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Quantum Chromodynamic Quark Model Study of Hadron and Few Hadron Systems

Technical Report
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This report details research progress and results obtained during the entire period of the research project, entitled "Quantum Chromodynamic Quark Model Study of Hadron and Few Hadron Systems", which was supported by grant DE-FG05-90ER40589 between North Carolina State University and the United States Department of Energy from 1990 to 1996. In compliance with grant requirements the Principal Investigator, Professor Chueng-Ryong Ji, has conducted a research program addressing theoretical investigations of hadron structure and reactions using quantum chromodynamic quark models. This Principal Investigator has devoted 50% of his time during the academic year and 100% of his time in the summer. This percent effort has continued during the entire period of the grant. The new, significant research results are briefly summarized in the following sections. Finally, full, detailed descriptions of completed work can be found in the project publications which are listed at the end of this technical report.

Quantum Chromodynamic Quark Models

A new progress has been made in our long term, ambitious program dedicated to developing more realistic quantum chromodynamic quark models. A comprehensive, relativistic many-body approach to hadron structure was advanced based on the Coulomb gauge QCD Hamiltonian. Our method incorporated standard many-body techniques which renders the approximations amenable to systematic improvement. Using BCS variational methods, dynamic chiral symmetry breaking naturally emerged and both quarks and gluons acquired constituent masses. Gluonia were studied both in the valence and in the collective, random phase approximations. Using representative values for the strong coupling constant and string tension, calculated quenched glueball masses were found to be in remarkable agreement with lattice gauge theory.

We have also studied nucleon structure in the relativistic quark model based on the Bakamjian-Thomas construction of the Poincare generators for an arbitrary quantization surface. The one body, single particle approximation to the current operators was used to calculate electromagnetic matrix elements. The Lorentz symmetry breaking resulted from such an approximation was fully investigated. The results for the light front and instant quantization limits were detailed. A suggestion for the resolution of the quark model inability to simultaneously describe the positive neutron electric form factor, $G_E^n(Q^2)$, at small Q^2 and the negative slope of the neutron to proton structure function ratio at large x was presented.

For the meson sector, we investigated the most general, relativistic, constituent $q\bar{q}$ meson wave function within a new covariant framework and found that, by including a tensor wave function component, a pure valence quark model was capable of reproducing not only all static pion data (f_π, $\langle r_\pi^2 \rangle$) but also the distribution amplitude, form factor $[F_\pi(Q^2)]$, and structure functions. Our generalized spin wave function provided a much better detailed description of meson properties than models using a simple relativistic extension of the $S = L = 0$ nonrelativistic wave function.

Light-Cone Field Theory

A new progress has been made in the analysis of vacuum problems using the light-cone quantization method. Motivated by an apparent puzzle of the light-cone vacuum incompatible with the axial anomaly, we have considered the two-dimensional massless Schwinger model for an arbitrary interpolating angle of Hornbostel's interpolating quantization surface. By examining spectral deformation of the Dirac sea under an external electric field semiclassically, we have found that the axial anomaly is quantization angle independent. This indicates an intricate nontrivial vacuum structure present even in the light-front limit.

Also, we investigated the self-energy effects in the scattering problem. Rotational invariance is violated in the light-cone quantization method when the Fock space is truncated for practical calculations. To what extent the rotation symmetry is broken in the light-cone quantization approach can be quantified by calculating the explicit rotation dependence of the two-body scattering phase shifts. We analyzed the scattering phase shifts incorporating the self-energy corrections. We found that the self-energy effects significantly restore the rotation symmetry. These effects made the phase shifts stabilize as the coupling constant grew, which was in good agreement with other bound-state results.

For the bound-state problem, the light-cone ladder approximation in the Wick-Cutkosky model was extended to the lowest order light-cone Tamm-Dancoss approximation which included the self-energy corrections and counter terms. The light-cone two-body equation was modified by the term corresponding to the self-energy corrections and counter-terms. The analytic relation between the coupled constant, α, and the binding energy, β, which was previously derived for all nl states with $l = n - 1$ under the light-cone ladder approximation was also modified by these corrections and compared with the numerical results obtained by a variational principle. The numerical estimate of this modification showed that self-energy effects are as repulsive as relativistic kinematic corrections and retardation effects and made β become frozen as α increases.

