Department of Energy Outstanding Junior Investigator Grant DE-FG03-01ER41196

EFFECTIVE THEORIES OF THE STRONG INTERACTION

Final Report

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1 INTRODUCTION

Abstract: This is the final report corresponding to the full funding period (08/01—07/04) in the Department of Energy Outstanding Junior Investigator Grant DE-FG03-01ER41196. The development of an understanding of the interplay between perturbative and non-perturbative effects in strong-interacting systems forms the broad context of this research. The main thrust is the application of effective theories to QCD. Topics included a new power counting in the pionful efective theory, low-energy Compton scattering, charge-symmetry breaking in pion production and in the two-nucleon potential, parity violation, coupled-channel scattering, shallow resonances and halo nuclei, chiral symmetry in the baryon spectrum, existence of a tetraquark state, and molecular meson states.

DOE grant DE-FG03-01ER41196 was used to partially support in the period 08/01—07/04 the research activities of the Principal Investigator, Dr. Ubirajara van Kolck, one post-doctoral research associate, Dr. Boris A. Gelman, and one graduate student, Mr. Will Hockings. During the grant period the PI was first Assistant then Associate Professor of Physics at the University of Arizona (UA), and a RHIC Physics Fellow at the RIKEN-BNL Research Center (RBRC). The association with RBRC ended in the Summer of 2004. Since September of 2002 the PI has also been partially supported by a Sloan Research Fellowship.

Dr. Boris Gelman was supported by the grant from September 2002 to May 2004. He joined the UA after receiving a Ph.D. from the University of Maryland in the Summer of 2002. He left to take a research associate position in the nuclear theory group of the State University of New York at Stony Brook. The support of a post-doctoral researcher on this grant for two years was only possible by carrying over first- and second-year funds to later years.

In addition, Mr. William Hockings started doing research under the PI's guidance. Mr. Hockings took Independent Study courses with the PI, while working as a teaching assistant in the UA Department of Physics. He learned the basic ideas of non-relativistic effective field theories, such as "reparametrization" invariance, and studied a simple application of effective field theory to Compton scattering on the nucleon at energies well below the pion mass. Mr. Hockings has passed the qualifying exam (called "comprehensive" at UA) with a solid performance, and is now pursuing a Ph.D. in nuclear physics, supported by the grant.

Grant activities are described in Sect. 2. They included the publication of research papers, the delivery of seminars and lectures, and the organization of scientific meetings and (together with UA colleagues) of a series of local seminars, as listed in the Appendix.

2 ACTIVITIES IN THE PERIOD 08/01—07/04

The technique of (low-energy) Effective Field Theories (EFTs), which incorporates the ideas of the renormalization group developed in particle and condensed matter physics, allows for the systematic treatment of a system with separate energy scales. Below some scale M we construct the most general Lagrangian involving the lowest-energy hadrons (and photons and leptons) that is consistent with the symmetries of QCD. Interactions are ordered according to a counting of powers of the small parameter Q/M, where $Q \ll M$ is the typical momentum of external particles in the reaction under study. Observables are then calculated to any given order in terms of renormalized parameters, which are not fixed by symmetry. Eventually these parameters will be calculated from an explicit solution of QCD, likely via lattice simulations. In the meantime, we use data to fit the parameters. At any given order in the expansion, a finite number of observables is used as input for the fit, so that all other observables can be predicted with an error given by the expected size of higher-order terms. This research program is geared toward building the theoretical tools required for an understanding of the structure of nuclei.

Much work on the development of EFTs for systems with $A \geq 2$ nucleons has been carried out by the PI and many others over the last ten years. We have recently reviewed the application to systems made out of few nucleons [1,2,3,4,5].

In the past three years, progress in the description of one- and two-nucleon (NN) systems was made on several fronts, including the renormalization of nuclear forces [6,7], low-energy Compton scattering [8,9], charge-symmetry breaking in pion production [10,11,12,13,14], charge-symmetry breaking in the NN force [15,16], and parity violation [17,18]. The EFT framework can be extended to more complex systems. As an example, coupled-channel scattering was considered [19]. More importantly, we have broken new ground with the development of a new EFT designed to describe loosely-bound (halo) nuclei and shallow resonances [20,21,22,23]. We have also examined some issues related to the particle spectrum in QCD, including the implications of chiral symmetry to the mass of excited baryons [24], of quark models to the binding of a multi-quark "exotic" state [25], and of meson exchange to the binding of certain molecular meson states [26]. Finally, we have dedicated some time to outreach, in connection to our work on charge-symmetry breaking. We have reported the recent experimental and theoretical developments in a popular article [27], in addition to communicating directly with science reporters.

