Jefferson Laboratory
Theory Group

Annual Report

June 2002

I. OVERVIEW

A. ORGANIZATION OF THIS REPORT

This report summarizes the work done by the Jefferson Laboratory (JLab) Theory Group from January 1, 2001 to December 31, 2001. This Overview Section includes a list of staff supported by the Theory Group, and a Summary of some of the major research results. Section II presents a more complete summary of the research work. Publications and talks are listed in Section III, and an Appendix lists visitors and seminars for the period covered by the report.

In this report we include only work done by the Senior Staff, including the Distinguished Visiting Fellow, and Post-doctoral fellows associated with the group during the past year (2001). The JLab Theory Group interacts with many faculty, post-doctoral associates, and students. However, the work done by these associates and visitors is not included in the present report.

B. MEMBERS OF THE THEORY GROUP

The JLab Theory Group currently consists of 9 Senior Staff, 3 post-doctoral associates, and 3 active Associate Senior Staff (i.e., those who spend several days per month with the Theory Group). In the past year (2001), the Theory Group senior staff also included the JLab Distinguished Visiting Fellow. The Senior Staff are listed in Table I, the JLab Distinguished Visiting Fellow in Table II, post-doctoral associates in Table III, and the active Associate Senior Staff in Table IV.

Table I

JLab Senior Staff	
	half-time affiliation (if any)
Ian Balitsky	Old Dominion University
Robert Edwards	
Josè Goity	Hampton University
Franz Gross	College of William and Mary
Anatoly Radyushkin	Old Dominion University
David Richards	
Winston Roberts	Old Dominion University
Rocco Schiavilla	Old Dominion University
Wally Van Orden	Old Dominion University

The JLab Theory Group environment is also enhanced by several post-docs and students supported by neighboring institutions. In 2001, these included post-docs Gary Prezeau (Hampton), Cetin Savkli (W&M), Dirk Lehmann (Germany and Hampton), and Carlos Schat (Argentina and JLab).

Table II

JLab Distinguished Visiting Fellow		
	period	home institution
Yuri Simonov	10/01–04/02	ITEP, Moscow

Table III

JLab Post-docs	
	period of employment
Deirdre Black	10/01–present
Sabine Jeschonnek	10/99–09/2001
Wally Melnitchouk	08/01–present
Igor Musatov	10/01–present

C. RESEARCH HIGHLIGHTS

In this section highlights of the research undertaken by the JLab Theory Group are described in less technical language. The discussion is organized into four overlapping topics: *quark structure of hadrons, few-nucleon systems, deep inelastic scattering and duality, and solving QCD*.

1. QUARK STRUCTURE OF HADRONS

The word *hadrons* refers to neutrons and protons (referred to collectively as nucleons), their excited states, and the mesons that interact with them and bind them together into nuclei. These are the nuclear building blocks we observe in nature, yet they are not elementary particles. Nucleons are composed of three quarks surrounded by a sea of gluons and quark-antiquark pairs. Mesons are composed of a sea of quark-antiquark pairs and gluons. The force that binds the quarks and gluons into hadrons *confines* them, so that it is impossible to study quarks and gluons as free particles. Hence, an understanding of the structure of nuclear matter begins with the study of the structure of hadrons, the simplest pieces of nuclear matter we can observe in the laboratory.

Table IV

JLab Associate Senior Staff	(active)
	home institution
Carl Carlson	College of William and Mary
Chris Carone	College of William and Mary
Marc Sher	College of William and Mary

At JLab these theoretical studies are carried out using a variety of tools. Models that treat the quarks relativistically are being developed (Gross and Savkli). In systems where one of the quarks is very heavy, so that it moves very slowy, an approximate theory known as Heavy Quark Effective Theory (HQEF) has been developed that works very well (Roberts). For light quark systems, one may sometimes exploit the fact that the bare quark masses are very small. This gives rise to an approximate symmetry known as chiral symmetry, and leads to the development of Chiral Perturbation Theory, also being studied at JLab (Goity and Roberts). At high energy the charge structure of hadrons can be calculated using QCD sum rules (Radyushkin), and the structure of the quark-antiquark sea inferred from arguments based on chiral symmetry (Melnitchouk). Finally, in a few cases exact results for the masses of hadrons can be obtained by solving QCD on the lattice (Richards).

2. FEW-NUCLEON SYSTEMS AND THE NN FORCE

The simplest nuclei consisting of a "few" nucleons (in practice 2 to 10 nucleons) are easiest to study both theoretically and experimentally. The force between two nucleons can be inferred from the structure of the deuteron, the only bound state of two nucleons, and the scattering of two free nucleons. Then, using the forces inferred from two-nucleon studies, the properties of three-, four-, . . ., ten-nucleon systems can be predicted. Comparison of these results with experiment confirms the correctness of the *NN* force, and tells us whether or not three-nucleon (*NNN*) or many-nucleon forces are important. The goal of this work is to fully determine the nuclear forces and currents, explain the structure and interactions of few nucleon systems, and then to explain these forces and currents in terms of the underlying quark structure of matter and QCD.

It has recently been shown by the ANL-UIUC-LANL collaboration that it is possible to reproduce quite well the observed low-lying energy spectra of nuclei with mass number $A \leq 10$ by including *NN* and *NNN* forces. Using the resulting wave functions and electro-weak current operators constructed consistently with these forces, it has also been shown that a variety of nuclear properties ($A \leq 7$), such as elastic and inelastic electromagnetic form factors, radiative widths, β-decay and electron-capture rates, are well predicted by theory (Schiavilla). In collaboration with the Pisa group and members of the ANL-UIUC-LANL team, studies of low-energy radiative and weak capture reactions involving systems with $A \leq 7$ have also been carried out based on the same realistic forces and currents (Schiavilla). Some of these processes are of considerable interest in astrophysics in relation to energy and neutrino production in main-sequence stars and primordial nucleosynthesis.

Relativistic models based on the exchange of mesons between nucleons have also been developed and have been shown to be successful in explaining deuteron form factors (Gross, Schiavilla, Van Orden) and in describing electrodisintegration of few body nuclei (Gross, Jeschonneck, Schiavilla, and Van Orden). Effective field theories (EFT) provide a systematic expansion of the interaction valid at low energies (Goity, Roberts) and work is in progress to develop a relativistic EFT for the *NN* interaction (Goity, Prezeau, and Lehmann).

3. DEEP INELASTIC SCATTERING AND DUALITY

When electrons are used to probe the structure of hadrons and few-body nuclei in their normal ground state, the energy transferred to the hadronic or nuclear target is kept to a minimum, leaving the target largely undisturbed. Alternatively, the structure of hadrons and nuclei can be studied by explicitly exciting the underlying quark degrees of freedom. This is most effectively done when both the momentum and energy transferred by the electron are large. Under these conditions, known as deep inelastic scattering (DIS), the quarks are "torn" from the initial hadronic/nuclear target, and because they cannot exist in isolation, reform into different hadrons as they leave the target. The DIS Stanford Linear Accelerator (SLAC) experiments of Friedman, Kendall and Taylor, who received the Nobel Prize in 1990, were among the first to tell us of the existence of quarks, and this method continues to be a major source of information about quark structure.

A new theoretical tool, the so-called generalized parton distributions (GPDs), has been recently developed at JLab (Radyushkin) and elsewhere. The GPDs provide an effective tool for the study of quark distributions through deeply virtual Compton scattering and deep exclusive scattering (Balitsky, Radyushkin). This advance is one of the major new campaigns driving the JLab 12 GeV Upgrade proposal. The proton sea can also be studied in DIS (Melnitchouk).

At moderate energies excited states of hadrons appear as resonance "bumps" in DIS, and it has long been observed that the average of the cross section over these bumps reproduces the smooth result one obtains from DIS at very high energies. This phenomenon is known as "duality". New work at JLab is providing a better understanding of how this comes about (Jeschonnek, Melnitchouk, and Van Orden; and Batiz and Gross).

4. EXACT SOLUTIONS OF QCD

QCD can be solved to high precision at very high energies, where the forces between quarks and gluons become vanishingly small (a phenomenon known as "asymptotic freedom"). However, at the moderate energies of quarks in a cool hadronic medium the QCD forces are very strong, the theory is very difficult to solve. Only one way is known to obtain exact solutions of QCD in this region. It is a numerical method known as "lattice gauge theory". Since QCD is believed to be the theoretical foundation of nuclear physics, using lattice gauge theory to obtain exact numerical solutions remains one of the highest priorities of the Theory Group. Only a few results can be obtained on the lattice (masses of low lying states, couplings and decay amplitudes, and some moments of the DIS structure functions), but these provide guidance for the construction of the accurate models and effective theories that will provide a broader understanding.