QCD Phenomenology

A new program was underway in our QCD phenomenology project. We studied the exclusive production of heavy mesons in polarized e^+e^- annihilations using a perturbative QCD calculation. We discussed the significance of polarized beams in isolating electroweak effects at high energies, and calculated the left-right asymmetry and forward-backward asymmetry for different collider energies.

It was also pointed out in the example of the pion form factor that the usual factorized hard scattering amplitude T_H in perturbative QCD is derived from the light-cone time-ordered perturbative expansion. In the light-cone perturbative expansion, the natural variable to make a separation of perturbative contributions from contributions intrinsic to the bound-state wave function itself is the light-cone energy. We found that the legal PQCD contribution defined by the light-cone energy cut saturates to the full PQCD prediction without any cut in the smaller Q^2 region as compared to that defined by the gluon four-momentum square cut. Using heavy quark symmetry we constructed a QCD energy sum rule for heavy meson systems. The sum rule related the meson's form factor to the light quark energy distribution amplitude. The results indicated a broad energy distribution implying an appreciable nonvalence content.

We have also presented a recursive diagrammatic method for evaluating tree-level Feynman diagrams involving multi-fermions which interact through gauge bosons (gluons and photons). Based on this method, a package called COMPUTE, which can generate and calculate all the possible Feynmann diagrams for exclusive processes in perturbative QCD, has been developed. The COMPUTE is available in both Mathematica and Maple. Using COMPUTE, we calculated the nucleon Compton scattering amplitude. We were invited to write a review article on this topic in Computers in Physics which was published in December, 1995.

Crossing and Duality Constraint

New results were obtained in our crossing and duality constraint project. Using our previously developed crossing and duality constrained electroproduction model, we calculated the kaon capture, electron pair and hyperon (Y) production reactions $p(K^-, e^+e^-)Y$ for $Y = \Lambda, \Sigma^0$ and $\Lambda(1405)$. Because there is no constraint on the minimum 4-momentum transferred by the timelike photon ($q^2 \geq 2M_e^2 \sim 0$), we observe that the low-lying ρ, ω, and ϕ vector mesons are kinematically accessible producing up to four orders of magnitude enhancement in the theoretical hyperon production cross section. The significance and utility of this dramatic enhancement were investigated to probe the nucleon's strangeness content, medium modifications of hadronic properties, weak and radiative hyperon decays, and for extracting timelike electromagnetic form factors in a new kinematic regime.

We found that baryon resonances with spin greater than 1/2 are necessary to describe the higher energy photoproduction data ($1.4 \leq E_\gamma^{lab} \leq 2.2$ GeV). We also extended our use of duality by representing these higher-spin s- and u- channel baryon resonances with the low-lying t-channel vector, K*(980), and pseudovector, $K_1(1270)$, mesons. Using this extended crossing and duality consistent model, we obtained reasonable agreement with the data for both photoproduction and electroproduction processes.

Refereed Journal Publications During the Funding Period (1990-1996)

1. Heavy Meson Pair Production in Polarized e^+e^- Annihilation, Phys. Lett. **B384**, 241 (1996) (with F. Amiri).

2. Light-Front View of the Axial Anomaly, Phys. Rev. **D53**, 5815 (1996) (with S. J. Rey).

3. Glueball Spectroscopy in a Relativistic Many-Body Approach to Hadron Structure, Phys. Rev. Lett. **76**, 2011 (1996) (with A. Szczepaniak, E. Swanson, and S.R. Cotanch).

4. Nucleon Structure in a Relativistic Quark Model, Phys. Rev. **C52**, 2738 (1995) (with A. Szczepaniak and S.R. Cotanch).

5. Quantization Dependence in a Constituent Quark Model, Phys. Rev. **D52**, 5284 (1995) (with A. Szczepaniak and S.R. Cotanch).