2.1 A new power counting in the pionful EFT

Despite the first successes, issues remain about power counting in processes involving more than one nucleon at energies comparable to the pion mass. The fundamental difficulty in formulating power-counting schemes for multi-nucleon systems is that the interaction of two or more nucleons near threshold is intrinsically nonperturbative. Weinberg's original proposal for an EFT describing multi-nucleon systems was to determine the nuclear potential using the organizational principles of the well-established EFT describing the meson sector and the single-nucleon sector (chiral perturbation theory), and then to insert this potential into the Schrödinger equation to solve for NN wavefunctions. Unfortunately, there seem to be formal inconsistencies in Weinberg's power counting: divergences that arise in the iteration of leading-order interactions apparently cannot be absorbed by the leading-order operators themselves. This formal issue was partially solved by Kaplan, Savage and Wise who introduced a power counting in which pions are treated perturbatively. Yet, Fleming, Mehen and Stewart showed that pion exchange in the ${}^3S_1 - {}^3D_1$ coupled channels is not perturbatively convergent for momenta around 100 MeV.

We have investigated [6,7] the renormalization of the pion ladder in the ${}^1S_0$ channel and in the ${}^3S_1 - {}^3D_1$ coupled channels. The key idea comes from work in the three-body system in the EFT where pions are integrated out. There it was seen that the renormalization of the nonperturbative equation was very different from the renormalization of individual terms in the associated perturbative series. We confirmed that Weinberg's power counting is formally inconsistent in the ${}^1S_0$ channel, but that it *is* consistent in the ${}^3S_1 - {}^3D_1$ coupled channels. We also confirmed that part of the pion contribution to scattering in the ${}^1S_0$ channel requires perturbative treatment in order to obtain a consistent theory, but that there is no such requirement in the ${}^3S_1 - {}^3D_1$ channels. Moreover, we argued, supported by numerical evidence, that an *expansion about the chiral limit* provides a systematic power counting for multi-nucleon systems. This expansion is found to be equivalent to Kaplan-Savage-Wise power counting in the ${}^1S_0$ channel and equivalent to Weinberg power counting in the ${}^3S_1 - {}^3D_1$ coupled channels, *i.e.* it selects only the desirable features of both power countings. We also argued that the previous problems found with the slow convergence of the perturbative-pion expansion in the ${}^1S_0$ channel stem from the short-distance physics, not the long-range pion physics itself. We discussed possible scenarios for the light-quark mass dependence of the deuteron binding energy and NN scattering amplitudes, and illuminated the long and winding road between nuclear physics and lattice QCD. Since we removed existing obstacles to a chiral (derivative and pion-mass) expansion, we expect that all other corrections can be treated perturbatively, although we have not worked this out in detail yet.

2.2 Low-energy Compton scattering

The electromagnetic polarizabilities are a fundamental property of any composite object. For example, in a simple quark-model picture the polarizabilities contain averaged information about the charge and current distribution produced by the quarks inside the nucleon. Photon tagging can be used to measure Compton scattering on weakly-bound systems, since it facilitates the separation of elastic and inelastic cross sections. Proton electric and magnetic polarizabilities, α_p and β_p, can be obtained from elastic scattering on hydrogen targets. In contrast, the absence of free neutron targets requires that the neutron polarizabilities α_n and β_n be extracted from scattering on deuterium targets. Data exist for coherent $\gamma d \to \gamma d$ from 49 to 95 MeV, and for quasi-free $\gamma d \to \gamma pn$ from 200 to 400 MeV. The coherent process is particularly sensitive to the isoscalar combination of polarizabilities, $\alpha_N = (\alpha_p + \alpha_n)/2$ and $\beta_N = (\beta_p + \beta_n)/2$, via interference with the larger Thompson term. The extraction of neutron polarizabilities from these data requires a consistent theoretical framework to separate nucleon properties from nuclear effects. In the long-wavelength limit of interest such a framework is EFT.

