Quantum Chromodynamic Quark Model Study of Hadron and Few Hadron Systems

Technical Report
1990 – 1996

Chueng-Ryong Ji
Department of Physics
North Carolina State University
Raleigh, North Carolina 27695-8202

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
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, $G_E(Q^2)$, 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 ($f_{\pi}, <r_{\pi}^2>$) 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-Dancoff 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, $\alpha$, and the binding energy, $\beta$, 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 $\beta$ become frozen as $\alpha$ 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 = Λ, Σ^0 and Λ(1405). Because there is no constraint on the minimum 4-momentum transferred by the timelike photon (q^2 ≥ 2M^2_C - 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 ≤ E_{lab}^γ ≤ 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)


19. Comment on “Understanding Electroweak Couplings of the Pion as a $q\bar{q}$ Composite”, Phys. Rev. Lett. 64, 1848 (1990) (with S. R. Cotanch).


Conference Papers Publication and Presentation (1990-1996)


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.