An exciting development in 2001 was the award of three years of support to Jefferson Laboratory, totaling around \$2M, as part of a US effort to create a *National Computational Infrastructure for Lattice QCD*, under the Department of Energy's Scientific Discovery through Advanced Computing (SciDAC) initiative. Historically, the emphasis in lattice QCD research has been on particle physics applications, and in particular on the calculation of the weak-interaction matrix elements and investigations of the finite-temperature transition. The crucial rôle that lattice QCD plays in hadronic physics is now being recognized not only within the nuclear physics community, but also by the lattice community. This recognition has enabled JLab, together with colleagues at MIT, to attain an equal status with Fermilab and Brookhaven as national centers in the SciDAC program.

The goals of this project are to create a unified programming environment for the US lattice community on diverse, multi-architecture machines. The five-year plan is to site three such machines, of ten teraflops/second scale, i.e. capable of 10^{13} floating-point operators per second, at each of the national centers, including JLab. The physics of JLab, and in particular the calculation of the spectrum of hadrons and the calculation of their quark and gluon structure, is accorded similar prominence.

The JLab Theory Group has been pivotal in this national effort. Robert Edwards is a leading member of the National Software subcommittee, coordinated the submission of the successful proposal in March 2001, and has been instrumental in the design and implementation of the QCD API (*Application Program Interface*). Since joining the Theory Group full-time in December, David Richards involvement has increased through his rôle in coordinating the porting of hadronic physics code, and development of new codes, to the emerging QCD-API, and in the maintenance of the national lattice QCD web site hosted at JLab (www.lqcd.org). Chip Watson, of the High-Performance Computing Group, is a PI on the national SciDAC Executive Committee.

While the emphasis of the current grant is on software development, a substantial investment in hardware is being made, with a 256-node cluster, with fast interconnection, expected to be installed by the end of 2002. This cluster will be not only a test-bed for a future terascale facility, but also a substantial resource for lattice hadronic physics; the first projects will include the calculation of the proton and neutron electric and magnetic form factors, the moments of the polarized and unpolarized structure functions, and the spectrum of excited baryons and hybrid mesons.

The LQCD program is very promising, but can only be used to compute a limited number of observables in the simplest cases, and the numerical solutions it yields often do not provide the physical insight needed to generalize the results to more complicated systems. For these reasons it is of critical importance to the JLab program to find alternative ways to solve QCD. Yuri Simonov, last year JLab Distinguished Visiting Fellow, and his collaborators have developed a very promising method for obtaining approximate solutions to QCD. This method was studied and further developed at JLab, resulting in several new collaborations between Simonov and JLab theorists.

The technique exploits the properties of the QCD vacuum that have been extracted from lattice calculations, and allows the effective hamiltonian for two and three quark systems to be derived directly from QCD. In the process, that part of the confining interaction that is independent of the distance (the constant term), and the spin dependence of the confining interaction, both of which are usually treated in a purely phenomenological manner, are completely given in terms of the string tension (which determines the strength of the linear part of the confining force). This allows one to understand quark and gluon confinement and the spectrum of meson and baryons largely in terms of a string tension fixed by lattice calculations. (The quark masses and the quark-gluon coupling also play a role.) The results are very promising; as good as any model calculations, but with parameters obtained entirely from QCD. The method is currently being used to study the baryon spectrum, and meson and baryon decays.

An alternative method for the exact numerical solutions of field theories is also being developed at JLab (Savkli and Gross). This is known as the "Feynman-Schwinger" technique, and has not yet been applied to QCD.

II. DESCRIPTION OF CURRENT RESEARCH

IAN BALITSKY

- Deep Inelastic Scattering from Nucleons and Nuclei at Small x

  In view of the JLab upgrade it is very important to study the behavior of structure functions of deep inelastic scattering (DIS) at small x (i.e. large energies). DIS provides a unique opportunity which allows us to take "snapshots" of the constituents inside a hadron or nucleus at different moments of time with different resolutions. At low x, we probe the high-density domain of QCD where the constituents are small, but their density is so large that the packing factor for partons $\kappa > 1$ and therefore we cannot use ordinary pQCD methods. This high-density regime of QCD may serve as a bridge between the domain of pQCD and the "real" non-perturbative QCD regime governed by the physics of confinement. It turns out that the small-x behavior of structure functions in the high-density regime is governed by the non-linear evolution for the Wilson-line operators suggested in my paper several years ago.

  In 2001, I have published several papers related to this topic. Firstly, I have found the solution of this equation in form of a functional integral [Phys. Lett. **B518**, 235 (2001)]. This is the first known example of an effective (2+1)-dimensional field theory formulated in terms of the effective high-energy degrees of freedom (Wilson lines) rather than in terms of original QCD quarks and gluons. Secondly, in collaboration with A. Belitsky we have found the next-to-leading corrections to the non-linear equation in the large N_c limit [Nucl. Phys. **B629**, 290 (2002)].

- Scattering of Color Dipoles at Intermediate Energies in QCD

  At high energies, the hadron-hadron scattering is conveniently described in terms of color dipoles, two-Wilson-line operators corresponding to fast quark-antiquark pairs. However, at the intermediate energies of order of 10 GeV it is not clear whether this high-energy language is adequate. My student A. Babansky and I are calculating the dipole-dipole scattering in the first two orders in pQCD as an exact function of the energy. When completed, this calculation will give us the rate at which the dipole-dipole amplitude approaches the high-energy asymptotics so it will be clear whether the JLab energies of order of few GeV can be described by the small-x methods.

DEIRDRE BLACK

The scalar mesons are a long-standing puzzle in meson spectroscopy since their properties do not fit neatly those expected from the constituent quark model. Experimentally there are too many states to fit into a conventional SU(3) $q\bar{q}$ multiplet and several states, notably the controversial σ and κ mesons as well as the $a_0(980)$ and $f_0(980)$, are significantly lighter than expected. Previously I was involved in developing a non-linear chiral Lagrangian description of low energy meson-meson scattering in which the scalar, as well as the vector, meson fields are included explicitly. Recently I have been looking at other processes from which we may hope to learn more about the scalar mesons.

In collaboration with Harada and Schechter I have come up with a new approach to studying radiative decays involving light scalar mesons. Using an effective Lagrangian and vector meson dominance we have a unified description of various decays which allows us to make various predictions. Of particular current interest are rare radiative decays of the ϕ meson (to $\pi\eta\gamma$ and $\pi\pi\gamma$) which were measured over the past two years at Novosibirsk and Frascati. Results are also expected soon from Jefferson Lab. It had been suggested that these branching fractions could distinguish between different conventional and exotic scenarios for the $a_0(980)$ and $f_0(980)$ states. In fact the experimental results have still not been fully understood. So far we, in agreement with other authors, have found that a resonance-dominated approximation cannot fit the data as had been originally hoped. We are currently extending our calculation to include interference with non-resonant backgrounds and are exploring the effect of mixing in the scalar sector on the ϕ decay rates and in general. The latter involves extension of our previous work on mixing to the isoscalar scalar mesons, including a scalar glueball.

With Abdel-Rahim, Fariborz and Schechter I have also been studying the isospin-violating strong decay $\eta \to 3\pi$. Historically theoretical estimates of this decay rate have been a factor of four or five too small. In the early 1980s Gasser and Leutwyler extended the original current algebra result to next-to-leading order in Chiral Perturbation Theory and later other authors have investigated the effects of final state interactions and violations of Dashen's Theorem which together bring theory into closer agreement with experiment, although the shape of the Dalitz plot is still not fully understood. We have explored the effect of explicitly including scalar mesons, taking into account symmetry breaking, and found that at tree level the scalar contributions also improve the theoretical prediction for the $\eta \to 3\pi$ rate. We are currently making a more detailed study of the spectrum.

In parallel with non-linear chiral Lagrangian descriptions, I have with Schecter *et al.* also studied meson-meson scattering using SU(3) Linear Sigma models. There we found that the scalar mesons emerge with properties consistent with our previous work. In this case the mass of the scalar mesons is shifted from a "bare" value to a "physical" value by the effects of unitarization. With Abdel-Rahim, Nasri and Schechter I am currently applying the analogue of our analysis of low-energy $\pi\pi$ scattering to the Higgs sector. We are exploring the effect of unitarization on the mass of a strongly-coupled Higgs boson.

Also, based on recent indications of large μ-τ neutrino mixing I have with Sher *et. al.* been considering the possibility of large μ-τ lepton mixing. Using effective μ-τ transition operators and results from current algebra and Heavy Quark Effective theory, we have explored existing experimental constraints on such lepton flavor violation.

ROBERT EDWARDS

An exciting advance in lattice QCD has been the solution of the problem of regulating chiral fermions. The method developed–the Overlap/Domain Wall method–allows for the first time, the realization of exact chiral symmetry on the lattice free of doublers and any other approximations. There are exact zero modes related to topology and non-zero modes responsible for chiral symmetry breaking. In the Domain Wall approach, a flavor fifth dimension is introduced that is infinite in extent; once integrated out, a four dimensional Dirac operator with exact chiral symmetry is induced.