The amplitude for Compton scattering on the nucleon has been computed to $\mathcal{O}(Q^4)$ by J. McGovern. To this order, the only undetermined parameters are the short-range contributions to the polarizabilities. We have calculated the amplitude for coherent Compton scattering on the deuteron to the same order in Weinberg's power counting [8]. The single-nucleon amplitude is boosted to the relevant deuteron frame, and all two-nucleon diagrams up to $\mathcal{O}(Q^4)$ are added. The kernel for Compton scattering on the deuteron is the sum of the single-nucleon amplitude and two-nucleon contributions. The full amplitude is obtained by sandwiching the kernel between deuteron wavefunctions obtained within EFT to the appropriate order. There are no unknown parameters in the two-nucleon sector.

We have now fitted the world's low-energy proton and coherent deuteron data, and extracted both the proton and neutron polarizabilities [9,8]. From the proton data (ω, $\sqrt{|t|} < 200$ MeV), we find

$$\begin{aligned} \alpha_p &= (12.1 \pm 1.1)^{+0.5}_{-0.5} \times 10^{-4}\,\mathrm{fm}^3, \\ \beta_p &= (3.4 \pm 1.1)^{+0.1}_{-0.1} \times 10^{-4}\,\mathrm{fm}^3, \end{aligned} \tag{1}$$

while from the deuteron data (ω, $\sqrt{|t|} < 160$ MeV),

$$\begin{aligned} \alpha_N &= (13.0 \pm 1.9)^{+3.9}_{-1.5} \times 10^{-4}\,\mathrm{fm}^3, \\ \beta_N &= (-1.8 \pm 1.9)^{+2.1}_{-0.9} \times 10^{-4}\,\mathrm{fm}^3. \end{aligned} \tag{2}$$

This is the first time such a consistent extraction is done. Our values for the proton are close to existing model-dependent analyses that include higher-energy data, but with considerably larger error bars that result from our restriction to low energies. Neutron polarizabilities are comparable to proton values within (rather large) errors.

2.3 Charge-symmetry breaking in pion production

The observed nucleon-mass splitting has far-reaching consequences in nucleosynthesis, but it is not well understood. It originates from both electromagnetic and quark-mass-difference effects. An empirical determination of the latter component of the nucleon-mass difference could allow, together with its calculation in lattice QCD, for an extraction of the down-up mass difference. While electromagnetic interactions break isospin in general, the quark mass difference breaks explicitly charge symmetry, a particular isospin rotation that interchanges up and down quarks. Within the framework of the EFT with explicit pion fields, additional experimental information on the relative size of the two mechanisms comes from associated s-wave pion-nucleon interactions required by chiral symmetry. Lacking accurate low-energy pion-nucleon scattering data, we turn [10,11,12,27] to reactions where a π^0 is emitted near threshold after being created by one nucleon and rescattered by a second. Just-released results of the TRIUMF $np \to d\pi^0$ experiment have confirmed the prediction of Miller, Niskanen and van Kolck that the two contributions to the nucleon-mass difference can produce —via pion rescattering— a relatively large contribution to the front-back asymmetry, of opposite sign to more conventional mechanisms. Unfortunately, the interference with the largest of these standard mechanisms, pi-eta mixing, makes the final result also sensitive to the poorly-known eta-nucleon coupling and pi-eta mixing angle.

We have argued that more experimental information is needed to separate these various CSB mechanisms. With our theoretical support, an IUCF collaboration led by A. Bacher and E. Stephenson has recently reported [13] the first unambiguous observation of the CSB reaction $dd \to \alpha\pi^0$ near threshold. Near the threshold at 225.5 MeV, one avoids other pion-producing channels and takes advantage of the clean experimental conditions afforded by the IUCF electron-cooled storage ring. A 6° bend located in one section of the ring provided a site where ^{4}He nuclei, produced in a narrow forward cone just above threshold, could be separated from the circulating deuteron beam. By placing a gas jet target sufficiently upstream of the 6° magnet, it became possible to cover a large solid angle with an array of Pb-glass detectors that was selectively sensitive to photons from the target region. Kinematic reconstruction permitted the separation of $\alpha\pi^0$ events from double radiative capture $\alpha\gamma\gamma$ events. The 66 and 50 events recorded above background at the two energies of 228.5 and 231.8 MeV lead to total cross section values of 12.7 ± 2.2 pb and 15.1 ± 3.1 pb respectively, including a 6.6% scale error for all systematic effects. These cross sections are consistent with being proportional to $\eta = p_\pi/m_\pi$ with a combined slope of

