effects

The effects of chiral symmetry lead one to the conclusion that higher twist effects, which correct the asymptotic results, are important⁵⁷; these are enhanced by the huge factor $m_\pi/(m_u + m_d)$. J. Pasupathy (Bangalore) and I plan to combine the higher twist effects of Ref. 57 with the calculation of Li and Sterman.³⁰ We expect to obtain larger values for predicted form factors which will be in closer agreement with the data.

B. Equation of motion study

Yan Zhang and I plan to solve the light-front equation of motion⁵⁸⁻⁶⁰ using a restricted Hilbert space. We intend to include, with proper relativistic kinematics, the effects of the one-gluon exchange interaction to all orders. The effects of simplified treatments of confinement will also be included. The recent lattice work of Chin and Huang⁶¹ provides some indication that confinement is not the dominant effect. The goals

are to obtain an improved phenomenology of the $\vec{b}$ dependence of the pion wave function, gain an improved understanding of the twist expansion, and perhaps derive a better wave function to be used in computations of the pion form factor. As discussed above, the b -dependence of the wave function determines whether or not color transparency can occur. Thus we expect that our study will have a different emphasis than that of Ref. 60.

C. Lattice QCD investigation of the time dependence of $b^2(Q^2)$

Student D. Makovoz and I plan to use lattice techniques to investigate quantities of relevance to color transparency physics. In particular, we wish to study the (Euclidean) time dependence of transverse separation between quarks in a wave packet generated by the interaction of a momentum-transfer dependent current operator acting on the pion. We hope to gain insight into questions involving the initial size and expansion time of the ejectile. Lattice studies of form factors and wave functions have been limited to low momentum transfer processes^{62,63} because of various known computational difficulties. Even so, the results of a successful computation at low Q^2 will provide significant insight. There already is an important indication from lattice calculations⁶³ that the $q\bar{q}$ component of the pion is smaller than the measured pionic size. Performing a lattice calculation is a new endeavor for me. But our efforts will be aided by heavy use of local people such as S. Huang and S. Sharpe, and resources such as the upcoming INT summer school on "Phenomenology and Lattice QCD". In a preliminary investigation, Makovoz has reproduced early SU(2) computations of the Wilson loop reviewed in Ref. 65.

D. QCD Sum Rule Approach to $\psi(x, \kappa_t^2)$

The usual light-cone "wave function" $\phi(x)$ is really $\phi(x, \mu^2) \equiv \int^{\mu^2} d^2\kappa_t \psi(x, \kappa_t^2)$ where ψ is the wave function of the pion $q\bar{q}$ components. But color transparency effects are controlled by the κ_t dependence of $\psi(x, \kappa_t^2)$. T. Hatsuda, S. Lee and I plan to use QCD sum rules to investigate this dependence. It seems that a few moments of the form $\int_0^1 dx x^n \int^{\mu^2} d^2\kappa_t \kappa_t^{2m} \psi(x, \kappa_t^2)$ can be determined.

5. EMC effect

The EMC effect generated much theoretical and experimental attention. The observed nuclear dependence of the nucleon structure function could have very important consequences for all aspects of nuclear physics. However, the full implications of the EMC effect for nuclear physics are not clear, even some dozen years after the first observations. A number of interesting explanations and issues have been raised and addressed by various workers. What is the importance of conventional effects such as nuclear binding and Fermi motion? What are the implications of the failure to observe the influence of pionic enhancement? Does the gluon distribution in a nucleus differ from that of a nucleon? Editor George Bertsch of Reviews of Modern Physics asked me to review this subject. There is an recent excellent review⁶⁵ but the importance and implications of the newest data relevant to the EMC effect for nuclear physics have not yet been clearly reviewed. Therefore, I have accepted the invitation.

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Lawrence Wilets

1. A Chirally Invariant Chromo-dielectric Soliton Model.

A number of color-dielectric models^{1,2,3} have been proposed to simulate QCD in the regime of confinement, which is of particular interest to nuclear structure and reactions. In an extension of the Friedberg-Lee model^{4,5}, G. Fai, R. Perry and I⁶ proposed a chirally invariant model which enforces absolute color confinement. In two subsequent papers, G. Krein, A. Williams, P. Tang and I^{7,8} demonstrated spatial confinement and exhibited the emergence of the pion as a Nambu-Goldstone boson in the “locally uniform” approximation. The difficult non-local problem of massless quarks in a dielectric bag was the topic of my student, Ping Tang, for his doctoral dissertation. Meson and baryon states were constructed in collaboration with S. Hartmann. Of particular note is that the pion, which should be a massless Goldstone boson, emerges (within the approximations) as a light particle with substructure.⁹ Two important refinements are being pursued: The summation of ladder diagrams for the quark-quark interaction and the proper handling of the center-of-mass problem by variation following projection, using techniques studied in detail previously. The spectra of all low-lying hadrons is being studied.

