Coulomb Gauge QCD-based Studies of Hadronic Structure and Interactions

Termination Report
December 1996 – December 2000

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Prepared for the U.S. Department of Energy
under grant number DE-FG02-96ER40944

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This document summarizes the work carried out under DOE grant DE-FG02-96ER40944, *Coulomb Gauge QCD-based Studies of Hadronic Structure and Interactions.*

I. Research Summary

The research conducted during the term of this grant may be roughly divided into three topics: the phenomenology of QCD exotica (including hybrids and glueballs), quark model studies of hadronic interactions (including strong decays and scattering), and the development of a comprehensive new model of strong QCD which is based on the Coulomb gauge QCD Hamiltonian.

I.1 Coulomb Gauge Model of QCD

I.1.a Model Definition

The PI and A. Szczepaniak have been developing a new model capable of describing low energy hadronic phenomena [4,17,19,22,25,31,33]. This model may be thought of as a continuum field theory extension of the constituent quark model which is capable of describing bound states, reactions, gluonic degrees of freedom, and chiral pions. To summarize, the model is

- relativistic
- contains explicit gluonic degrees of freedom
- goes beyond the valence approximation
- is ultraviolet and infrared finite
- joins for the first time perturbative QCD with low energy QCD (via the similarity transformation renormalization program)
- contains a low energy phenomenology which is heavily constrained by heavy quark effective theory
- has a nontrivial vacuum
- dynamical chiral symmetry breaking occurs
- chiral pions emerge
- and constituent quarks are generated as pseudoparticles.

The properties of the quark sector of the model under renormalization group flow have been examined in Ref. [4]. A similar study for the gluonic sector was made in Ref. [25]. In both cases the vacuum structure of the model was also examined with the aid of a specific nonperturbative vacuum ansatz.

The model has a rich structure and therefore allows the examination of many topical issues in hadronic physics. Two such topics follow.

I.1.b Glueballs

There have been a variety of previous glueball studies: the Bag Model, QCD Sum Rules, the Constituent Glue Model, and the Flux Tube Model. These approaches differ markedly in their mass predictions, sometimes by as much as 1 GeV, and no single approach has consistently reproduced lattice gauge measurements.

We have computed the low lying glueball mass spectrum using the model described in Section I.1.a with the Tamm Dancoff and RPA formalisms. The results were reported in Ref. [1] and are in strikingly good agreement with lattice data.

I.1.c Dirac Structure of Confinement

Although it has been postulated for more than 30 years, the phenomenon of quark confinement remains an enigmatic feature of QCD. Quenched lattice gauge theory and heavy quark phenomenology indicate that the static ($m_q >> \Lambda_{QCD}$) long range potential should be linear with a slope of $b \approx 0.18\,\mathrm{GeV}^2$. The order $1/m_q^2$ quark-antiquark long range spin-dependent structure has also been studied. Comparison with spin splittings in the J/ψ and Υ spectra indicate that the spin-dependence can only arise from the nonrelativistic reduction of a scalar current quark-antiquark interaction. This picture is also supported by calculations of the long range spin-dependent effective potentials on the lattice. It is therefore disconcerting that attempts to build Hamiltonian-based models of QCD seem to require vector confinement. For example, we have found [4] that it is impossible to construct a stable BCS-like vacuum of QCD when scalar confinement is assumed. This is problematical if one wishes to dynamically generate constituent quark masses. Furthermore, attempts at modeling chiral pions will be hindered by the explicit lack of chiral symmetry in a scalar interaction. These observations appear to stand in contradiction to the well established scalar confinement hypothesis.

This issue was resolved by the PI and Szczepaniak [5] by examining the heavy quark limit of the Coulomb gauge QCD Hamiltonian. The physics is most transparent after performing a Foldy-Wouthuysen transformation on the QCD Hamiltonian. The calculations prove that confinement is vector in nature with an effective scalar $1/m^2$ structure generated by nonperturbative mixing with hybrids. Furthermore, the structure of the spin-dependent terms depends crucially on the nature of the ground state gluonic degrees of freedom and clearly favors a collective rather than a single particle picture of them.