This new theoretical development has been a major focus of my research in the last few years. I have investigated how symmetry breaking effects are manifested in the Domain Wall approach with a finite fifth dimensional extent [Phys. Rev. D **63**, 054509 (2001)] and how these chiral symmetry breaking effects are related to an induced four dimensional kernel of the Dirac operator. In work with Heller [Phys. Rev. D **63**, 094505 (2001)], I showed how the Domain Wall operator can be made to have exact chiral symmetry even with finite fifth dimensional extent. Many important properties of the Dirac operator were clarified.

Recently, Isgur proposed an interesting test of the fundamental question: what is the origin of spontaneously induced chiral symmetry breaking ? In collaboration with Heller I used the overlap operator to study in a clean way, free of the systematic errors endemic to other methods, the properties of near-zero fermion modes in gauge backgrounds [Phys. Rev. D **65**, 014505 (2002)]. A certain local chirality operator determines the near locking of chromo-electric and magnetic fields in the vacuum as expected from instantons. Tests in SU(3) show that there indeed appears to be a non-zero contribution to the infinite volume chiral condensate from what could be described as instantons and indeed the effects vanish in U(1) where instantons do not exist. These results show consistency in the expectation of chromo E and B locking. However, previous results of mine showed that the phenomenological prediction in the Instanton-Liquid model of the scaling of the zero-mode size distribution does not hold. Something is causing "lumps" in gauge fields, and it is not what many authors (strictly) call instantons. Studying the QCD vacuum is an active area of investigation.

JOSÈ GOITY

Recently my research activity has focused on the following areas: i) large N_c QCD in baryons, ii) chiral perturbation theory, iii) effective field theory for few nucleons, and iv) heavy mesons.

In the following I give a brief description of the research work carried out in each of these areas, highlighting the chief results in each case.

- Large N_c QCD in Baryons

  The theoretical study of excited hadrons has in general been carried out in the framework of the quark model. The non-perturbative QCD dynamics that determines the physics of hadronic resonances cannot be represented in the standard form of an effective theory as it is the case for the light ground state hadrons where an effective theory, Chiral Perturbation Theory, can be implemented. The quark model has thus provided in a rather simple framework a good level of predictivity that has served as a strong guidance in the understanding of that non-perturbative domain. The quark model is, however, not an effective theory, and therefore it is incomplete at some level. In QCD there is one expansion parameter that can be used to formulate effective theories even in that domain, namely $1/N_c$, where N_c is the number of colors. Some time ago Dashen, Jenkins and Manohar formulated such effective theory for ground state baryons (octet and decouplet) in terms of the $1/N_c$ expansion, and later on we extended this analysis to excited baryons, focusing in particular on the negative parity 70-plet. This work, carried out in a first collaboration with C. Carlson, C. Carone and R. Lebed, was recently extended and refined in a collaboration with C. Schat and N. Scoccola. The large N_c analysis only introduces the assumption that the expansion makes sense for $N_c = 3$; the rest is general enough, so that once the effective couplings of the theory are phenomenologically fixed, the resulting theory should be a faithful representation of QCD to the given order in $1/N_c$. The analysis of the 70-plet shows the following important features: i) The dominant contributions to masses are the same as in the quark model: the constituent quark masses and spin-independent binding energy, and the hyperfine interaction. ii) The subdominant contributions that are crucial to explain effects such as the splittings between spin-orbit partners, mixings, etc., require in general effective operators that the quark model does not include, such as operators that involve flavor exchanges. In particular the so called spin-orbit puzzle can be consistently resolved by one such operator. iii) The approach has a substantial degree of predictivity, leading to novel mass relations across SU(3) multiplets.

  We expect that the $1/N_c$ expansion will eventually provide a well established framework in baryons that will help for a better understanding of the experimental results for masses and transitions, as well as of results stemming from lattice QCD simulations.

- Chiral Perturbation Theory

  Work has been carried out in two different projects, namely, i) the study of the π^0 decay rate into two-photons to next to leading order, and ii) the study of isospin breaking in the π-N couplings through the Goldberger-Treiman relation.

  The $\pi^0 \to \gamma\gamma$ decay is currently of direct importance to Jefferson Lab, as it will be measured to a new level of precision by the PRIMEX experiment. In collaboration with A. Bernstein, J. Donoghue and B. Holstein, I have analyzed this decay beyond the leading order using a combined framework of Chiral Perturbation Theory and the $1/N_c$ expansion. It is shown that there is a correction that increases the rate with respect to the one obtained by using the decay amplitude given by the anomaly induced by the EM field on the isotriplet axial current, which is the proper amplitude in the limit of massless u and d quarks. The dominant correction is driven by the isospin breaking effects stemming from $m_u \neq m_d$ that give an admixture of the pure U(3) states associated with the η and the η' into the physical π^0. This admixture is such that it produces an enhancement of about 4% in the rate. This effect is a definite theoretical prediction that can be tested by the PRIMEX experiment where the expected error will be in the range of 1.5%. The PRIMEX will therefore be able to test the anomaly as well as the corrections induced by quark masses.

  The possibility of predicting isospin breaking on the π-N couplings is being investigated. This is a long standing issue on which we can now shed some light. The study involves the Goldberger-Treiman relations in SU(3) and their discrepancies, where both isospin breaking due to the $m_u - m_d$ mass difference and to EM corrections are considered. This work is being completed in collaboration with one graduate student, J. Saez.

- Effective Field Theory for Few Nucleons

  One important open problem in strong interactions is the construction of an effective field theory for the N-N system. This has proven to be a very difficult problem because to be realistic the one-pion exchange needs to be resummed to all orders in the S-wave channels where the scattering lengths are large. This requirement has proven to be difficult to implement in a rigorous way within an effective theory. Different approaches have been so far attempted, and work is still in progress.

  At a level of perturbation theory, a new regularization was developed for the two-nucleon system. The regularization allows for implementation of a low energy power counting while preserving Lorentz covariance. This work was carried out in collaboration with D. Lehmann, G. Prezeau and J. Saez.

- Heavy Mesons

  Heavy mesons are the simplest environment to study the dynamics of light quarks in QCD; they are the "Hydrogen atom" of QCD. In the ongoing project studying heavy mesons and their excited states in collaboration with W. Roberts, I have recently studied the radiative transitions from excited heavy mesons. This work is based on the relativistic quark model, employing the same potential and constituent quark masses as in the case of the chiral quark model used previously to study the strong decays. It was shown that the observed ratios $\Gamma(D^{0*} \to D^0\gamma)/\Gamma(D^{0*} \to D^0\pi^0)$ and $\Gamma(D^{+*} \to D^+\gamma)/\Gamma(D^{+*} \to D^+\pi^0)$ require contributions from the heavy quark component of the EM current as well as a non-vanishing anomalous magnetic moment for the light quark. Although the experimental study of radiative transitions in heavy mesons is in its infancy, it is observed that some of the transitions will indeed be measurable, leading together with the strong transitions to a well constrained picture of the dynamics of light quarks in heavy mesons. Currently we are working on improving a calculation of the so called $B_{\ell 4}$ decays that we had done in a non-relativistic quark model. Th. These decays are important in context of the measurements on B-decays being carried out at CLEO as well as at the B-factories BABAR and Belle. As it had been emphasized in that previous work, the $B_{\ell 4}$ decays provide an indirect access to the excited heavy mesons, in particular the excited B-mesons, and represent one of the few possible ways to obtain empirical information on such excited states.

FRANZ GROSS

- Exact Solutions of Field Theory

  Using the Feynman-Schwinger (FS) path integral formalism, exact numerical solutions to scalar field theories can be found. In this promising approach, integrations over fields are replaced by path integrals over particle trajectories. The method allows a study the effect of particle exchange mechanisms and self-energy corrections *independently*.

  It has long been known (since Baym's proof in 1959) that the scalar $\chi^2\phi$ theory is unstable. The FS technique was used [Phys. Rev. D **64**, 076008 (2001)] to show that this theory is stable in quenched approximation (the approximation in which heavy χ particle loops are neglected), and that the introduction of heavy particle loops produces the instability. This explains why scalar meson exchange theories are a useful model for the study of relativistic equations (which usually neglect heavy particle loops), answering a long standing puzzle and clarifying a recent controversy.