2. The N-N Interaction and Six-quark Structure in the Chromo-dielectric Soliton Model, in collaboration with W. Koepf, and Fl. Stancu & S. Pepin (Liège).

The fundamental nuclear physics Problem, the N-N interaction, has been pursued by several groups¹⁰ for more than a decade utilizing various models of QCD. For the case of relativistic (current) quark models, Schuh, Pirner and I¹¹ demonstrated that *dynamics* plays a very important role at short distances. Stancu and I showed that previously neglected configurations (spatially similar to those which had been considered) also were important at short distances.^{12,13,14} The present work is a logical extension of soliton model studies conducted here over several years. We incorporate important features neglected by others.¹⁰ One important application planned is to utilize the six-quark wave functions so obtained, in conjunction with two body correlation functions already available, in order to determine the quark structure of nuclear matter.

3. The Many-Nucleon System in Models of QCD with W. Hazelton.

The many nucleon problem is a formidable task in the context of QCD modelling. The transition from the system of quark clusters to the quark-gluon plasma is of particular interest to experiments involving relativistic heavy ion collisions. Two extreme limits of attacking the problem are: a Fermi gas of quarks, and the crystalline model of quark clustering. In both cases, one can attempt to evaluate the approximations that should lead toward realistic nuclear matter. We have investigated crude approximations to the crystalline model¹⁵ and the Wigner-Seitz approximation¹⁶ to the crystalline model. A more realistic approach to the crystalline model is now being undertaken utilizing the chromo-dielectric model. The close-packed fcc symmetry is assumed, with the elemental tetrahedron as the building block. We will work our way up from SU(2) (color) x SU(1) (flavor) x SU(2) (spin) through intermediate steps to SU(3) x SU(2) x SU(2). It is clear that the color-magnetic interaction plays a crucial role in clustering. Ultimately we hope to handle finite temperature and the phonon modes of the system.

4. Flux Tube Dynamics.

In many ways, the flux tube is the most elementary quark-gluon system. It has been studied in lattice gauge calculations and in color dielectric models. In fact, the flux tube is a simple and beautiful idealization, but in nature there is not a well-developed stable flux tube. Stretching a flux tube by only 1 fm will break it and 1 fm is comparable to the flux tube diameter. Nevertheless, it is useful to study the dynamical development and breaking of such objects. Several groups have studied quark-antiquark creation in flux tube using the Schwinger mechanism within the frame work of the MIT model. I propose to study the dynamics of soliton flux tubes in order to determine lifetimes.

5. $\bar{p}$ - p to $\bar{\Lambda}$ - Λ and $\bar{\Lambda}$ - Σ Collisions, with Mary Alberg, E.M. Henley and D.A. Kunz (Colorado).

Analysis of experimental data in terms of a quark model using both vector and scalar interactions has yielded the best fits for $\bar{\Lambda}$ - Λ to date. Two essential features of the calculation are the use of *both* vector and scalar interactions, and adjustment of the final state interaction which cannot be well deduced from the N-N interaction on the basis of current techniques using SU(3) symmetry. Several papers and conference proceedings have resulted.^{17,18,19,20} The work is continuing, with the prediction of a complete set of spin observables, and extension to other rare processes.

6. Isotopic Effects in Atomic Parity Nonconservation, with S. Pollock and E.N. Fortson.

Precise atomic PNC experiments are now feasible on short-lived nuclides. The hope is to test the standard model and to extract "new physics," such as further generations of leptons and quarks. A major problem in the interpretation of the experiments has been evaluating the atomic structure. However, by taking ratios of PNC effects in strings of isotopes, it had been proposed to eliminate uncertainties in the atomic calculations. While this is true, we find that uncertainties in neutron distributions limit the utility of this approach. However, this does provide a method for uniquely determining neutron distributions in nuclei! If confidence in nuclear structure calculations can then be gained, then by bootstrapping one may extract accurate weak coupling parameters. A Phys. Rev. Letter (including Y. Pang)²² was published previously, and an extensive review of nuclear calculations and their implications to the atomic experiments has been published in Phys. Rev. C.²³ We plan to keep abreast of nuclear and atomic structure calculations, and possibly explore PNC effects in mu-atoms (with M. Musolf).