6. Lightcone View on the Applicability of Perturbative QCD for Exclusive Processes, Phys. Rev. **D52**, 4038 (1995) (with C.-Y. Pang and A. Szczepaniak).

7. The Self-Energy Effects on the Rotation Symmetry in the Lightcone Quantized Scalar Fields Scattering, Phys. Rev. **D52**, 879 (1995) (with Gwang-Ho Kim and Dong-Pil Min).

8. A Spinor Technique in Symbolic Feynman Diagram Calculation, Journal of Computational Physics **115**, 267-275 (1994) (with C.-Y. Pang).

9. Significant Nonvalence components in Heavy Quark Systems, Phys. Rev. Lett. **72**, 2538 (1994) (with A. Szczepaniak and S.R. Cotanch).

10. The Self-Energy Corrections to the Lightcone Two-Body Equation in ϕ^3-theories, Phys. Lett. **B322**, 389 (1994).

11. Generalized Relativistic Meson Wave Function, Phys. Rev. **D49**, 3466 (1994) (with A. Szczepaniak and S. R. Cotanch).

12. Kinematically Accessible Vector Meson Resonance Enhancements in $p(K^-, e^+e^-)\Lambda$, Σ^0, $\Lambda(1405)$, Phys. Rev. **C48**, 1318 (1993) (with R.A. Williams and S.R. Cotanch).

13. Λ, Σ^0 and $\Lambda(1405)$ electroproduction in a crossing- and duality- constrained model, Phys. Rev. **C46**, 1617 (1992) (with R. A. Williams and S.R. Cotanch).

14. Calculation of Scattering with the Light-Cone Two-Body Equation in ϕ^3-theories, Phys. Rev. **D46**, 3565 (1992) (with Y. Surya).

15. Light-Cone Quark-Model Axial Vector Meson Wavefunction, Phys. Rev. **D45**, 4214 (1992) (with P.L. Chung and S.R. Cotanch).

16. Anomalous Dimensions of Baryon Multiplets in SU(N) ($N \geq 3$) Flavor Symmetry, Phys. Rev. **D44**, 1516 (1991) (with C.-Y. Pang).

17. Crossing and Duality Consistent Study of Λ, Σ^0 and $\Lambda(1405)$ Production by Kaon Photoproduction and Radiative Capture, Phys. Rev. C43, 45 (1991) (with R. A. Williams and S.R. Cotanch).

18. Perturbative QCD Analysis of the Pion and Kaon Form Factors and Pair Production in Photon-Photon Collisions Using a Frozen Coupling Constant, Phys. Rev. D42, 3764 (1990) (with F. Amiri).

19. Comment on "Understanding Electroweak Couplings of the Pion as a qq Composite", Phys. Rev. Lett. 64, 1848 (1990) (with S.R. Cotanch).

20. Simple Relativistic Quark Model Analysis of Flavored Pseudoscalar Mesons, Phys. Rev. **D41**, 2319 (1990) (with S.R. Cotanch).

21. Crossing Consistent Analysis of Kaon Photoproduction and Radiative Capture, Phys. Rev. **D41**, 1449 (1990) (with R. A. Williams and S. R. Cotanch).

Conference Papers Publication and Presentation (1990-1996)

1. Cooling Modes of Neutron Star, in *the 9th Summer School and Symposium on Nuclear Physics*, (with D.-P. Min), **Kwangju**, August 19-23, 1996.

2. Multiquark QCD Evolution and Anomalous Dimensions of Meson, Baryon and Deuteron Systems, in *Inauguration Conference of Asia Pacific Center for Theoretical Physics*, **Seoul**, June 4-10, 1996.

3. Radiative Decays and Transition Form Factors of Strange Mesons in the Relativistic Constituent Quark Model, in *Strangeness '96*, Heavy Ion Phys, Vol. 4, pp. 369-380 (1996) (with H.-M. Choi), **Budapest**, May 15-17, 1996.