- Quark-Antiquark Bound States

  It was shown how to model confinement in the $q\bar{q}$ system using the covariant Spectator (or Gross) equation [Phys. Rev. C **63**, 035208 (2001)]. In this approach individual quarks can be on their mass shell (i.e. the quark propagator can have real mass poles), but two interacting quarks can never *both* be on mass shell (i.e. there are no elastic cuts). For example, in the treatment of $q\bar{q}$ bound states, the quark is on mass-shell and confinement is realized by the condition that the bound state $q\bar{q}$ vertex function is zero at precisely the kinematic point where the antiquark would also be on mass-shell (kinematically possible if $M_b < m_q + m_{\bar{q}}$, which frequently occurs for confined systems). This condition occurs naturally and automatically whenever a confining interaction is present. One advantage of this approach is that it has a smooth non-relativistic limit, and the vanishing of the vertex function can be shown to also occur in systems described by the Schrödinger equation using a nonrelativistic confining potential.

- Charge Conjugation Invariance of the Spectator Equations

  The Spectator equation was recently criticized for failing to satisfy charge conjugation (C) invariance. This occurs if the equation is not even or odd under change in sign of the external energies W_i. Since the equation was not defined originally for negative energies, this problem is easily eliminated (or, more correctly, would not occur at all) by defining the equation for negative energies in the correct manner. It was shown [Few Body Syst. **30**, 21 (2001)] that this is easily done be defining all external energies to be positive, so that W_i is replaced by $\sqrt{W_i}$. This definition is also consistent with (and even required) by the physics underlying the derivation of the Spectator equations.

WALLY MELNITCHOUK

- Quark-Hadron Duality

  Quark-hadron duality addresses one of the core issues in strong interaction physics–the nature of the transition from quark to hadron degrees of freedom. A classic example of quark-hadron duality is in inclusive electron-hadron scattering (known as Bloom-Gilman duality). Recent experiments at Jefferson Lab have observed a remarkable equivalence between the inclusive structure function in the resonance region, averaged over appropriate W intervals (where W is the mass of the hadronic final state), and the scaling structure function measured in the deep-inelastic region, to low values of Q^2 below 1 GeV^2. The equivalence is also found to hold for each of the low-lying resonance region, so that the resonance-scaling duality exist locally as well as globally.

  Building on earlier work with N. Isgur, S. Jeschonnek and J.W. Van Orden [Phys. Rev. D **64**, 054005 (2001)], I am extending the study of duality in structure functions to QCD in 1+1 dimensions in the limit of a large number of colors ('t Hooft model). The model provides exact solutions for the form factors from which the inclusive structure functions are constructed. Because resonances here are infinitely narrow, the model provides a unique opportunity to study the transition from low energy, where the structure function is dominated by resonance spikes, to high energy, where dominance of single quark scattering leads to a smooth function of Bjorken-x.

  Following earlier work on the applications of local duality to asymptotic relations between nucleon form factors and deep-inelastic structure functions [Phys. Rev.

Lett. **86**, 35 (2001); Nucl. Phys. **A680**, 52 (2001)], I am currently investigating duality relations for the simplest QCD bound state, the pion. This study will aim to test the validity of the relationship between the pion structure function at large x and the pion form factor at high Q^2. The pion form factor is being measured at JLab in Hall C, and there are plans to measure the pion structure function in Hall A at JLab with 12 GeV.

A study is also being carried out (in collaboration with Yu. Simonov) on generalizations of the Veneziano model of s and t channel duality to deep-inelastic structure functions. In addition, a major review of quark-hadron duality is currently being completed with R. Ent and C. Keppel.

- Hadron Spectrum in Lattice QCD

  The hadron spectrum is a defining problem in QCD. At present the only practical method for obtaining hadron masses directly from QCD is a numerical solution on the lattice. With collaborators at the Centre for the Subatomic Structure of Matter (CSSM) at the University of Adelaide, Australia (D. Leinweber *et al.*), I have studied the hadron mass spectrum in lattice QCD using an $\mathcal{O}(a^2)$ improved gluon action and a novel fat-link clover fermion action in which only the irrelevant operators are constructed with fat links. This action exhibits superior scaling behavior compared to mean-field improvement, and a reduced exceptional configuration problem compared with nonperturbative $\mathcal{O}(a)$ improvement [Nucl. Phys. (Proc. Suppl.) **109**, 101 (2002)].

  As an application of this action, masses of positive and negative parity excited baryons have been computed [Nucl. Phys. (Proc. Suppl.) **109**, 96 (2002)]. The results are in agreement with earlier calculations of N^* resonances using improved actions and exhibit a clear mass splitting between the nucleon and its chiral partner, the $N^*(1535)$. However, we find no evidence of overlap with the $1/2^+$ Roper resonance. The study of different Λ interpolating fields reveals a clear mass splitting of ~ 400 MeV between the octet Λ and its parity partner, although again we find no evidence of the empirical mass suppression of the $\Lambda^*(1405)$. This suggests either an important role for the meson cloud of the $\Lambda^*(1405)$ and/or a need for more exotic interpolating fields.

  The results of this work have direct bearing on the experimental program at CLAS in Hall B, as well as on other theoretical approaches such as those based on large N_c counting or on QCD-inspired models. The recent progress made in tackling the hadronic mass spectrum in lattice QCD was one of the motivations for the formation of a discussion group on excited hadrons with the Theory Group and JLab experimentalists, in order to assess the interconnections between different theoretical approaches, as well as the impact on the N^* program at JLab.

  As part of the Lattice Hadron Physics Collaboration, I plan to continue lattice studies of excited baryon and meson spectra, which will provide an important complement to the experimental program in Hall B, and to the exotic (hybrid) meson spectroscopy program at a future Hall D.

- Chiral Symmetry and Lattice QCD

  The fundamental role played by the dynamically broken chiral symmetry of QCD in nuclear physics is well known. However, the importance of chiral symmetry constraints on the small quark mass (m_q) behavior of observables calculated on the lattice is only now beginning to be fully appreciated [Pramana–Journal of Physics **57**, 251 (2001)]. In particular, it is vital to take into account the correct m_q dependence when extrapolating lattice calculations, which are currently performed at quark masses $m_q > 50$ MeV, to the physical point.

  This was dramatically illustrated for the case of moments of quark distributions calculated on the lattice, which when extrapolated linearly to the physical region overestimates the experimental values by up to 50%. In collaboration with researchers in Adelaide (A.W. Thomas and W. Detmold), and MIT (J. Negele and D. Renner), I reanalyzed moments of the u-d quark distribution, taking into account general constraints imposed by the chiral symmetry of QCD [Phys. Rev. Lett. **87**, 172001 (2001)]. The inclusion of the (model-independent) leading non-analytic behavior of the moments arising from Goldstone boson loops leads to an excellent description of both the lattice data and the experimental values of the moments, and resolves this long-standing discrepancy.

  Subsequently, the x dependence of the valence u-d distribution in the nucleon has been extracted from the lowest few moments calculated on the lattice, using an extrapolation formula which ensures the correct behavior in the chiral and heavy quark limits [Eur. Phys. J. C **13**, 1 (2001)]. This study found important implications for the quark mass dependence of meson masses lying on the $J^{PC} = 1^{--}$ Regge trajectory.

  Currently the analysis is being extended to the polarized sector, where the chiral corrections arising from $N\pi$ and $\Delta\pi$ loops are being calculated for moments of the helicity and transversity moments. No empirical information exists on the latter distribution, and future measurements may be possible in Hall A at 12 GeV.

- Nuclear Effects in Few-Nucleon Systems

  Ongoing work on nuclear corrections to bound nucleon structure functions has focussed on the A=3 system. Since the polarization of ^{3}He resides mainly on the neutron, ^{3}He is often used as an effective polarized neutron target. I have calculated the nuclear corrections to the g_1 and g_2 structure functions of the neutron extracted from ^{3}He, which are necessary for the analysis of current and future data from Hall A. The measurement of the g_2 structure function in particular will reveal new information on the structure of higher twists (quark-gluon correlations) in the nucleon.

  In addition, a comprehensive analysis of nuclear corrections to the unpolarized ^{3}He and ^{3}H structure functions is being carried out, in which different theoretical approaches (including those based on the Faddeev and variational methods) are compared, as well as corrections to the standard impulse approximation. A major report on this analysis is currently being prepared.

IGOR MUSATOV

Generalized Parton Distributions (GPDs) are a subject of intensive research, both theoretical and experimental, and a significant part of the JLab research program. Recently, there was significant progress in the theoretical understanding of GPDs in the specific kinematics of vanishing four-momentum transfer.

To establish the relationship between theoretical models for GPDs and experimental observables within currently accessible kinematical regions, one needs to extend the theoretical description of the physical amplitudes to incorporate the momentum transfer dependence. Particularly, the parameterization of the DVCS and hadron annihilation amplitudes beyond the leading twist is required to restore gauge invariance in the case of not-very-small momentum transfers [Musatov and Radyushkin, in progress].

A practical way to build t-dependent GPDS is to relate the GPDs to known physical observables (structure functions and form factors) along with QCD-inspired models of hadron structure. It was found that light cone wave functions with power-law momentum behavior may be used to derive realistic GPDs [Mukherjee, Musatov, Pauli, Radyushkin, to be published].