I.2 Quark Model Phenomenology

I.2.a Hadronic Decays in the $^3P_0$ Model

The major difficulty in identifying hybrids with non-exotic quantum numbers is in distinguishing them from conventional quarkonia. This is especially true because hybrids have masses greater than roughly 1.9 GeV, placing them in a dense region of the spectrum. In an effort to address this issue, the PI, Barnes, Close, and Page [6] have surveyed all radial and orbital excitations of light quarkonia anticipated up to approximately 2 GeV in the I=0 and I=1 systems, and have given detailed predictions of their quasi-two-body branching fractions in the $^3P_0$ decay model. These were then compared to flux tube model hybrid decay predictions (the DQM hybrid decay model had not been invented yet) in order to identify possible exotic states. Characteristic "quarkonium fingerprint" patterns of decay amplitudes were noted for some states. The "missing mesons" with $L_{q\bar{q}} = 2$ and $L_{q\bar{q}} = 3$ are predicted to decay dominantly into certain S+P modes, and may appear in the course of experimental searches for hybrids in the same mass region.

I.2.b J/ψ Scattering

Along with Barnes and Wong, the PI has investigated J/ψ scattering in the 'Quark Born Diagram' formalism of Barnes and Swanson [28,29,30]. This topic is directly relevant to searches for the quark-gluon plasma at RHIC since $c\bar{c}$ dissociation due to hadronic interactions may mask putative signals for quark deconfinement. Our results were found to disagree strongly with naive perturbative QCD computations and to agree with the data.

I.2.c $\gamma\gamma \to \pi\pi$

The process $\gamma\gamma \to$ meson-meson is ideal for studying hadronic interactions. For example, it is nontrivial to maintain consistency of the production amplitude (by which I mean the initial state interaction) at a microscopic level with low energy theorems. Doing so will teach us much about nonperturbative dynamics. Furthermore the final state hadronic interactions can lead to dramatic experimental effects – indeed much of the data is mysterious and the field is rife with speculation. A simple example of this is the measured $\pi^0\pi^0$ cross section. At low energy, the production amplitude is rigorously given by scalar QED, and hence the neutral pion cross section must follow from final state interactions. In terms of the quark model this is possible if the $\pi\pi$ interactions vary with isospin, thereby causing a rotation in isospin space and leading to the neutral pion final state. Whether this works in detail (without destroying the agreement with $\sigma(\gamma\gamma \to \pi^+\pi^-)$ for example), is a subject of inquiry.

Along with S. Godfrey, the PI has demonstrated that both the charged and neutral pion cross sections may be explained with a combination of scalar QED and quark model final state interactions [27]. While the production of pions is typically the purview of chiral perturbation theory, we may now proceed to examine the production of vector mesons something which is inaccessible to chiral perturbation and which is poorly understood.

I.2.d Hadronic Reactions

The application and extension of the quark model were continued on several fronts in this research program. In Ref. [26], the effective interaction between heavy B mesons was calculated using a technique developed by Barnes and I. The results agreed well with recent lattice calculations of the same potentials.

Encouraged by this and previous successes, Barnes and I are now evaluating spin-dependent effective hadron-hadron forces generated at the quark level (for the $\pi - \rho$ system). We hope to extend these results to the KN and NN systems in the next year.

I.3 QCD Exotica

I.3.a The Hall D Project

The PI has been involved with the 'Hall D' project during most of the duration of this grant. This is an effort to build a new experimental hall at Jefferson Lab which would take advantage of the proposed CEBAF energy upgrade. The major goal of Hall D is to discover light hybrid mesons in photoproduction. The Hall D collaboration has written several design reports and has passed several hurdles. Full details may be found at `http://dustbunny.physics.indiana.edu/HallD/`. The PI has coauthored a popular level article [32] describing this project in *American Scientist*.

