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RESEARCH IN THEORETICAL NUCLEAR PHYSICS PROGRESS REPORT*

Keh-Fei Liu; Principal Investigator
Terrence Draper; Co-principal Investigator
Bing An Li; Co-principal Investigator
University of Kentucky
Lexington, KY 40506

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Contents

1 Progress Description	3
1.1 Form Factors (Refs. 93,98,100,105,107,108,109)	3
1.2 Mesoniums and Glueballs (Refs. 89,92,95,96,97,106)	4
1.3 Soliton Model of Hadrons (Refs. 99,101,102)	4
2 List of Reprints and Preprints	5
3 Invited Presentations at International Schools & Conferences	8
3.1 K.F. Liu	8
3.2 T. Draper	9
4 Seminars at Institutions	9
4.1 K.F. Liu	9
4.2 T. Draper	10
5 Proposed Research Projects for the Second Year	10
5.1 Form Factors	10
5.2 Color Transparency	11
5.3 Soliton-soliton Interaction	12
5.4 Proton Spin — by B.A. Li	12
5.5 Strange Quark Content of the Proton — by B.A. Li	12
6 Attachments: reprints and preprints (removed) —	13

1 Progress Description

1.1 Form Factors (Refs. 93,98,100,105,107,108,109)

Simulations on a $16^3 \times 24$ lattice at a coupling constant of $\beta = 6.0$, have explored the electric and magnetic form factor of proton and nucleon as a function of momentum transfer. There are tantalizing indications that the results of the simulation are better fit (at the 1-sigma level or so) with a dipole form (just as in experiment) rather than with, say, a monopole form. It is encouraging that this calculation (directly from the underlying quark dynamics, with no tunable parameters) is accounting for the structure of the nucleon form factor, particularly since models have been unable to do so satisfactorily. Preliminary results on the form factors of the isovector and isoscalar axial-vector currents are also obtained. The axial form factors are found to be harder than the electric form factor of the proton which seems to be consistent with the experiments.

On a $24 \times 12 \times 12 \times 24$ lattice at $\beta = 5.9$, we have focussed our attention on zero-momentum observables (electric charge radii, magnetic charge radii and magnetic moments and transitions) for the entire baryon-octet, including the neutron and proton. We have seen that the electric charge radius squared of the neutron is negative, and agrees with experiment in both sign (very important) and magnitude (although, so far, only at a 1-sigma level). Systematics of the whole octet have revealed the interplay between the contributions to baryonic radii and magnetic moments from heavy and light quarks. The simulations have shown the importance of spin-spin dynamics, and the failure of constituent quark models to account for details of hadron structure. Already, the lattice results out-perform the results of model calculations (quark models, Skyrme model) as well as the results of sum-rule calculations. This is impressive because all but the lattice calculation have several adjustable parameters which are tuned to give the best agreement between theory and experiment. However, we notice that the magnetic moments and charge radii of all the particles in the simulation are underestimated. These finite size effects must be controlled by moving to larger lattices. The coupling constant must be changed to closer approximate the continuum limit.

1.2 Mesoniums and Glueballs (Refs. 89,92,95,96,97,106)

The $\rho\rho$ mesoniums with 4 different spin-isospin channels are calculated on the $24 \times 12 \times 12 \times 24$ lattice at $\beta = 5.9$ and 4 κ values. But it is found that in certain channels, there indeed exist bound states with exotic quantum numbers. In other channels, the effect has been blurred by the two-pion thresholds. The dependence on spin and isospin seems to agree with the trend of the experimental findings.

The glueball matrix elements are calculated on 12^4 and 14^4 lattices at $\beta = 5.9$ and 5.96. They are calculated with hybrid fuzzy plaquette operators. These scalar, pseudoscalar and tensor glueball matrix elements can be used to calculate the branching ratios of glueball production in J/Ψ radiative decays. The wavefunctions of the scalar and tensor glueballs are calculated in $SU(2)$ lattice gauge theory at $\beta = 2.2$ and 2.4. It confirms the speculation that the tensor glueball is much larger than the scalar one. In fact, we find that the tensor is about 3 times larger than the scalar one. This helps us understand various puzzles about the phenomenology of the glueballs.