$$\frac{\sigma}{\eta} = 80 \pm 11 \text{ pb.} \tag{3}$$

The measured cross section depends on the same CSB mechanisms as does the $np \to d\pi^0$ asymmetry, but with different weights. It is proportional to the square of the CSB pion production amplitude, but the interpretation of the experimental result is complicated by the rich isospin-conserving interactions among the four nucleons. In order to tackle this issue, we have assembled a theoretical collaboration, which has by now identified the leading CSB operators in ChPT and evaluated the main tree-level mechanisms near threshold, using a simplified set of d and α wave functions and a plane-wave approximation for the dd initial state [14]. The leading-order term stemming from the nucleon-mass contributions is shown to be suppressed because of poor overlap of initial and final states, while the higher-order pi-eta-mixing and heavy-meson-exchange amplitudes contribute coherently to the cross section. Our preliminary results suggest that the largest contribution comes from pi-eta mixing, and is of the same order of magnitude as the measured cross section. Incorporation of a realistic α wave function and dd interactions is in progress.

2.4 Charge-symmetry breaking in the NN potential

Given their importance in pion production it is natural to wonder what role the s-wave pion-nucleon CSB interactions associated with the nucleon-mass difference play in other nuclear CSB observables. They contribute, for example, to the two-pion-exchange CSB NN potential.

We have investigated [15] CSB in the NN force within the EFT with explicit pion fields, using a classification of isospin-violating interactions based on power-counting arguments. The class-III CSB interactions corresponding to the first two orders in the power counting were discussed, including their effects on the $^3\mathrm{He} - {}^3\mathrm{H}$ binding-energy difference. The static two-pion-exchange NN potential linear in the nucleon-mass difference was constructed, and explicit formulas in momentum and configuration spaces were presented, completing previously-obtained results. The resulting potential can be incorporated in the Nijmegen phase-shift analysis and other phenomenological approaches. It seems that the observed CSB can be accommodated with low-energy constants of natural size.

We have also shown [16] that this and other previously-obtained results about the effects of the nucleon-mass difference on the nuclear potential can be obtained more simply after a field redefinition. This field redefinition eliminates the nucleon-mass difference from external states in favor of new isospin-violating interactions. It makes it simple to derive also the remaining component of the CSB NN potential, the class-IV force, which breaks charge symmetry by mixing $I = 0$ and $I = 1$ channels. We have found that in the EFT the leading class-IV force comes from the same one-pion exchange already established in the literature.

2.5 Parity violation

Renewed interest exists in hadronic parity violation (PV), as current experiments do not seem consistent with the conventional parametrization in terms of one-boson-exchange models, PV electron scattering on the proton and deuteron marginally fits with existing theory, and new measurements are underway. Various PV observables have been analyzed within EFT; for example, we have calculated the anapole form factor of the nucleon to sub-leading order in ChPT, which we summarized in Ref. [17]. However, there has been no systematic study of PV nuclear forces within EFT.

For some time we have been reexamining the PV NN force in light of EFT. We have now built [18] the complete EFT framework for the analysis of PV utilizing Weinberg's formulation. We organize the PV NN interaction in powers of derivatives and inverse powers of gauge-boson masses, truncating the discussion at $\mathcal{O}(Q)$ and lowest order in the Fermi coupling. The lowest-order interaction, from one-pion exchange, occurs at $\mathcal{O}(Q^{-1})$. At $\mathcal{O}(Q)$ there exist five contact interactions together with a mid-range component arising from two-pion exchange. We compare this description to the conventional parametrization, and discuss how the short-range parameters can in principle be determined empirically from existing and future experiments. We find that the novel two-pion-exchange potential is significant when compared to one-heavier-boson exchange in the same channels, and might therefore affect the fits to observables.

2.6 Coupled-channel scattering

In certain situations cross sections are much larger than the size set by the range of the interactions. One example is NN scattering near threshold, for which an EFT without pion fields has been constructed. In general, more than one channel might be involved, and one or more can be considered open, as for annihilation channels in low-energy proton-antiproton scattering. Open channels are usually described using optical potentials. What is the EFT counterpart?