7. Quantum Molecular Dynamics, with W. Beck.

The terminology has been applied by others to the model introduced here²⁴ to describe many-body collisions (and structure) by classical equations of motion with momentum-dependent interactions to simulate the Pauli and Heisenberg principles. Comparisons with H. Feldmeier's gaussian wave packet formulation²⁹ have been made.

Extensive calculations have been performed for the "trapping" of antiprotons on atomic (liquid) helium. Such trapping has been observed²⁹ at KEK and CERN, where 3% of incident protons are found to have lifetimes of microseconds compared with prompt decays of picoseconds. Various researchers have hope for possible experiments

on such trapped antiprotons, but I have not seen credible proposals yet. The calculations, however, provide a better understanding of exotic atom formation than any previously.

W. Lunch of Michigan State has proposed a collaboration to calculate the intermediate-weight nucleus-nucleus collisions at intermediate energy systems being investigated experimentally there.

8. Shielding of the Nuclei in a Finite Temperature Electron Plasma, with M. Watrous.

An important factor in understanding nuclear fusion in stellar and laboratory plasmas is the shielding of the nuclear charge. We have undertaken a study of the problem using finite temperature Green's functions.

9. Non-perturbative Renormalization and the Elimination of Ghost States in Relativistic Field Theories, with R. Puff, G. Krein and M. Nielsen (the latter two of São Paulo).

The consistency of local relativistic field theories (without asymptotic freedom) is an old and vexing problem. A manifestation of the inconsistency of the theories *or* of the approximations used is the appearance of complex poles (ghost) in the nucleon (fermion) propagator. This was the case found by Brown, Puff and Wilets³⁰ in a relativistic nucleon-meson field theory which summed planar graphs in the π , ρ and ω mesons without cutoffs. Inspired by recent work by Allendes and Serot³¹, we introduced the Sudakov³² vertex function generated by vector mesons (in analogy to QED), and found that the ghost did disappear, rendering the theory consistent *in this approximation*.³³ We plan to extend the work to the evaluation of nucleon properties.

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Suzhou Huang

There are two major aspects in my research activities, which can be roughly classified according to the approaches involved. The first is numerical related to lattice QCD simulations. The second is analytical related to model studies of hadronic phenomenology and the development and understanding of new methods. Of course, the physics goal is always centered around the manifestation of QCD at the hadronic level from non-perturbative point of views.

1. Lattice QCD and Related Work

(a) Hadron Current-current Correlations in the QCD Vacuum (with M. Chu (Caltech), J. Grandy (Los Alamos) and J. Negele (MIT)).

Two-point current correlation functions in the QCD vacuum provide rich information in understanding the structure of hadrons. On one hand these correlations can be related to the experimental data through dispersion relations; on the other hand they can be calculated theoretically either through lattice gauge simulations or through various hadron models. We had carried out the relevant simulation in the quenched approximation and measured these correlation functions on the lattice, from small distances, where the asymptotic freedom is apparent, to large distances, where the hadronic resonances are dominating.¹ In mesonic channels our numerical results are nicely consistent with the available experimental data. In baryonic channels, where there is no experimental result known, our lattice results can serve as complementary information to check other studies, such as QCD sum rule and the interacting instanton models.

(b) The Relevance of the Dilute Instanton Ensemble to Light Hadrons (with M. Chu, J. Grandy and J. Negele)

About one year ago Ming Chu and I studied the relevance of the dilute instanton ensemble to light hadrons, directly from lattice QCD simulation with cooling technique.² Our result indicates qualitatively that indeed the dominant gluonic configurations in the QCD vacuum are the weakly interacting instantons and antiinstantons, as far as the light hadrons are concerned. Now a much more careful and systematic study is underway³, in an attempt to make the relevance of the dilute instanton ensemble to light hadrons more quantitative. The preliminary analysis of the new simulation data supports the claim in [2]. In addition, the new lattice simulation also allows us to measure gluonic observables, such as the average instanton size and the density of instantons in the QCD vacuum, which can be directly compared with the instanton liquid model assumptions of Shuryak.

(c) Hadron Masses and Matrix Elements at Finite Temperature

Lattice plays a special role in understanding the nature of QCD at finite temperature, due to its non-perturbative character. On the other hand, due to the Euclidean formulation, most of the lattice work is largely concentrated on the static and equilibrium aspects, which are unfortunately not easily observable in experiments. Recently I have pointed out the possibility of calculating real-time hadron properties, which are

more likely experimentally observable, from Euclidean lattice simulations.⁴ The observation here is that, although the analytic continuation of lattice data to Minkowski space is very difficult, the converse can be easily done through a dispersion relation provided we have enough qualitative knowledge of the spectral density involved. This method has been explicitly demonstrated in a soluble model with relatively small lattice sizes.⁴ M. Chu (Caltech), S. Schramm (University of Indiana) and I have planned to apply the same method to the case of QCD at finite temperature.⁵ Coding and checking have been finished. Hopefully the first result of this kind will come out in several months.