1.3 Soliton Model of Hadrons (Refs. 99,101,102)

The missing Yukawa coupling in the soliton approach has been an outstanding problem in soliton physics. We show in the $1 + 1$ dimensional ϕ^4 theory that the leading order Yukawa coupling is derived from the classical soliton solution. Furthermore, the Born amplitude calculated with this Yukawa coupling is identical to that from the potential scattering with small fluctuation to the leading order.

The quark spin content of the proton is computed in terms of the background field method. It is shown that the ω meson, through its coupling to the anomaly, gives rise to the leading order (order 1) in the large N_c contribution to the quark spin in the proton. The result in the Skyrme model with the ω meson agrees with the experiment.

New mass splitting formulae for the octet and decuplet baryons are obtained in the sub- $SU(3)$ Skyrme model in $SU(N)$ with $N = 3, 8$ by the perturbative treatment. We find the $N=5$ or 6 make the mass spectrum most compatible with data. They are much better than the pure $SU(3)$ model.

2 List of Reprints and Preprints

1989

Published in Refereed Journals

89. UK/88 - 12 B.A. Li and K.F. Liu
 $K^\bar{K}^*$ Mesoniums in $\gamma\gamma$ Reactions and Hadronic Collisions*
Phys. Rev. D **40**, 2856-2860 (1989)
92. UK/89 - 4 K.F. Liu, B.A. Li and K. Ishikawa
On the Identification of $\Theta(1720)$ as a Tensor Glueball
Phys. Rev. D **40**, 3648-3654 (1989)
93. UK/89 - 6 T. Draper, R.M. Woloshyn and K.F. Liu
Electromagnetic Properties of Nucleons from Lattice QCD
Phys. Lett. B **234**, 121-126 (1990)
94. UK/89 - 7 S. Nadkarni
Asymptotic Freedom and Running Charge in High Temperature QCD
Phys. Lett. B **232**, 362 (1989)

Conference Proceedings

95. UK/89 - 5 K.F. Liu
Vector Dominance and Identification of θ as a Tensor Glueball
Proc. of Tau-Charm Workshop, (SLAC, 1989)
96. UK/89 - 8 K.F. Liu
Vector Mesoniums and Glueball Wavefunctions on the Lattice

Proc. of Int. Conf. on Hadron Spectroscopy, (Ajaccio, 1989)

97. UK/89 - 9 Y.G. Liang, B.A. Li, K.F. Liu, T. Draper, and R.M. Woloshyn
 $\rho\rho$ Mesoniums on the Lattice
Nucl. Phys. B (Proc. Suppl) **17**, 408-412 (1990)
98. UK/89 - 10 W. Wilcox, K.F. Liu, T. Draper, and C.M. Wu
Lattice Nucleon Electromagnetic Form Factors
Nucl. Phys. B (Proc. Suppl) **17**, 382-386 (1990)

1990

Published in Refereed Journals

99. UK/90 - 1 Y.G. Liang, B.A. Li, K.F. Liu, and R.K. Su
Born Amplitudes and Seagull Term in Meson-Soliton Scattering
Phys. Lett. **243B**, 133-140 (1990)
100. UK/90 - 2 K.F. Liu
Hadron Structure and Interaction from Lattice QCD Calculations
Int. Jour. of Supercomputer Applications, **4**, 72-80 (1990)

Unpublished Reports of Articles Submitted

101. UK/90 - 3 G.W. Wu, M.L. Yan and K.F. Liu
Flavor Symmetry and Mass Splitting Formulas
Phys. Rev. D, Dec. issue (1990)

102. UK/90 - 4 B.A. Li, M.L. Yan and K.F. Liu
Quark Spin Content of the Proton in the Skyrme Model
Submitted to *Phys. Rev. D*

103. UK/90 - 5 K.F. Liu, H.D. Luo, Z.Y. Ma and M. Feng
Sum Rules for Nuclear Excitations with Skyrme-Landau Interaction
Submitted to *Nucl. Phys. A*

104. UK/90 - 6 K.F. Liu, Z.Y. Ma and H.D. Luo
*Skyrme-Landau Particle-Particle Interaction
and Application to O^{18} and F^{18}*
Submitted to *Nucl. Phys. A*