We have developed [19] an EFT for coupled-channel scattering with short-range forces that can be used when the cross sections in two or more channels are much larger than the interaction range. We showed how one can obtain a cutoff independent T-matrix starting with the EFT Lagrangian with contact interactions. We have obtained a low-energy expansion of the coupled-channel T-matrix analogous to the effective-range expansion in the case of a single-channel elastic scattering. We have shown also how one recovers the well-known analytic structure —cusps and steps— of the coupled-channel T-matrix. In the case of an open channel, the T-matrix can be expanded in powers of the ratio of the energy above threshold to the threshold energy. As a result one obtains an effective-range-like expansion with complex parameters, which is analogous to what one derives using optical potentials.

2.7 Shallow resonances and halo nuclei

Nuclear halo states have been found in a number of light nuclei close to the nucleon drip lines. They are characterized by a very low separation energy of one or more valence nucleons. The large size of halo nuclei leads to threshold phenomena with consequences for low-energy reaction rates in nuclear astrophysics. Two-body halos are very simple; more complex are three-body halos consisting of a core and two slightly bound nucleons. Particularly interesting are Borromean three-body halos, where no two-body subsystem is bound. Typical examples are ^{6}He and ^{11}Li, which consist of ^{4}He and ^{9}Li cores, respectively, and two neutrons.

The inherent separation of length scales in halo nuclei makes them an ideal playing ground for EFT. If, as in halo nuclei, the core is much more tightly bound than the remaining nucleons, one can write an EFT for the interaction of the nucleons with the core and include the substructure of the core perturbatively in a controlled expansion. This approach is appropriate for energies smaller than the excitation energy of the core. The situation is similar for continuum structures —resonances— that show up in the low-energy scattering of nucleons on tightly-bound nuclei. We have formulated the appropriate EFT and applied it to shallow resonances.

First, we considered [20,21,22] the virtual p-wave state in $n\alpha$ scattering as a test case. The $p_{3/2}$ partial wave displays a shallow resonance, while the low-energy $s_{1/2}$ and $p_{1/2}$ partial waves are nonresonant. The p-wave resonance leads to a power counting different from the one for shallow s-wave bound states that has been discussed extensively in the literature because of its relevance to NN scattering. In particular, a proper description throughout the resonance region requires two low-energy parameters at leading order, namely the scattering "length" and the effective "range". We have fitted $n\alpha$ phase shifts, finding good convergence and excellent agreement with measured cross sections.

Later, we studied [23] the nature of the two fine-tunings required by shallow resonances that are also narrow, which are associated with poles of the S-matrix near the real axis in the complex momentum plane. We showed that one fine-tuning is a *bona-fide*, "dynamical" fine-tuning of the underlying theory, while the second is "kinematical", being caused by the proximity to the resonance. We again illustrated this point in $n\alpha$ scattering. We also generalized the power counting to resonances in other partial waves.

2.8 Chiral symmetry in the baryon spectrum

Understanding the pattern of excited-baryon masses and couplings from QCD remains an open challenge for theorists. The need for theoretical progress is driven by the prospect of new experimental results: for example, the CLAS collaboration at JLab expects to significantly improve knowledge of excited baryon masses and decays. Efforts are also underway to compute properties of excited baryons using lattice QCD and the large-N_c expansion. One particularly pressing and interesting issue is that of the role of the Roper resonance. In the most naive interpretation, this resonance is a three-quark radial excitation of the nucleon with the same spin-parity quantum numbers. However, this interpretation has been questioned because the calculated mass is too high in quark models with one-gluon exchange. To further the mystery, several quenched lattice QCD calculations find a spectrum inverted with respect to experiment, with the Roper heavier than the first excited state with opposite parity. The consequences of $SU(4)$ for the Roper multiplet have been worked out in the large-N_c approximation, assuming that the Roper is in a **20**-dimensional representation of $SU(4)$, leading to several predictions to be tested experimentally at JLab.

We have studied [24] the relevance of chiral symmetry to the spectroscopy of non-strange baryons. We discussed a number of possible representations of the chiral group. Guided by data, we showed that the nucleon, $N(940)$, the delta, $\Delta(1232)$, and the Roper, $N'(1440)$, naturally fall into a *reducible* $(0, \frac{1}{2}) \oplus (\frac{1}{2}, 1)$ representation of $SU(2) \times SU(2)$. With a single free parameter (the mixing angle between the two irreducible representations), this representation offers a compelling explanation of the measured value of g_A and of the special role of the Roper resonance in QCD, making also predictions such as for the Roper-pion coupling. We found that our result is consistent with large-N_c QCD; however, the naive large-N_c counting is badly violated by experiment. Moreover, our results are not consistent with placing the Roper in a **20** dimensional representation of spin-flavor $SU(4)$; rather, consistency of our results with large N_c would appear to require that the Roper be in the fundamental representation of $SU(4)$.