I.3.b Exotica Phenomenology

Although explicit nonperturbative gluonic degrees of freedom have been anticipated for many years, no clear experimental evidence for their existence has emerged. The search for nonperturbative glue, in particular as manifested in hybrid mesons, would be greatly facilitated by a rudimentary knowledge of the hybrid spectrum and decay characteristics. Even though it appears that lattice estimates of light quenched hybrid masses are forthcoming, hadronic decays remain difficult to calculate on the lattice. Thus one is forced to rely on model estimates of the couplings of hybrids to ordinary mesons. Historically, there have been two approaches to such estimates. The first assumes that hybrids are predominantly quark-antiquark states with an additional constituent gluon and that decays proceed via constituent gluon dissociation. The second was introduced by Isgur, Kokoski, and Paton (IKP) and assumes that hybrids are predominantly quark-antiquark states moving on an adiabatic surface generated by an excited "flux tube" configuration of glue. Decays then proceed by a phenomenological pair production mechanism (the "$^3P_0$ model") coupled with a flux tube overlap.

Our approach [14,24] is based on the successful description of the Dirac structure of confinement given above. The idea is to use the heavy quark expansion of the Coulomb gauge QCD Hamiltonian to identify relevant operators. The gluonic portion of these are then evaluated using the extended flux tube model mentioned in the previous section. In the heavy quark limit the interaction contains the kinetic energy term: $H_{int} = -\int h^\dagger \sigma \cdot \mathbf{D} \chi + \text{H.c.}$, where $\mathbf{D} = i\nabla + g\mathbf{A}$. It should be noted that this interaction only contains terms which produce or annihilate a $Q\bar{Q}$ pair (i.e., gluon production or annihilation by a through-going quark line is not present). This implies that contributions to the decay which are higher order in the S-matrix expansion are also higher order in $1/M_Q$. Our model is therefore rather simple: calculate the decay of a (flux tube model) hybrid into two ordinary mesons to first order in H_{int}. The essential new feature is that the gluon field operator should be expressed in terms of the nonperturbative phonon modes of the flux tube model. Explicit computations of decay widths have been made [14,24] and indicate that hybrids have typical hadronic widths (although some are very narrow).

The nature of the appropriate effective degrees of freedom for glue can only be determined by a long process of calculation and comparison with experimental and lattice data. We have already seen several indications that it is stringlike. Alternatively, pointlike models of low energy glue have a long history, originating with MIT bag model calculations of Barnes and the potential model of Horn and Mandula. As another test of the structure of soft glue and our understanding of the confinement mechanism, the PI and Szczepaniak have calculated the static hybrid spectrum in our model of QCD [13,20,23]. This became a useful endeavor with the appearance of extensive and accurate lattice data showing the dependence of the hybrid energy on the interquark separation (ie., the adiabatic potentials).

Our results indicate that models of hybrids with pointlike gluons cannot reproduce the lattice data unless a velocity-dependent potential is added to the interaction (recently such a potential has been found).

I.3.c QCD Exotica Database

The PI and several students have created a web database for QCD exotica and related information. It may be viewed at `http://fafnir.physics.ncsu.edu/exotica/`. This site contains an annotated bibliography of experimental and theoretical papers on exotica, critical discussions of common models, tables of predicted decay widths, and a graphical interface to the PDG experimental data and a variety of lattice and model theoretical data.

II. Bibliographic Information

II.1 1996-2000 Papers, Seminars, and Conferences

II.1.a Publications

33. *Nonperturbative Renormalization and the QCD Vacuum*
A.P. Szczepaniak and E.S. Swanson; Phys. Rev. **D62**, 094027 (2000).

32. *The Search for QCD Exotics*
A. Dzierba, C. Meyer, and E.S. Swanson; *American Scientist* **88**, 406 (2000).

31. *Studies of Coulomb Gauge QCD*
A.P. Szczepaniak and E.S. Swanson, Seventh International Conference on the Intersections of Particle and Nuclear Physics, Quebec, May 22-28, 2000.

30. *Charmonium plus Light Hadron Cross Sections*
T. Barnes, E.S. Swanson, and C.-Y. Wong, Fifth International Workshop on Heavy Quark Physics, Dubna, Moscow Region, Russia, 5-9 Apr 2000.

29. *Cross Sections for the Dissociation of J/ψ and ψ' by π and ρ at low Energies*
C.Y. Wong, E.S. Swanson, and T. Barnes, 28th International Workshop on Gross Properties of Nuclei and Nuclear Excitation: Hadrons in Dense Matter, Hirschegg, Austria, 16-22 Jan 2000.