105. UK/90 - 7 K.F. Liu
Hadron Structure and Interaction in Lattice QCD Calculation
*Proc. of 2nd Int. Conference on Medium- and High-Energy
Nuclear Physics, (Taiwan, May 1990)*

106. UK/90 - 8 Y.G. Liang, K.F. Liu, B.A. Li and K. Ishikawa
Lattice Calculation of Glueball Matrix Elements
To appear in the proceedings of
Lattice '90, Int. Conference on Lattice Field Theory,
(Tallahassee, October 1990)

107. UK/90 - 9 D.B. Leinweber, R.M. Woloshyn and T. Draper
Electromagnetic Structure of Octet Baryons
Accepted for publication in *Phys. Rev. D*

108. UK/90 - 10 T. Draper, K.F. Liu, D.B. Leinweber and R.M. Woloshyn
Lattice Calculation of Baryonic Electromagnetic Form Factors

To appear in the proceedings of
Panic XII, Int. Conference on Particles and Nuclei,
(Massachusetts Institute of Technology, June 1990)

109. UK/90 - 11 D.B. Leinweber, R.M. Woloshyn and T. Draper
On the Electromagnetic Properties of the Baryon Octet
To appear in the proceedings of
Lattice '90, Int. Conference on Lattice Field Theory,
(Tallahassee, October 1990)

3 Invited Presentations at International Schools & Conferences

3.1 K.F. Liu

1. "Hadron Structure and Interaction in Lattice Calculation", Int. Conf. on Medium- and High-Energy Nuclear Physics, Taiwan, May 14-18, 1990.
2. "Tensor Glueball", Kaon Workshop, TRIUMF, July 23-25, 1990.
3. "Hadron Structure and Interaction on the Lattice", Int. Conf. on High Energy Physics, Singapore, Aug. 2-9, 1990.
4. "Glueball Matrix Elements", Int. Conf. on Lattice Field Theory, Tallahassee, Oct. 8-12, 1990.
5. "Nucleon Axial-Vector Form Factors", Int. Conf. on Lattice Field Theory, Tallahassee, Oct. 8-12, 1990.

3.2 T. Draper

1. "Lattice Calculation of Baryonic Electromagnetic Form Factors", *Panic XII, International Conference on Particles and Nuclei*, Massachusetts Institute of Technology, June 25 - 29, 1990.
2. "On the Structure of Octet Baryons", Workshop on *Lattice Gauge Theory: the Standard Model and Beyond*, Institute for Theoretical Physics, University of California at Santa Barbara, August 21, 1990.

4 Seminars at Institutions

4.1 K.F. Liu

1. "Lattice Calculation of Hadron Structure", Taiwan Univ., Jan. 10, 1990.
2. "Lattice Calculation of Hadron Structure", Academia Sinica, Taiwan, Jan. 11, 1990.
3. "Large N_c QCD, Skyrmon and Meson-exchange Models", Univ. of Kentucky, Feb. 26, 1990.
4. "Large N_c QCD, Skyrmon and Meson-exchange models", SUNY/ Stony Brook, Mar. 22, 1990.
5. "Hadron Structure in Lattice QCD", ITP, SUNY/Stony Brook, Mar. 21, 1990.
6. "Hadron Structure in Lattice QCD", Hollifield Theory User Workshop, Oak Ridge, Mar. 24, 1990.
7. "Hadron Structure in Lattice Calculation", Oak Ridge, Jun. 21, 1990.
8. "Hadron Structure and Interaction on the Lattice", TRIUMF, Jul. 11, 1990.
9. "Hadron Structure and Interaction on the Lattice", Univ. of Washington, Jul. 16, 1990.

10. "Large N_c QCD, Skyrmion and Meson-exchange models", Univ. of Connecticut, Oct. 22, 1990.
11. "Nucleon Axial-Vector Form Factor on the Lattice", SUNY/Stony Brook, Oct. 24, 1990.

4.2 T. Draper

1. "Electromagnetic Form Factors from Lattice QCD", Seminar at the University of Virginia, April 24, 1990.
2. "Ab Initio Calculations of Particle Structure", Seminar at the University of Kentucky, September 20, 1990.
3. "Numerical Simulations of Strongly-Interacting Particles", Colloquium at the University of Louisville, November 9, 1990.