2.9 Existence of the tetraquark state $c\,c\,\bar{u}\,\bar{d}$

Most of the presently-observed hadrons are mesons that have quantum numbers of the quark-antiquark pair, and (anti)baryons with quantum numbers of three (anti)quarks. In addition to such "ordinary" hadrons one can consider the existence of other hadronic systems that are color neutral, for example states with quantum numbers of $q\,q\,\bar{q}\,\bar{q}$ and $q\,q\,q\,\bar{q}\,\bar{q}$, where q and $\bar{q}$ stand for quark and anti-quark degrees of freedom. Such "exotic" hadrons have been discussed and searched for for many years. Whether such states are indeed bound depends on a highly non-perturbative dynamics given by QCD. Understanding and —if they exist— observing such hadrons is important to further our knowledge of strongly-interacting systems.

We have attempted [25] to estimate the mass of the putative $c\,c\,\bar{u}\,\bar{d}$ state. This tetraquark state is bound in the heavy-quark limit. However, the effects of the finite mass of the charm quark are expected to be important. An analysis based on confined constituent quarks interacting through pairwise hyperfine interactions leads to relations among masses of exotic and conventional states. In our work we used the masses of doubly-charmed baryons ($c\,c\,u$ and $c\,c\,d$), whose initial signatures were observed by the SELEX collaboration. We have estimated the mass of the tetra-quark state $c\,c\,\bar{u}\,\bar{d}$ to be about 3.9 GeV, only slightly above the $D\,D^*$ threshold. We have also discussed possible experimental signatures of such a state, which might be observed at hadron and lepton colliders.

2.10 Molecular meson states

For many years it has been speculated that the scalar mesons $f_0(980)$ and $a_0(980)$, whose masses are only about 10 MeV below the $K\bar{K}$ threshold, could be considered two-body molecular-like states. Recently, a new near-threshold, narrow $D^*_{sJ}(2317)$ meson was found at BaBar, CLEO and Belle, with a mass 40 MeV below the KD threshold.

We have investigated [26] the possibility that these mesons can further bind into more complex molecular states of the type $D\,D^*_s$, $f_0\,K$, $a_0\,K$, $f_0\,\bar{K}$ and $a_0\,\bar{K}$. These are additional examples of "exotic" hadrons. In general, a description of such states requires detailed knowledge of the non-perturbative dynamics of the quarks and gluons. However, in this case there is a separation of scales, namely between the small binding energies and the kaon mass, m_K. As a consequence, the range of the one-kaon-exchange potential is abnormally long compared to the usual $1/m_K$ range, and the dependence on short-range dynamics is diminished. We have shown that — provided the relevant coupling constants have reasonable values— the above mesons can be expected to be bound by about 10-40 MeV.

APPENDIX

Here we list representative activities carried out under the period of DOE support.

Publications

1. U. van Kolck, "Nuclear Effective Field Theory", *Proc. RBRC Work.* **38** (2001) 509, `BNL-52649`.

2. U. van Kolck, "Recent Progress in Nuclear Effective Field Theory", *Proc. RBRC Work.* **49** (2002) 153, `BNL-52679`.

3. U. van Kolck, "Recent Developments in Nuclear Effective Field Theory", *Nucl. Phys. A* **669** (2002) 33c.

4. P. F. Bedaque and U. van Kolck, "Effective Field Theory for Few–Nucleon Systems", *Ann. Rev. Nucl. Part. Sci.* **52** (2002) 339, `nucl-th/0203055`.

5. U. van Kolck, L.J. Abu-Raddad, and D.M. Cardamone, "Introduction to Effective Field Theories in QCD", in *New States of Matter in Hadronic Interactions*, H.-Thomas Elze et al. (editors), AIP, New York (2002), `nucl-th/0205058`.

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12. U. van Kolck, “Charge Symmetry Breaking in Few–Nucleon Systems”, *RIKEN Accel. Prog. Rep.* **37** (2003) to appear.

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14. A. Gårdestig, C.J. Horowitz, A. Nogga, A.C. Fonseca, C. Hanhart, G.A. Miller, J.A. Niskanen, and U. van Kolck. “Survey of Charge Symmetry Breaking Operators for $dd \to \alpha\pi^0$”, *Phys. Rev. C* **69** (2004) 044606, `nucl-th/0402021`.