4. Lightcone Quark Model Studies of Meson Structure, in *Meson '96*, Workshop on Production, Properties and Interaction of Mesons, Acta Physica Polonica **B27**, pp. 3377-3380 (1996), **Cracow**, May 10-14, 1996.

5. Bound-State and Scattering Problems on the Light-Front, in *the School on Light-Front Quantization and Non-Perturbative QCD*, pp. 36-64, published by the International Institute of Theoretical and Applied Physics (IITAP) in 1997 and edited by J. Vary and F. Wolz, based on Fundamental Issues in the Lightcone Field Quantization (Lecture 1), Bound-State and Scattering Problems on the Lightcone (Lecture 2), Lightcone Quark Model Studies of Hadron Structure (Lecture 3) **Ames**, May 8-10, 1996.

6. Light-Front Description of Axial Anomaly, in *International Workshop on the Structure of the η' Meson*, pp. 45-61, published by World Scientific Publishing Co. in 1997 and edited by M. Burkardt, J. Goity, V. Papavassiliou and S. Pate, **Las Cruces**, March 8-9, 1996.

7. Lightcone Quark Model Studies of Hadron Structure, in *KOSEF-JSPS Winter School*, Recent Developments in Particle and Nuclear Theory, Journal of Korean Physical Society (Proc. Suppl.), **Vol. 29**, S286 (1996), **Seoul**, February 21-28, 1996.

8. Light-Cone View of the Applicability of PQCD in Medium Energy Exclusive Processes, in *Fifth International Workshop on Light-Cone QCD*, **Telluride**, August 14-26, 1995.

9. Axial Anomaly on the Lightcone, in *Advanced HUGging*, 10th Annual Hampton University Graduate Studies at CEBAF, **CEBAF**, June 8-10, 1995.

10. Axial Anomaly on the Lightcone, in *the Institute for Nuclear Theory's Program (INT-95-1) on Chiral Dynamics in Hadrons and Nuclei*, organized by M. Rho, B. Holstein, G. Brown and D.P. Min, **Seattle**, May 20-27, 1995.

11. Light-Cone Quark Model of Mesons, in *Proceedings of the XVII International Kazimierz Meeting on Particle Physics, The Madison Phenomenology Symposium: Particle Theory and Phenomenology*, pp. 311-316 (with A. Szczepaniak and S.R. Cotanch), published by the World Scientific Pub. Co. and edited by K.E. Lassila, J. Qiu, A Sommerer, G. Valencia, K. Whisnant and B.-L. Young, **Iowa State University**, May 17-19, 1995.

12. Challenges in Lightcone Field Quantization (SNUTP-95-031), in *Proceedings of the Second Pacific Winter School for Theoretical Physics; Topics in Theoretical Physics*, pp. 237-246, published by the World Scientific Pub. Co. in 1997, and edited by Y. M. Cho, **Sorak**, January 19-24, 1995.

13. Self-Energies and Rotational Symmetry, in *Proceedings of the Fourth International Workshop on Light Cone Quantization and Non-Perturbative Dynamics: Theory of Hadrons and Light-Front QCD*, pp. 203-207, published by World Scientific Publishing Co. and edited by S. Glazek, **Polana Zgorzelisko**, August 15-25, 1994.

14. Solving Scattering and Bound State Problems on the Light Cone, in *Proceedings of the 14th International IUPAP Conference on Few Body Problems in Physics*, AIP Conference Proceedings No 334, pp. 883-886, edited by F. Gross, **Williamsburg**, May 26-31, 1994.

15. On the Constituent Quark Structure, in *Proceedings of the 14th International IUPAP Conference on Few Body Problems in Physics*, AIP Conference Proceedings No. 334, pp. 647-650 (with A. Szczepaniak and S. R. Cotanch), edited by F. Gross, **Williamsburg**, May 26-31, 1994.

16. Relativistic Quark Model Description of Baryon Properties, in *Proceedings of the 14th International IUPAP Conference on Few Body Problems in Physics*, AIP Conference Proceedings No. 334, pp. 575-578 (with S.R. Cotanch and A. Szczepaniak), edited by F. Gross, **Williamsburg**, May 26-31, 1994.