28. *Cross Sections for π- and ρ-induced Dissociation of J/ψ and ψ'.*
C.-Y. Wong, E.S. Swanson, and T. Barnes; Phys. Rev. **C62**, 04520 (2000).

27. *A Quark Model Calculation of $\gamma\gamma \to \pi\pi$ Including Final State Interactions*
H. Blundell, S. Godfrey, G. Hay, and E.S. Swanson; Phys. Rev. **C61**, 025203 (2000).

26. *BB Potentials from the Quark Model*
T. Barnes, N. Black, D. Dean, and E.S. Swanson; Phys. Rev. **C60**, 045202 (1999).

25. *Renormalized Effective QCD Hamiltonian: Gluonic Sector*
D.G. Robertson, E.S. Swanson, A.P. Szczepaniak, C.-R. Ji, and S.R. Cotanch; Phys. Rev. **D59**, 074019 (1999).

24. *Hybrid Meson Decay Phenomenology*
P.R. Page, E.S. Swanson, and A.P. Szczepaniak; Phys. Rev. **D59**, 034016 (1999).

23. *Heavy Hybrids in a Constituent Glue Model*
E.S. Swanson, Proceedings of the QCD Euroconference, July 7 13, 1999, Montpellier, France.

22. *Solving the QCD Hamiltonian for Bound States*
E. Gubankova, E.S. Swanson, C. Ji, and S. Cotanch, Eleventh International Light Cone School and Workshop, Seoul, South Korea, May 26-June 6, 1999.

21. *Science Goals of Hall D*
E.S. Swanson, Proceedings of Rensellaer-JLab Workshop on a New Facility for High Energy Photoproduction, March 11 13, 1999.

20. *Heavy Hybrids with Constituent Gluons*
E.S. Swanson and A.P. Szczepaniak; Phys. Rev. **D59**, 014035 (1999).

19. *Developing the Dynamical Quark Model*
D.G. Robertson *et al.*, Proceedings of Confinement III, Newport News, VA, June, 1998.

18. *Soft Glue and the Dirac Structure of Confinement*

E.S. Swanson, Proceedings of Confinement III, Newport News, VA, June, 1998.

17. *QCD Hamiltonian Approach to the Glueball Spectrum*
S.R. Cotanch, A.P. Szczepaniak, E.S. Swanson, and C.-R. Ji, Proceedings of Few Body XV, July, 1997, Groningen; Nucl. Phys. **A31**, 640c (1998).

16. *Searching for Soft Glue: Hybrids and Glueballs*
E.S. Swanson, Proceedings of the JLab Conference on Physics and Instrumentation with 6-12 GeV Beams, Newport News VA, June, 1998.

15. *Final State Interactions*
E.S. Swanson, Proceedings of the CMU/JLab Workshop on Physics with 8+ GeV Photons, March 1998, CMU (CEBAF).

14. *Decays of Hybrid Mesons*
E.S. Swanson and A.P. Szczepaniak; Phys. Rev. **D56**, 5692 5695 (1997).

13. *Heavy Hybrids*
E.S. Swanson and A.P. Szczepaniak, Proceedings of the NCSU/JLab Workshop on Hybrids and Photoproduction Physics, November, 1997, NCSU (CEBAF).

12. *Assiette de Colle*
E.S. Swanson, Proceedings of the IUJL Workshop on Physics with 8+ GeV Photon Beams, July, 1997, Bloomington IN (CEBAF).

11. *Hybrids and Quark Confinement*
E.S. Swanson, Proceedings of the QCD Euroconference, July 3-9, 1997, Montpellier, France; Nucl. Phys. B (Proc. Suppl.).

10. *Glueball Spectroscopy in a Many-body QCD Hamiltonian Approach*
S.R. Cotanch, A. Szczepaniak, E.S. Swanson, and C.R. Ji, Proceedings of the 6th Conference on Intersections of Particle and Nuclear Physics, May 1997, Montana, USA (AIP, 1997).

9. *Hybrids and Quark Confinement*
E.S. Swanson, Proceedings of the Conference on Perspectives in Hadronic Physics, May 12-16, 1997, ICTP, Trieste, Italy, (World Scientific); Nucl. Phys. Proc. Suppl. **64**, 312 (1998).