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25. B.A. Gelman and S. Nussinov, “Does a Narrow Tetraquark $c\,c\,\bar{u}\,\bar{d}$ State Exist?”, *Phys. Lett. B* **551** (2003) 296, `hep-ph/0209095`.

26. T.D. Cohen, B.A. Gelman, and S. Nussinov, “New Threshold Mesons”, *Phys. Lett. B* **578** (2004) 359, `hep-ph/0309210`.

27. G.A. Miller and U. van Kolck, “Big Break for Charge Symmetry”, *Physics World* **16** (2003) 19,
www.physicsweb.org/article/world/16/6/3.

Lectures and Seminars

- U. van Kolck, “Effective Field Theories of Light Nuclei”, invited talk at the Workshop on New Perspectives on P-Shell Nuclei: The Nuclear Shell Model and Beyond, Michigan State University, East Lansing, July 2004; and at the 8th Conference on the Intersections of Particle and Nuclear Physics, New York, May 2003.

- U. van Kolck, “Effective Field Theory Approach to Few-Nucleon Systems”, invited talk at the International Nuclear Physics Conference, Göteborg, June/July 2004.

- U. van Kolck, “Halo Effective Field Theory, or Trying to Catch Up with Bruce But Being Nowhere Near”, invited talk at the International Workshop on Blueprints for the Nucleus: From First Principles to Collective Motion, Feza Gürsey Institute, Istanbul, May 2004.

- U. van Kolck, “Charge Symmetry Breaking in the NN Potential”, contributed talk at the APS April Meeting, Denver, May 2004.

- U. van Kolck, “Effective Field Theory of Short–Range Forces”, talk at Iowa State University, Ames, April 2004.

- U. van Kolck, “Charge Symmetry Breaking in Few–Nucleon Systems”, talk at the RIKEN BNL Research Center Review Workshop, BNL, Brookhaven, November 2003.

- U. van Kolck, “Charge Symmetry Breaking in Pion Production”, invited talk at the 4th International Workshop on Chiral Dynamics – Theory and Experiment, Bonn, September 2003; talk at the Instituto de Física Teórica, São Paulo, Brazil, June 2003; and at the University of São Paulo, Brazil, June 2003.

- U. van Kolck, “Effective Field Theory of Halo Nuclei”, invited talk at the Gordon Research Conference on Nuclear Physics, Waterville, July 2003; and at the Workshop on Pushing the Limits of QCD, Benasque, Spain, July 2002; talk at the Helsinki Institute of Physics, Helsinki, September 2003; and at the Ohio State University, Columbus, March 2002.

- U. van Kolck, “Narrow Resonances in Effective Field Theory”, invited talk at the Effective Summer, Berkeley, July 2003.

- U. van Kolck, “Nucleon Polarizabilities from Low-Energy Compton Scattering”, invited talk at the US-Japan Joint Workshop on Nuclear Chiral Dynamics, Honolulu, February 2003.

- U. van Kolck, “The Role of the Roper in QCD”, talk at the California Institute of Technology, Pasadena, January 2003; and at the State University of New York, Stony Brook, May 2002.
- U. van Kolck, “Recent Progress in Nuclear Effective Field Theory”, talk at the RIKEN BNL Research Center Review Workshop, BNL, Brookhaven, November 2002.
- U. van Kolck, “Soft Light on Light Nuclei”, invited talk at the Gordon Research Conference on Photonuclear Reactions, Tilton, August 2002.
- U. van Kolck, “An Effective Theory for Nuclear Physics”, talk at KVI, Groningen, the Netherlands, May 2002; and at Rutgers University, Piscataway, May 2002.
- U. van Kolck, “Charge Symmetry Breaking in QCD and $np \to d\pi^0$”, talk at IUCF, Bloomington, March 2002; and at Ohio University, Athens, February 2002.
- U. van Kolck, “The Nucleus and the Neo–Impressionist”, colloquium at Ohio University, Athens, March 2002.
- U. van Kolck, “Three–Nucleon Forces in Chiral Perturbation Theory”, talk at Duke University, Durham, February 2002.
- U. van Kolck, “Compton Scattering on the Deuteron at Low Energies”, talk at TUNL, Durham, February 2002; and at the California Institute of Technology, Pasadena, January 2002.
- U. van Kolck, “Effective Field Theory of the Triton”, talk at the University of South Carolina, Columbia, February 2002.
- U. van Kolck, “Introduction to Effective Field Theories in QCD”, lectures at the Pan-American Advanced Study Institute on New States of Matter in Hadronic Interactions, Campos do Jordão, Brazil, January 2002.
- U. van Kolck, “One Two Three ... Infinity: Nucleons in EFT”, invited talk at the WE-Heraeus-Seminar on Effective Field Theories of QCD, Physikzentrum Bad Honnef, November 2001.
- U. van Kolck, “Effective Field Theory of Shallow P–Wave States: n+^{4}He”, contributed talk at the Fall Meeting of the Division of Nuclear Physics of the APS, Hawaii, October 2001.
- U. van Kolck, “Charge Symmetry Breaking in QCD”, invited talk at the Mini-Workshop on Computing $\sigma(dd \to \alpha\pi^0)$ and Charge Symmetry Breaking, INT, Seattle, August 2001.
- B.A. Gelman, “What Can Large N Tell Us About the Nucleon-Nucleon Interaction?”, invited talk at the Program on Theories of Nuclear Forces and Nuclear Systems, INT, Seattle, November 2003; talks at Rutgers University, Piscataway, December 2003; and at the State University of New York, Stony Brook, December 2003.