Another promising approach is to use a Bethe-Salpeter-type equation to study the relation between the Regge behavior and t-dependence of the GPDs. As a first step, this work is being done with the scalar model. The structure of the equations hints that in the QCD case this approach may lead to a unified model, suitable for description of both the Regge behavior and DGLAP evolution [Musatov and Simonov, in progress].

An important task is to provide experimentalists an effective algorithm which will allow the evaluation of observables for DVCS using different theoretical models for GPDs as an input [Kuchina and Musatov, in progress]. The work is being done in cooperation with JLab experimental groups.

ANATOLY RADYUSHKIN

- Studies of Generalized Parton Distributions

  The main focus of my theoretical studies is on the investigation of hadronic structure using hard scattering processes. This structure can be described in terms of various functions: hadronic form factors, parton distribution functions, distribution amplitudes, etc. Recently, it was established that these functions can be treated as limiting cases of so-called Generalized Parton Distributions (GPDs) which provide a unified description of many inclusive and exclusive hard processes. I participated in the development of the GPD formalism, in particular, in its application for calculating the cross section of deeply virtual and wide-angle Compton scattering in quantum chromodynamics.

The most recent development of the formalism is the incorporation of the kinematical twist-3 contributions to the DVCS amplitude, required to restore electromagnetic gauge invariance of the twist-2 amplitude up to $O(t/Q^2)$ level. In my previous papers (published in 1996-2000) I introduced two types of nonperturbative functions parameterizing such matrix elements: double distributions (DDs) and nonforward (or skewed) distribution functions. I developed simple models for DDs with correct spectral and symmetry properties and established the reduction relations connecting them to the usual parton densities. In 2001, I started a collaboration on this project with German colleagues from Ruhr-Universität in Bochum and University of Regensburg. In collaboration with Weiss (University of Regensburg), we developed a new approach [Phys. Rev. D **63**, 114012 (2001)] to the analysis of DVCS beyond the leading twist. We parameterize non-forward matrix elements of the elementary twist-2 operators in terms of two-variable spectral functions (double distributions), from which twist-2 and -3 skewed distributions are obtained through reduction formulas. Our approach is equivalent to a Wandzura-Wilczek type approximation for the twist-3 distributions. The resulting Compton amplitude is manifestly transverse up to terms of order t/Q^2. We also demonstrated in [Phys. Rev. D **64**, 097504 (2001)] that the kinematical twist-3 corrections can be understood as a spin rotation applied to the twist-2 quark density matrix in the target. This allows for a compact representation of the twist-3 effects, as well as for a simple physical interpretation. The studies of generalized parton distributions was recently included as one of the major directions of futurergy studies at Jefferson Lab. A review of my work on generalized parton distributions was published as a chapter in the book "At the Frontier of Particle Physics/Handbook of QCD", edited by M. Shifman (World Scientific, 2001).

- Studies of Hadronic Form Factors

  I performed the studies of the basic hard exclusive processes: $\pi\gamma^*\gamma$–transition and pion electromagnetic form factors. I wrote a short review (published in the proceedings of 3rd Workshop on Chiral Dynamics) of calculations of the pion electromagnetic and transition form factors within the framework of quantum chromodynamics. I argued that both the perturbative and nonperturbative aspects of the Q^2 dependence of these form factors are rather well understood in QCD. However, new experimental data at higher Q^2 would be extremely helpful for detailed tests of the transition to the regime where the pQCD hard contribution plays the dominant role.

DAVID RICHARDS

- Spectroscopy of Excited Baryons

  The exploration of the excited baryon spectrum provides a theater to explore many of the central questions in hadronic physics, including the applicability of the quark model, the rôle of excited glue, and the existence of "molecular" states. It is thus a critical component of the Jefferson Lab experimental program. The lattice study of the excited baryon spectrum is a vital complement to this program that can both guide and inform the experiments, and extract the crucial physics from the experimental data.

I computed, within the quenched approximation, the mass of the lowest-lying negative parity baryon state, the $N^{1/2-}$, using the improved fermion action [Nucl. Phys. (Proc. Suppl.) **94**, 269 (2001) and to be published]. By performing the calculation at a variety of lattice spacings and lattice volumes, finite-volume effects could be estimated, and an extrapolation performed to the continuum limit. After this extrapolation, remarkably good consistency was found between the lattice calculation and the physical hadron masses, even in the quenched approximation, encouraging investigation of the higher resonances.

One of the long-standing puzzles of N^* spectroscopy has been the nature of the light Roper resonance at around 1440 MeV. On a subset of the lattices, the mass of the first radial excitation of the nucleon was determined, and found to be around 2 GeV, far higher than the experimental Roper mass [Nucl. Phys. (Proc. Suppl.) to be published]; such an observation is also seen in other lattice calculations. Thus lattice calculations are questioning the interpretation of the Roper as a naive three-quark state, and emphasizing their importance in interpreting the experimental program.

This research program is developing in collaboration with other members of the Lattice Hadron Physics Collaboration, employing a variety of lattice technology to extract higher excitations, such as the use of lattices anisotropic in time and the adoption of Bayesian statistics to analyze the data. An important extension of the work is the calculation of the masses of the light hybrid mesons, where the presence of excited glue can be most clearly identified.

- Weak Interaction Matrix Elements

The experimental determination of the CKM matrix elements requires a quantitative description of the strong interaction effects masking the weak interactions of the quarks. Lattice QCD calculations can provide an *ab initio* description of these effects.

We performed a calculation of the leptonic decay constants of B, D and K mesons in quenched lattice QCD, using a $\mathcal{O}(a)$-improved fermion action [Nucl. Phys. **B619**, 507 (2001)]. The decay constant f_B is profoundly important in phenomenology, since the combination $f_B\sqrt{B_B}$, where the B-parameter is expected to be close to unity, is required in the experimental extraction of CKM matrix elements, and CP violation parameters. However, the phenomenological utility of lattice results depends crucially on careful control of the systematic uncertainties impinging on the calculation. By performing the calculation at two lattice spacings, we were able to demonstrate good scaling of the data, and by careful consideration of the heavy-quark dependence of the results, show that many of the heavy-quark-effective-theory relations satisfied.

WINSTON ROBERTS

All of my research focuses on aspects of hadron spectroscopy using two somewhat different approaches. One of these is the effective Lagrangian approach, such as the heavy quark effective theory (HQET). The other is the use of specific constituent quark models, both relativistic and non-relativistic. Although such models are, for the most part, not rigorously derived from QCD, they are nevertheless very useful in helping us to understand and integrate a wide range of data in hadron phenomenology. As an example of the possible impact of such models, note that HQET grew out of work that had been done in non-relativistic quark models of this type.

- Heavy Quark Effective Theory

  Recently I have used the tensor formalism of HQET to examine the strong decays of heavy hadrons in a manner that allows treatment of decays involving light daughter hadrons other than pions. The formalism reproduces the results of the spin-counting arguments of the late Nathan Isgur and his collaborator Mark Wise, but this formulation, in principle, could allow study of the $1/m$ corrections to ratios of decay rates. As there are not much data on the strong decays of charm and beauty hadrons, with N. Trégourès, a graduate student (M. S. completed in the fall of 1998), I have applied this formalism to hadrons with strangeness to see if we can understand the global features of these decays within this framework. We have found that treating the strange quark as a heavy one leads to surprisingly good results in most cases. This formalism is now being applied to the decays of heavy baryons. However, since data in this sector are even more scarce than in the meson sector, the predictions of HQET will be compared with those of a quark model.

  My most recent work in this area focused on the extraction of V_{ub} from the semileptonic decays of B mesons. Using HQET as it applies to the transitions between heavy mesons and light ones, I found a number of measurements that could be used to extract this important element of the CKM matrix. In particular, I found that the ratio of differences of differential helicity decay rates, measured in the semileptonic decays of B mesons to ρ mesons and D mesons to ρ mesons, denoted $(d\Gamma_+^B/dq^2 - d\Gamma_-^B/dq^2)/(d\Gamma_+^D/dq^2 - d\Gamma_-^D/dq^2)$, was independent of any form factors, in leading order. This may turn out to play a significant role in the extraction of V_{ub}.

- Relativistic Quark Model

  We have applied a model of heavy mesons to strong decays of heavy mesons using a chiral quark model to describe the decays (with J.L. Goity). Our results show that relativistic effects are quite large, as some of the results obtained here are very different from those obtained using a non-relativistic model of the mesons, with the same chiral quark model for the decays.

  We have also applied this relativistic model of the mesons to their electromagnetic decays. For mesons like the D^*, the electromagnetic decay width is comparable to the strong one, because of the very limited phase space for strong decays. In the case of some excited mesons like D_s^{**} and B_s^{**}, the electromagnetic decays are expected to be dominant, as the only kinematically allowed strong decays are both OZI and isospin violating.