8. *QCD and Hadronic Physics*
E.S. Swanson, Proceedings of the Fourth Biennial Conference on Low Energy Antiproton Physics (LEAP 96), August 27-31, 1996, Dinkelsbühl, Germany; Nucl. Phys. B (Proc. Suppl.) **56A** (1997) 166.

7. *QCD Exotica: Theory Perspectives*
E.S. Swanson, Proceedings of Hadron 97, August 1997, Brookhaven National Laboratory (World Scientific).

6. *Higher Quarkonia*
T. Barnes, F.E. Close, P. Page, and E.S. Swanson; Phys. Rev. **D55**, 4157 4188 (1997).

5. *On the Dirac Structure of Confinement*
A.P. Szczepaniak and E.S. Swanson; Phys. Rev. **D55**, 3987 3993 (1997).

4. *From Current to Constituent Quarks: a Renormalization Group Improved Hamiltonian Based Description of Hadrons.*
A.P. Szczepaniak and E.S. Swanson; Phys. Rev. **D55**, 1578 1591 (1997).

3. *On the Mechanism of Open Flavor Strong Decays*
E.S. Ackleh, T. Barnes, and E.S. Swanson; Phys. Rev. **D54**, 6811-6829 (1996).

2. *QCD Hamiltonian Approach to the Glueball Spectrum*
S.R. Cotanch, A.P. Szczepaniak, E.S. Swanson, and C.-R. Ji, Proceedings of the International Workshop on Quark Confinement and the Hadron Spectrum, July, 1996, Como, Italy (World Scientific).

1. *Glueball Spectroscopy in a Relativistic Many-body Approach to Hadron Structure*
A. Szczepaniak, E.S. Swanson, C.-R. Ji, and S.R. Cotanch; Phys. Rev. Lett. **76** (1996) 2011 2014.

II.1.b Seminars

39	Quarks and Gluons	U Pitt	Oct	2000
38	On the Viability of the Quark Model	CMU	Oct	2000
37	Open Issues in Hadronic Physics	Argonne Theory Institute	Aug	2000
36	Aspects of QCD in Coulomb Gauge	Uni-Bonn	Jul	2000
35	Aspects of QCD in Coulomb Gauge	IKP Jülich	Jul	2000
34	Hall D Theory Status	JLab Review Committee	Dec	1999
33	Searching for Exotic Mesons (colloq)	NCSU	Aug	1999
32	Hall D Science Goals	Hall D Design Report Mtg	Aug	1999
31	Heavy Hybrids with Constituent Gluons	QCD Euroconference 99	Jul	1999
30	QCD in Coulomb Gauge	U Pittsburgh	May	1999
29	Science Goals of Hall D (invited)	RPI/JLab Workshop	Mar	1999
28	The Search for Exotic Mesons (colloq)	New Mexico State	Mar	1999
27	QCD in Coulomb Gauge	Los Alamos (T5)	Mar	1999
26	The Search for Exotic Mesons (P/T colloq)	Los Alamos	Mar	1999
25	QCD in Coulomb Gauge (invited)	Aspen Winter Conf.	Jan	1999
24	QCD Exotica: Theory Status (invited)	DNP Meeting	Oct	1998
23	QCD in Coulomb Gauge	Argonne	Sep	1998
22	Theory Summary Talk (invited)	JLab UGM	Jun	1998
21	Searching for Soft Glue: Hybrids and Glueballs (invited)	JLab UGM	Jun	1998
20	Soft Glue and the Dirac Structure of Confinement	Conf III	Jun	1998
19	QCD in Coulomb Gauge	Ohio State	Mar	1998
18	Theory Summary Talk (invited)	CMU/JLab Workshop	Mar	1998
17	Final State Interactions (invited)	CMU/JLab Workshop	Mar	1998
16	QCD in Coulomb Gauge	Indiana-Bloomington	Mar	1998
15	Are Hybrids Found?	SLAC	Dec	1997
14	Are Hybrids Found? (colloq)	Lawrence Berkeley Lab	Dec	1997
13	QCD Exotica: Theory Perspectives (invited)	Hadron '97	Aug	1997
12	Constructing the Universe: the Particle Explosion	NCSU	Jul	1997
11	Hybrid Phenomenology (invited)	IUJL Workshop	Jul	1997
10	Hybrids and Quark Confinement (invited)	QCD97, Montpellier	Jul	1997
9	Hybrids and Quark Confinement (invited)	Perspectives, ICTP	May	1997
8	The Dirac Structure of Confinement	Univ. of Maryland	Nov	1996
7	QCD and the Dynamical Quark Model	DNP, Cambridge	Oct	1996
6	QCD and the Dynamical Quark Model	Rutherford Appleton Lab.	Sep	1996
5	QCD and Hadronic Physics	LEAP 96, Dinkelsbühl	Aug	1996
4	QCD and the Dynamical Quark Model	TRIUMF	Aug	1996
3	The Dynamical Quark Model: Applications	FSU	Jun	1996
2	The Dynamical Quark Model: Theory	FSU	Jun	1996
1	Microscopic Models of Strong Decays	Panic '96	May	1996