17. Pion Form Factor, in *Workshop Report on CEBAF at Higher Energies*, pp. 231-236 (with C.-Y. Pang and A. Szczepaniak), published by CEBAF and edited by N. Isgur and P. Stoler, **CEBAF**, April 14-16, 1994.

18. Quark Structure of Meson, Nucleon and Deuteron, in *Proceedings of the XVII Symposium on Nuclear Physics*, Revista Mexicana de Fisica, Vol. 40, Suplemento 1, 330-336 (1994), **Oaxtepec**, January 4-7, 1994.

19. The Lightcone Vacuum, in *Proceedings of the Cornelius Lanczos International Centenary Conference*, pp. 615-617, published by the Society for Industrial and Applied Mathematics, and edited by J. D. Brown, M. T. Chu, D. C. Ellison and R. J. Plemmons, **North Carolina State University**, December 12-17, 1993.

20. The Role of Symmetry in Kaon Electromagnetic Production and Capture Reactions, in *Proceedings of the 2nd Korea-Japan Joint Workshop on Strangeness in Nuclear Matters*, pp. 103-111, published by Research Institute of Basic Science, Seoul National University, and edited by H. C. Ghang, D. Cha, J. Chiba and K. Nakai, **Seoul National University**, December 6-7, 1993.

21. The Deuteron Form Factors at High Momentum Transfer, in *'93 Fall Meeting of Korean Physical Society*, **Kyungbuk University**, October 23-24, 1993.

22. Crossing Constraint in Kaon Production and Capture, in *Proceedings of the 6th Symposium on Nuclear Physics (Astro-Nuclear Physics and Related Topics)*, pp. 156-191 (with R. A. Williams and S.R. Cotanch), published by Han Lim Won, and edited by D.-P. Min and B.-Y. Park, **Muju**, August 20-25, 1993.

23. Lightcone Quantum Field Theory, in *The 6th Annual Summer School in Nuclear Physics Research*, **North Carolina State University**, July 11-24, 1993.

24. Spin-1 Form Factors, in *Proceedings of the International Workshop on Exclusive Reactions at High Momentum Transfer*, pp. 206-213, published by World Scientific Publishing Co. and edited by C. Carlson and P. Stoler, **Marciana Marina**, June 24-26, 1993.

25. Meson and Nucleon Form Factors in PQCD, in *Proceedings of the International Conference (Vth Blois Workshop) on Elastic and Diffractive Scattering*, pp. 366-370, published by World Scientific Publishing Co. and edited by H. Fried, K. Kang and C.-I. Tan, **Brown University**, June 8-12, 1993.

26. Rotational Symmetry, in *the Light-Cone QCD Workshop*, organized by S. Pinsky, **Telluride**, August 17-21, 1992.

27. Meson in the Light-Cone Model, in *The First Haengdang Symposium*, organized by H.K. Lee, **Seoul**, August 3, 1992.

28. Mesons in the Light-Cone Quark Model, in *the Institute for Nuclear Theory's Program 8(INT92-2) on Strangeness in Hadrons and Nuclei*, organized by C. Dover, B. Gibson and G. Miller, **Seattle**, June 8-August 31, 1992.

29. Restoration of Rotational Symmetry in the Light-Cone Field Quantization, in *the Workshop on Light-Cone Quantization*, a copy of transparencies published by G. McCartor, **Dallas**, May 26-29, 1992.

30. Strong-Interaction Scattering Problems on the Light Cone, in *DIRKFEST '92, Proceedings of a Symposium in Honor of John Dirk Walecka's Sixtieth Birthday*, pp. 147-163, published by World Scientific Publishing Co. and edited by W. Buck, K. Maung and B. Serot, **CEBAF**, April 24-25, 1992.

31. Two-Body Bound State and Scattering Problems in Lightcone Formalism, in *13th International Conference on Few Body Problems in Physics*, organized by I. T. Cahill, **Adelaide**, January 5-11, 1992.