- Hadron Spectroscopy

  In addition to the projects described above, I am also working on quark models for the semileptonic decays of baryons (and mesons), as well as a description of meson photoproduction and electroproduction processes using a phenomenological Lagrangian approach.

ROCCO SCHIAVILLA

In the last few years, a "Standard Nuclear Physics Model" (SNPM) has been emerging, in which nuclei are viewed as assemblies of individual nucleons interacting among themselves via two- and three-body potentials, and with external electro-weak probes via currents consisting of one- and many-body components [for a recent review of the SNPM, see Rev. Mod. Phys. **70**, 743 (1998)]. How these effective potentials and currents arise from the underlying quark and gluon degrees of freedoms, the ultimate building blocks of nuclear matter, is still an open question.

The deceptively simple picture put forward in the SNPM, however, has been shown to provide a quantitatively accurate description of nuclear structure and dynamics over a wide range of energy, from the few keV of astrophysical relevance to the MeV regime of nuclear spectra to the tens to hundreds of MeV measured in nuclear response experiments. In the nuclear astrophysics realm, the SNPM has led to accurate predictions for the cross sections of the $pp \to d\, e^+\nu_e$, $pd \to ^3\mathrm{He}\, \gamma$ and $p^3\mathrm{He} \to ^4\mathrm{He}\, e^+\nu_e$ processes occurring in the pp chain, whose network of reactions, converting hydrogen into helium, constitute the principal source of energy and neutrinos in the Sun.

In the few MeV energy region relevant for nuclear structure, the SNPM has successfully predicted the observed energy spectra of low-lying states of nuclei with mass numbers in the range A=2–10 [the Argonne-Los Alamos-Urbana group, Phys. Rev. C **62**, 014001 (2000)], the measured rates of radiative and weak transitions between some of these states, and lastly the experimentally known elastic and inelastic electromagnetic form factors of nuclei with A=2–6 up to momentum transfers of $\simeq 1$ GeV/c.

Finally, in the hundreds of MeV energy regime, the SNPM has produced a quantitative understanding of the electromagnetic response of light nuclei, in particular of the role played by correlations and many-body currents in the distribution of longitudinal and transverse strength in the quasi-elastic region and beyond.

My research interests deal, in general terms, with the development and application of the SNPM and of methods, in particular quantum Monte Carlo techniques, for its practical implementation. Recently, I have been interested in:

- parity-violating effects, due to the weak interaction, on the properties of few-nucleon systems, such as the asymmetry induced by γ-Z interference in deuteron electrodisintegration at quasielastic kinematics [Phys. Rev. C **63**, 044007 (2001)] and the longitudinal asymmetry in pp elastic scattering originating from parity-violating components in the NN interaction [Phys. Rev. **C65**, 035502 (2002)];

- weak transitions, in particular β-decays and electron- and muon-captures in A=3–7 nuclei [nucl-th/0112008 and Phys. Rev. C **65**, 054302 (2002)].

YURI SIMONOV

The main research activity is the development of the nonperturbative QCD based on the method of field correlators, which has a universal character.

The topics include:

- chiral symmetry breaking in the confining vacuum;

- structure of hadrons (mesons, baryons, hybrids, and glueballs);

- nonperturbative theory of scattering and structure functions;

- perturbation theory in the nonperturbative confining background.

WALLY VAN ORDEN

- Duality

  One of the more intriguing experimental results to come from Jefferson Lab has been the verification of Bloom-Gilman duality, in which the inclusive structure function at low W (where W is the mass of the hadronic final state) is found to follow a global scaling curve which describes high W data, to which the resonance structure function averages. The equivalence of the averaged resonance and scaling structure functions was also found to hold for each resonance region, so that the resonance–scaling duality appears to exist locally as well as globally. To help understand the physics of duality, we have constructed a simple, quantum-mechanical model in which qualitatively reproduces the features of Bloom-Gilman duality. The model consists of a light quark bound to an infinitely heavy quark by a relativistic harmonic oscillator potential. The excitation spectrum of this system consists of an infinite number of infinitely narrow resonances. We find that this simple system reproduces the qualitative features Bloom-Gilman duality and illuminates the minimal physical conditions for this phenomenon to occur. An additional finding of this study is that the usual separation of deep inelastic scattering into a "resonance region" at low W and a "scaling region" at high W is totally spurious, and that resonances are an integral part of the scaling structure functions. This has important practical consequences for global analyses of parton distributions, and could open the way to an enormously rich program at Jefferson Lab extending structure functions into previously inaccessible regions of kinematics. The original model contained only scalar particles including a "scalar photon" probe. We have now extended the model to include a vector photon and have shown that the model satisfies the appropriate sum rules and that the scaling and duality of the simpler model are retained.

- Elastic Electron-Deuteron Scattering

  Over the last several years we have developed a relativistic, gauge-invariant model of elastic electron-deuteron scattering. This model is in excellent agreement with the new data for $A(Q^2)$, $B(Q^2)$ and $t_{20}(Q^2)$ obtained at Jefferson Lab. We continue to study the sensitivity of this model to nucleon electromagnetic form factors, and to the $\rho\pi\gamma$ and off-shell form factors. A review of the deuteron related to this work was published during 2001.

A. PUBLICATIONS IN REFEREED JOURNALS (1/1/01 to 12/31/01)

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(Talks published in the period 1/1/01–12/31/01)

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[46] **D.G. Richards**, M. Göckeler, R. Horsley, D. Pleiter, P.E.L. Rakow, G. Schierholz, and C.M. Maynard, *Excited Nucleon Spectrum Using a Non-Perturbatively Improved Clover Fermion Action*, Proceedings of the Workshop on "Lattice Hadron Physics (LHP 2001)", Cairns, Australia, 2001, Nucl. Phys. (Proc. Suppl.) **109**, 89 (2002).

[47] **D.G. Richards**, *Review of NN Interaction from Lattice QCD*, Proceedings of the workshop "Chiral Dynamics 2000: Theory and Experiment", (World Scientific, Singapore, 2001), p. 444.

[48] **R. Schiavilla**, *Electro-Weak Reactions for Astrophysics*, Proceedings of the XVIth International Conference on "Few-Body Problems in Physics", Nucl. Phys. **A684**, 157c (2001).

[49] **R. Schiavilla**, *Interactions, Currents, and the Structure of Few-Nucleon Systems*, Proceedings of the International Conference "Bologna 2000–Structure of the Nucleus at the Dawn of the Century" Vol. "Hadrons, Nuclei, and Applications" (World Scientific, Singapore, 2001), p. 10.

[50] **R. Schiavilla**, *Electromagnetic Structure of Few-Nucleon Systems*, Proceedings of the XVIIth European Conference on "Few-Body Problems in Physics" Nucl. Phys. **A689**, 84c (2001).

[51] **R. Schiavilla**, *The hep Astrophysical Factor*, Proceedings of the 2nd International Workshop "Neutrino Oscillations and their Origin–NOON2000" (World Scientific, Singapore, 2001), p. 23.

[52] **R. Schiavilla**, U. van Kolck, and H.R. Weller, *Summary of Few-Nucleon Working Group*, Proceedings of the workshop "Chiral Dynamics 2000: Theory and Experiment" (World Scientific, Singapore, 2001), p. 401.

[53] M. Viviani, A. Kievsky, L.E. Marcucci, S. Rosati, and **R. Schiavilla**, *Few-Nucleon Reactions of Astrophysical Interest*, Proceedings of the workshop "Selected Few-Body Problems in Hadronic and Atomic Physics", Bled Workshops in Physics, Ljubljana, 2001, Vol. 2, No. 1, p. 29.

C. UNPUBLISHED INVITED TALKS GIVEN AT CONFERENCES AND WORKSHOPS
(Talks given in the period 1/1/01–12/31/01)

[54] **I. Balitsky**, *Effective Field Theory for the Small-x Evolution*, 2001 DNP APS meeting, Maui, Hawaii, October 2001.

[55] **I. Balitsky**, *Effective Field Theory for the Small-x Evolution*, International Workshop on "High-Energy QCD: Beyond the Pomeron", BNL, New York, May 2001.

[56] **I. Balitsky**, *Renormalons as Dilatation Modes in the Functional Space*, 6th International Workshop on "Non-Perturbative QCD", Paris, France, June 2001.

[57] **D. Black**, *Scalar Mesons in Three-Flavor Linear Sigma Models*, International Workshop on "Chiral Fluctuations in Hadronic Matter", IPN, Orsay, France, September 2001.

[58] **R.G. Edwards**, *Quantum Field Theory on the Lattice*, HUGS 2001, Jefferson Lab, Newport News, June 2001.

[59] **R.G. Edwards**, *The QCD-API*, SciDAC Software Workshop, Jefferson Lab, Newport News, November 2001.