II.1.c Meetings

27. Key Issues in Hadronic Physics, Sanderling, N.C., Nov 5-10, 2000.
26. Argonne Theory Institute, Argonne National Lab, August 14-18, 2000.
25. Seventh International Conference on the Intersections of Particle and Nuclear Physics, Quebec, May 22-28, 2000.
24. N*2000, Jefferson Lab, February 16-19, 2000.
23. MIT/JLab Lattice Collaboration Meeting, Jefferson Lab, January 13-15, 2000.
22. Southeast Section of the APS Meeting, Chapel Hill, NC, November 7-9, 1999.

21. Hall B N^* Analysis Workshop, Jefferson Lab, October 1-2, 1999.
20. Hall D Design Report Workshop, Jefferson Lab, August 5-6, 1999.
19. QCD in Nuclear Physics Gordon Research Conference, Salve Regina University, Newport, RI, July 25-30, 1999.
18. QCD Euroconference 99, Montpellier, France, July 7-13, 1999.
17. Workshop on a New Facility for High Energy Photoproduction, Rensselaer Polytechnic Institute, Troy, NY, Mar 11-13, 1999.
16. Aspen Winter Conference on Nonperturbative Particle Dynamics, Jan 10-16, 1999.
15. APS Division of Nuclear Physics Meeting, Santa Fe NM, Oct 28-31, 1998.
14. JLab Conference on Physics and Instrumentation with 6-12 GeV Beams, June 15-18, 1998.
13. Confinement III, Newport News, VA, June 7-12, 1998.
12. Workshop on Hadronic Physics in the 21st Century, Washington, DC, March, 1998.
11. CMU/JLab Workshop on Physics with 8+ GeV Photons, Pittsburgh, PA, March, 1998.
10. NCSU Miniworkshop on Light Cone Physics, Raleigh, NC, Jan, 1998.
9. NCSU/JLab Workshop on Hybrids and Photoproduction Physics, Raleigh, NC, Nov, 1997.
8. Seventh International Conference on Hadron Spectroscopy (Hadron97), Brookhaven National Laboratory, August, 1997.
7. IUJL Workshop on Physics with 8+ GeV Photon Beams, Bloomington, IN, July, 1997.
6. QCD Euroconference, Montpellier, France, July, 1997.
5. Conference on Perspectives in Hadronic Physics, ICTP, Trieste, Italy, May, 1997.
4. Fall Meeting of the DNP, Cambridge, MA, Oct., 1996.
3. Low Energy Antiproton Physics (LEAP '96), Dinkelsbühl, Germany, Aug., 1996.
2. Particles and Nuclei International Conference, Williamsburg, VA, May, 1996.
1. First Annual Meeting of the NC AAPT, Raleigh, NC, March, 1996.

2.2 Advisees

- M. Binger (undergraduate)
- T. Cole (undergraduate)
- L. Elliot (Masters student)
- E. Gubankova (postdoc)
- D. Robertson (postdoc)
- A. Szczepaniak (postdoc)
- K. Waidelich (Masters student)