(d) Surface Free Energies of Hadronic and Gluonic Droplets from Lattice QCD⁶ (with J. Potvin and C. Rebbi (both at Boston University))

It has been shown that the surface tension between the hadronic and plasma phases is finite when the interface is flat or has very small curvatures. However, when the bubble radius is not too much larger than a typical hadron size the effects of the curvature may not be negligible. The stability of the hadronic droplet in a plasma medium and the plasma droplet in a hadronic medium are not necessarily reflected by the finiteness of the surface tension with a flat interface. We had computed the surface tension for both hadronic and gluonic droplets at finite temperature in quenched lattice QCD. The surface free energy was obtained by integrating the average action along a path in the coupling space corresponding to growing and melting a spherical droplet of a given radius. Our numerical result supports the claim of Mardor and Svetitsky in a Bag model study that the curvature effect tends to decrease the surface free energy for hadronic droplets. On the other hand, we also found a similar behavior for gluonic droplets, while the Bag model study gave the opposite effect.

2. Analytic Work

(a) The Role of Anomalous Singularity in Hadronic Form Factors⁷ (with Wei Lin (University of Washington))

By assuming chiral-symmetry breaking as the dominant dynamics in the light-hadron structure, we study the electromagnetic (EM) form factor of light hadrons in the Nambu-Jona-Lasinio (NJL) type of models in the large- N_c limit from a dispersion relation point of view. In addition to the expected vector-meson pole dominance picture for tightly bound states such as the pion, it is found that the anomalous singularity, occurring only to loosely bound states of the constituent quarks, could severely alter the form factors at low momentum transfers from the vector meson dominance behavior. This mechanism is explicitly demonstrated in a two-dimensional version of the NJL type models, the Gross-Neveu model, in which all the interested quantities are calculated analytically and a detailed comparison with two-dimensional QCD is made. The two-dimensional analysis is then argued to be qualitatively similar to the realistic four-dimensional case. The relevance of the anomalous singularity to the phenomenology of the rho and the nucleons is indicated by quantitative estimates of the anomalous thresholds in their form factors.

(b) Zero Mode Problem of the Light-cone Quantization⁸ (with Wei Lin)

The light-cone quantization for theories involving arbitrarily interacting scalars is studied systematically. The zero mode, which plays a special role in the light-cone

quantization, is treated explicitly. Our arguments utilize a lattice regularization and the constrained path-integral method. We show, to all orders in coupling constants or the loop expansion, that the ghost fields, introduced to enforce the constraints, decouple from all the virtual processes in the infinite-volume limit. The only possibility for the light-cone quantization to deviate from the equal-time quantization is when the interaction is such that the bosonic ghost fields develop expectation values and consequently alter the location of the minimum point of the effective potential.

(c) Nucleon Solution of the Faddeev Equation in the Nambu-Jona-Lasinio Model⁹ (with John Tjon (University of Utrecht)).

Given the phenomenological success of the Nambu-Jona-Lasinio model in describing the meson physics in the low energy limit, it is tempting to find the fully relativistically structured nucleon solution in the same model under the same approximation employed in the mesonic sector. To achieve this goal we need to solve a relativistic Faddeev equation, which is seemingly formidable. The crucial observation in simplifying the task is that the two-body T-matrix in the diquark channel has a factorizable form. The factorizability of the two-body T-matrix can reduce the three-body Faddeev equation to a tractable two-body Bethe-Salpeter equation without assuming the existence of the diquark bound state. At the moment all the analytic derivations and numerical solutions of the reduced two-body Bethe-Salpeter equation have been achieved. The preparation of a preprint⁹ is in its final stage.

(d) Other Topics In the Future

i) With the strong evidence^{2,3} that the chiral symmetry and its breaking dominate the dynamics of light hadrons at low energy and most of the light hadrons are weakly bound states of constituent quarks^{7,9} the role of the anomalous threshold (or singularity) in the light hadron hadron scattering processes will be investigated. ii) To interpret the physical meaning of "the spatial wavefunction of hadrons at high temperature calculated on lattices recently", which has a Euclidean origin, the relevant three-point function in the Minkowski space will be calculated in a soluble model. iii) The large order perturbation and the infrared renormalon phenomena will be studied at finite temperature in an asymptotically free theory to clarify the connection between symmetry breakings (or condensates) and singularities associated with the inverse transform of the Borel improved perturbation series.

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