[60] **J.L. Goity**, *Large N_c QCD in Mesons and Baryons*, three talks in Theory Group working group, Jefferson Lab, Newport News, December 2001.

[61] **F. Gross**, *Covariant Effective Field Theories*, INT Workshop on "Theories of Nuclear Forces and Few-Nucleon Systems", University of Washington, Seattle, June 2001.

[62] **W. Melnitchouk**, *Quark Hadron Duality, Resonances and the Onset of Scaling*, INT Workshop on "Correlations in Nucleons and Nuclei", University of Washington, Seattle, May 2001.

[63] **W. Melnitchouk**, *Chiral Extrapolation of Baryon Properties on the Lattice*, INT Workshop on "Lattice QCD and Hadron Phenomenology", University of Washington, Seattle, October 2001.

[64] **W. Melnitchouk**, *Extraction of Hadron Masses in Lattice QCD*, Workshop on "Hamiltonian Lattice Gauge Theories", Adelaide, Australia, April 2001.

[65] **W. Melnitchouk**, *Hadron Spectroscopy in Lattice QCD*, Hall D Collaboration Meeting, Indiana University, Bloomington, November 2001.

[66] **A.V. Radyushkin**, *Hadronic Form Factors in QCD*, INT Workshop on "Correlations in Nucleons and Nuclei", University of Washington, Seattle, March 2001.

[67] **A.V. Radyushkin**, *Generalized Parton Distributions*, INT Workshop on "Correlations in Nucleons and Nuclei", University of Washington, Seattle, May 2001.

[68] **A.V. Radyushkin**, *Double Distributions*, Workshop on "Generalized Parton Distributions", Santorini, Greece, October 2001.

[69] **A.V. Radyushkin**, *Spin Structure of the Nucleon in the Resonance Region*, 2001 DNP APS meeting, Maui, Hawaii, October 2001.

[70] **A.V. Radyushkin**, *The Uses of Double Distributions*, WE-HERAEUS-Seminar on "Generalized Parton Distributions", Bad Honnef, Germany, November 2001.

[71] **D.G. Richards**, *Lattice Status Report*, INT Workshop on "Correlations in Nucleons and Nuclei", University of Washington, Seattle, Washington, March 2001.

[72] **D.G. Richards**, *N* Physics and Lattice QCD*, INT Workshop on " Lattice QCD and Hadron Phenomenology", University of Washington, Seattle, September, 2001.

[73] **D.G. Richards**, *Lattice QCD and Hall D Physics*, Hall D Collaboration Meeting, Indiana University, Bloomington, November 2001.

[74] **R. Schiavilla**, *Standard Nuclear Model versus EFT: a Case Study in Weak Transitions*, INT workshop on "Theories of Nuclear Forces and Few-Nucleon Systems", University of Washington, Seattle, June 2001.

[75] **R. Schiavilla**, *Low-Energy Electro-Weak Reactions in Three- and Four-Nucleon Systems*, ECT* Workshop "Few-Body Systems at Low and Moderate Energies: Open Questions Beyond Computational Problems", Trento, Italy, June 2001.

[76] **R. Schiavilla**, *Open Discussion on $d(e,e'p)n$*, "OOPS Theory Workshop", MIT, Cambridge, July 2001.

[77] **J. W. Van Orden**, *Electron Scattering from Nuclei*, International Meeting on "Electron Scattering from Atoms Nuclei, Molecules and Bulk Matter", Magdalene College, Cambridge, U.K., December 2001.

D. SEMINARS AND COLLOQUIA
(Period 1/1/01 to 12/31/01)

[78] **I. Balitsky**, *Renormalons as Dilatation Modes in the Functional Space*, MIT, Cambridge, March 2001.

[79] **I. Balitsky**, *Effective Field Theory for the Small-x Evolution*, CEA Saclay, Paris, France, June 2001.

[80] **I. Balitsky**, *Small-x Evolution of Wilson Lines*, CERN, Geneva, Switzerland, June 2001.

[81] **I. Balitsky**, *Effective Field Theory for the Small-x Evolution*, University of Maryland, College Park, November 2001.

[82] **I. Balitsky**, *Small-x Evolution of Wilson Lines*, Penn State University, State College, November 2001.

[83] **D. Black**, *Chiral Lagrangian Approaches to the Scalar Meson Puzzle*, INT, University of Washington, Seattle, January 2001.

[84] **D. Black**, *Chiral Lagrangian Approaches to the Scalar Meson Puzzle*, Jefferson Lab, Newport News, February 2001.

[85] **D. Black**, *Chiral Lagrangian Approaches to the Scalar Meson Puzzle*, Physics Division, ANL, Argonne, February 2001.

[86] **D. Black**, *Chiral Lagrangian Approaches to the Scalar Meson Puzzle*, University of Maryland, College Park, March 2001.

[87] **D. Black**, *Scalar Mesons in Three-Flavor Linear Sigma Models*, Jefferson Lab, Newport News, November 2001.

[88] **J.L. Goity**, *The π^0 width at NLO in Chiral Perturbation Theory*, University of Bern, Switzerland, May 2001.

[89] **J.L. Goity**, *Towards Non Perturbative Pions in the Effective Field Theory for NN Interaction*, University of Bern, Switzerland, June 2001.

[90] **J.L. Goity**, *Towards Non Perturbative Pions in the Effective Field Theory for NN Interaction*, University of Barcelona, Spain, June 2001.

[91] **J.L. Goity**, *The Measurement of a Lifetime.*, Clark Atlanta University, Atlanta, November 2001.

[92] **W. Melnitchouk**, *Nuclear Physics Program at Jefferson Lab*, University of Sao Paulo, Brazil, January 2001.

[93] **W. Melnitchouk**, *Quark-Hadron Duality in Electron Scattering*, Universidade Federal Fluminense, Rio de Janeiro, Brazil, January 2001.

[94] **W. Melnitchouk**, *Duality in Electron Scattering*, University of Kentucky, Lexington, October 2001.

[95] **W. Melnitchouk**, *Chiral Extrapolation of Baryon Properties from Lattice QCD*, University of Pittsburgh, Pittsburgh, November 2001.

[96] **A.V. Radyushkin**, *Generalized Parton Distributions*, University of Rochester, New York, April 2001.

[97] **A.V. Radyushkin**, *Double and Skewed Parton Distribution Functions*, Ruhr University, Bochum, Germany, June 2001.

[98] **A.V. Radyushkin**, *Hadronic Form Factors and QCD in Spacelike and Timelike Regions*, University of Wuppertal, Germany, June 2001.

[99] **D.G. Richards**, *Baryon Spectroscopy from Lattice QCD*, Florida International University, Miami, May 2001.

[100] **D.G. Richards**, *N^* Spectrum Using Lattice QCD*, Hadron Physics Group seminar, University of Maryland, College Park, June 2001.

[101] **R. Schiavilla**, *Electro-Weak Structure, Capture Reactions, Parity Violation, and All That*, Theoretical Division, LANL, Los Alamos, January 2001.

[102] **R. Schiavilla**, *Longitudinal and Transverse Strength in Nuclei*, Kellogg Radiation Laboratory, Caltech, Pasadena, January 2001.

[103] **R. Schiavilla**, *G_{En}, L/T Strength in Nuclei, and More (Maybe)*, Jefferson Lab, Newport News, July 2001.

[104] **R. Schiavilla**, *Structure and Dynamics of Few-Nucleon Systems: a Progress Report*,

Department of Physics, University of Helsinki, Helsinki, Finland, August 2001.

[105] **R. Schiavilla**, *A Random Walk in the Physics of Few-Nucleon Systems*, Department of Physics, University of Virginia, Charlottesville, October 2001.

[106] **Yu.A. Simonov**, *QCD Vacuum and Hadrons*, three lectures, Jlab, October 2001.

[107] **Yu.A. Simonov**, *Method of Vacuum Correlators*, six lectures, Jlab, October-December 2001.

[108] **Yu.A. Simonov**, *New Developments in the nonperturbative QCD*, two lectures, Institute of Theoretical Physics, University of Minnesota, December 2001.

E. REVIEWS, EDITORSHIPS, AND MAJOR PROPOSALS (2001)

[109] The U.S. Lattice QCD Collaboration, **R.G. Edwards** and **D.G. Richards**, *National Computational Infrastructure for Lattice Gauge Theory*, funded under the SciDAC Program of the U.S. Dept. of Energy, July 2001.

[110] **J. L. Goity**, A. Bernstein, and U-G. Meissner, Eds., *Chiral Dynamics: Theory and Experiment III* (World Scientific, Singapore, 2001).

[111] **W. Melnitchouk**, A.W. Schreiber, P.C. Tandy, and A.W. Thomas, eds., *Lepton Scattering, Hadrons and QCD* (World Scientific, Singapore, 2001).