5 Proposed Research Projects for the Second Year

5.1 Form Factors

Since our studies of the electric and magnetic properties of the nucleon, and indeed of the entire low-lying baryon octet have proved to be so illuminating, we are encouraged to proceed to look at the baryon decuplet which includes the Δ and Ω^- . As an example of the physics which we can study, we'll focus on the electromagnetic transition properties of Δ to proton. The ratio of electric quadrupole to magnetic dipole transition amplitudes (EMR) in the processes $\gamma + N \leftrightarrow \Delta$ has been recognized to be a crucial quantity to test theories of hadronic structure.

The extraction of this ratio from experiment is unsettled, because of strong interaction background effects. There is even some controversy over the *sign* of the ratio. Attempts to model the background effects introduce additional theoretical parameters

and yield model-dependent values of +4% and -4% respectively. The more precise extraction of $(-1.5 \pm 0.2)\%$ is in magnitude significantly higher than what most hadronic models predict. Only in the skyrmion model does an EMR as large as 5% emerge.

Given the disparity in theoretical predictions, and the uncertainty in the extraction of this ratio from experiment, it is important to learn what the *ab initio* calculation of lattice QCD predicts. We expect to be able to extract a signal at the 1% level from an analysis of correlation functions to be constructed from existing quark propagators.

We have calculated the connected part of the axial form factor for the nucleon. For the isovector axial form factor, the disconnected diagram does not contribute for the flavor symmetric case. However, the disconnected piece will contribute to the isoscalar (flavor singlet) case. In fact, this is where the anomaly is produced. The calculation of the disconnected diagram poses a numerical problem which amounts to diagonalizing a $10^6 \times 10^6$ matrix. This is too hard a problem on today's supercomputers. We will not invert the matrix to obtain the disconnected diagram, instead we propose to explore the special gauge property of the quark propagator to approximate it with a statistical average. If this is successful, we will want to use the gauge fields and quark propagators generated with the inclusion of dynamic fermions. Some of these configurations are available from the grand challenge projects of DOE in the last two years. This is a very important problem as it is related to the spin anomaly of the nucleon.

Once the quark loops can be calculated, we plan to extend our study to the scalar and pseudoscalar form factors of the nucleon and the η, η' (U(1) anomaly) mass problem.

5.2 Color Transparency

Our methods of calculation are already set up to investigate the current "hot topic" of color transparency. Namely, we should be able to look at the intrinsic size of a nucleon before and after it interacts with a virtual photon, and at how this size evolves with time. If we see that the nucleon remains small (that is, remains a small colorless object) then one would have an explanation of how a nucleon could escape a nucleus without further interaction, in accordance with the ideas of color transparency. This simulation will require a calculation of a multi-point correlation function; the calculation will be

more expensive than the existing form factor calculations. The prototypical calculation should be done on a lattice at least as large as those used for the form factor calculations.

5.3 Soliton-soliton Interaction

Since we obtained the leading Yukawa coupling form factor between the meson and nucleon, it is natural to extend it to the soliton-soliton interaction case with meson exchanges. We plan to study the meson exchange mechanism up to two meson exchanges in the Sine-Gordon theory and compare with the exact result of soliton-soliton scattering available to this theory. If this turns out to be as successful as the meson-soliton scattering, then the case is made for a serious calculation of the skyrmion-skyrmion interaction based on meson exchanges.

5.4 Proton Spin — by B.A. Li

The background field method is developed to explore the quark spin content of the proton, which is a nonperturbative problem. Many authors believe that there is no flavor-singlet axial-vector current of order one in the large N_c expansion, either in the original Skyrme model or in the theory in which only the pion fields are involved. We are studying this problem and have found that there is indeed a flavor-singlet axial-vector current of order one in the theory where only pion fields are involved. This investigation, which includes a study of the strange quark polarization in the proton, is almost completed and gives results which are quite compatible with data.

We plan to work on the contribution of quark orbital angular momentum to the proton spin and to study the role of the $U(1)$ problem in the proton spin.

5.5 Strange Quark Content of the Proton — by B.A. Li

Compared to the u and d quark condensation of the proton, the strange quark condensation of the proton is not small. We are trying to understand this in terms of the background field method. The preliminary results are encouraging. We still have more work to do.

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