[112] A.C. Kalloniatis, D.B. Leinweber, **W. Melnitchouk**, and A.G. Williams, eds., *Lattice Hadron Physics*, Nuclear Physics B–Proceedings Supplement **109** (2002).

[113] **A.V. Radyushkin**, *Generalized Parton Distributions*, "At the Frontier of Particle Physics/Handbook of QCD", M. Shifman, ed., (World Scientific, Singapore, 2001), vol. 2, p. 1037.

[114] M. Garçon and **J.W. Van Orden**, *The Deuteron: Structure and Form Factors*, Adv. Nucl. Phys. **26**, 293 (2001).

F. WORKSHOP AND CONFERENCE ORGANIZATION (2001)

[115] **R.G. Edwards**, Co-organizer for the Workshop on "Lattice Hadron Physics (LHP 2001)", Cairns, Australia, July 9–19, 2001.

[116] **R.G. Edwards**, Organizer for the SciDAC Software Workshop, Jefferson Lab, Newport News, November 8–9, 2001.

APPENDICES

A. WORKSHOPS FUNDED JOINTLY WITH INT

March 12–16, 2001	Correlations in Nucleons and Nuclei

B. LONG TERM VISITORS IN 2001

W. Melnitchouk	University of Adelaide	01/01–31/07
C. Schat	Argentina (CONICET)	01/23–present
A. Stadler	University of Lisbon	02/03–02/18
I. Aznauryan	Yerevan Physics Institute	05/02–09/02
W. Melnitchouk	University of Adelaide	05/12–05/23
J.-M. Laget	Saclay	06/05–06/23
W. Wilcox	Baylor University	06/25–07/07
A. Stadler	University of Lisbon	07/21–09/14
T. Pena	University of Lisbon	07/21–09/14
J. Tjon	University of Utrecht	07/22–08/18
E. Lomon	Massachusetts Institute of Technology	09/09–09/21
J.-M. Laget	Saclay	10/15–11/03
V. Suslov	St. Petersburg State University	12/02–12/15
S. Kulagin	Russian Academy of Science	12/10–12/20

C. SHORT TERM VISITORS IN 2001

V. Mandelzweig	Hebrew University	01/24–01/31
W. Lee	Los Alamos National Laboratory	02/03–02/07
S. Puglia	Ohio State University	02/10–02/13
J. Tjon	University of Utrecht	02/11–02/17
T. Blum	Brookhaven National Laboratory	02/13–02/15
D. Black	Syracuse University	02/15–02/18
A. Williams	University of Adelaide	02/21–02/23
A. Arriaga	University of Lisbon	02/24–03/03
T. Cohen	University of Maryland	02/25–02/26
M. Paris	University of Illinois at Urbana-Champaign	03/07–03/11
V. Pandharipande	University of Illinois at Urbana-Champaign	04/12–04/13
A. Fonseca	University of Lisbon	05/01–05/04
F. Lee	George Washington University	07/02–07/06
S. Mintz	Florida International University	07/16
S. Mintz	Florida International University	08/02–08/09
J. Speth	University of Bonn	09/05–09/08
J. Speth	University of Bonn	09/16–09/22
W. Detmold	University of Adelaide	09/08–09/14
A. Belitsky	University of Maryland	09/23–09/26
S. Beane	University of Washington	10/29–10/30
N. Kalantar	Kernfysisch Versneller Instituut (KVI)	11/02
D. Riska	Helsinki Institute of Physics	11/03–11/11
L. Marcucci	University of Pisa	12/02–12/08
A. Rinat	Weizmann Institute of Science	12/02–12/07
T. Mizutani	Virginia Polytechnic Institute	12/12–12/16

D. THEORY SEMINARS IN 2001

V. Mandelzweig, Hebrew University, 01/29/01
Quasilinearization Method and Its Application to Physical Problems

W. Lee, Los Alamos National Laboratory, 02/05/01
Recent Progress in ϵ'/ϵ Calculation Using Staggered Fermions

R. Edwards, Jefferson Laboratory, 02/09/01
From 5D to 4D: Chiral Fermions on the Lattice

S. Puglia, University of Connecticut, 02/12/01
How Well Does the Chiral Expansion for Baryons Converge

T. Blum, Brookhaven National Laboratory, 02/14/01
Lattice QCD Using Domain Wall Fermions

D. Black, Syracuse University, 02/16/01
Chiral Lagrangian Treatment of the Scalar Meson Puzzle

D. Richards, Old Dominion University/Jefferson Laboratory, 02/21/01
Large Baryon Spectroscopy fromLattice QCD

A. Williams, University of Adelaide, 02/23/01
On Triviality, Regularization, and Renormalization in High Precision Studies of Nonperturbative QED

T. Cohen, University of Maryland, 02/26/01
Does the Vafa-Wittne Theorem Rule Out Spontaneous Parity Violation in Finite Temperature QCD ?

I. Musatov, Jefferson Laboratory, 02/28/01
Higher-Twist Skewed Parton Distributions and DVCS

H.-W. Hammer, Ohio State University, 03/05/01
Three-Body Forces in Effective Field Theory

T. Mehen, Ohio State University, 03/07/01
Effective Field Theory for Nuclear Physics

M. Paris, Univerity of Illinois at Urbana-Champaign, 03/09/01
Quantum Monte Carlo Calculations of Six-Quark States

J.-W. Chen, University of Maryland, 03/12/01
Measuring the Longest Range P-Odd π-N Coupling in π-Photoproduction Near Threshold

D. THEORY SEMINARS IN 2001 (cont'd)

W. Roberts, Old Dominion University/Jefferson Laboratory, 04/02/01
Phenomenological Lagrangian Description of Photo- and Electro-Production: Very Preliminary

D. Ernst, Vanderbilt University/Jefferson Laboratory, 04/09/01
Meson Cloud Contribution to the Masses of the Nucleon and Δ

V. Pandharipande, Univerity of Illinois at Urbana-Champaign, 04/13/01
Many-Body Theory Approach to Deep Inelastic Scattering

J. Juge, Fermi National Laboratory, 04/18/01
Heavy Hybrid Mesons

C. Jung, University of Maryland, 04/20/01
Hadronic Structure of the Photon in Lattice QCD

P. Bedaque, Lawrence Berkeley Laboratory, 04/23/01
Nonperturbative Effective Theories

W. Wilcox, Baylor University, 06/28/01
Lattice Methods

S. Mintz, Florida International University, 07/16/01
Neutrino Reactions in ^{56}Fe *and an Interesting Relation*

I. Balitsky, Old Dominion University/Jefferson Laboratory, 07/23/01
Effective Field Theory for the Small x*-Evolution*

C. Schat, Hampton University, 07/30/01
The Negative Parity 70-plet in Large N_C *QCD*

T. Peña, University of Lisbon, 08/13/01
Learning About the $N\eta$ *Interaction from the* $Np \rightarrow \eta d$ *Reaction Close to Threshold*

W. Melnitchouk, Jefferson Laboratory, 08/27/01
Lattice QCD and Chiral Extrapolation

A. Freund, University of Regensburg, 09/05/01
Deeply Virtual Compton Scattering in Next-to-Leading Order

W. Detmold, University of Adelaide, 09/10/01
Chiral Behavior of Quark Distributions from Lattice QCD

E. Lomon, Massachusetts Institute of Technology, 09/19/01
Physical Nucleon Electromagnetic Form Factor Models Fitted to Old and New Data

D. THEORY SEMINARS IN 2001 (cont'd)

J. Speth, University of Bonn, 09/21/01
Pion-Nucleon Reactions (Two-Pion Production)

A. Belitsky, Univerity of Maryland, 09/24/01
Theory and Phenomenology of Generalized Parton Distributions

S. Beane, University of Washington, 10/29/01
Quark-Hadron Duality at Large N_c

D. Riska, Helsinki Institute of Physics, 11/05/01
Pion Decay of Charm Mesons

D. Black, Jefferson Laboratory, 11/19/01
Scalar Mesons in Three-Flavor Linear Sigma Models

A. Rinat, Weizmann Institute of Science, 12/03/01
Extraction of the Neutron $F_2^n(x, Q^2)$ *on Inclusive Electron Scattering from D, C and Fe*

E. THEORY MINI-LECTURE SERIES IN 2001

I. Aznauryan, Yerevan Physics Institute, 08/20–08/24/01
Pion Electroproduction on the Nucleons in the Resonance Region:Unitary Isobar Model and Dispersion Relations

J.-M. Laget, Saclay, 10/22–10/29/01
Meson Photo-Production: a Window on the Quark-Gluon Structure of Hadronic Matter

Yu. Simonov, ITEP-Moscow, 11/12–11/16/01
Microscopic Structure of the QCD Vacuum and How it is Revealed in Normal (Mesons and Baryons) and Unusual (Hybrids, Glueballs, and Hybrid Baryons) Hadrons