- B.A. Gelman, “Exotic hadrons”, talk at the University of Arizona, Tucson, September 2003.

- B.A. Gelman, “How physicists do physics”, talk at Yeshiva University, New York, June 2003.

- B.A. Gelman, “Heavy Baryons in the Combined Heavy-Quark and Large-N Limits”, contributed talk at the 8th Conference on the Intersections of Nuclear and Particle Physics, New York, May 2003.

- W. Hockings, “Effective Field Theory Approach to Nucleon Compton Scattering”, contributed talk at the APS Four Corners Meeting, Tempe, October 2003.

Meetings Organized

- INT Program on Theories of Nuclear Forces and Nuclear Systems, Institute for Nuclear Theory, Seattle, Fall 2003 — organized by R. Furnstahl, B.F. Gibson, R.G.E. Timmermans, and U. van Kolck.

- Fall Meeting of the Division of Nuclear Physics of the APS, Tucson, October 2003 — organized by B.R. Barrett, I. Sarcevic, U. van Kolck, and others.

- INT Workshop on Charge-Symmetry Breaking in Few-Nucleon Systems, Institute for Nuclear Theory, Seattle, October 2003 — organized by R.G.E. Timmermans and U. van Kolck.

- Invited Session on “Rich QCD at RHIC” at the APS April Meeting, Philadelphia, April 2003 — organized by J. Thomas and U. van Kolck.

- Invited Session on “Charge–Symmetry Breaking” at the APS April Meeting, Philadelphia, April 2003 — organized by U. van Kolck.

- Invited Session on “Compton Scattering” at the APS April Meeting, Philadelphia, April 2003 — organized by E. Beise, K. de Jager, and U. van Kolck.

- Invited Session on “Effective Interactions from NN to Many Ns” at the DNP Fall Meeting, East Lansing, October 2002 — organized by D. Dean and U. van Kolck.

- Invited Session on “Solar Reactions” at the DNP Fall Meeting, East Lansing, October 2002 — organized by U. van Kolck.

- Invited Session on “Parity–Violation in Nuclear Physics” at the APS April Meeting, Albuquerque, April 2002 — organized by U. van Kolck.

- Joint DNP/FBG Invited Session on “Challenges for Effective Field Theory” at the APS April Meeting, Albuquerque, April 2002 — organized by V.R. Brown, B.F. Gibson, and U. van Kolck.

- Chiral Physics Session of the International Conference on the Structure of Baryons, Jefferson Laboratory, Newport News, March 2002 — organized by A. Bernstein, U.-G. Meißner, and U. van Kolck.
- Pan-American Advanced Study Institute on New States of Matter in Hadronic Interactions, Campos do Jordão, Brazil, January 2002 — organized by J. Rafelski, R.L. Thews, U. van Kolck, and others.
- INT Mini-Workshop on Computing $\sigma(dd \to \alpha\pi^0)$ and Charge Symmetry Breaking, Institute for Nuclear Theory, Seattle, August 2001 — organized by G.A. Miller and U. van Kolck.

Seminar Series on "Strong interactions and related areas" at UA

- Gerald Miller (University of Washington), "Even-parity pentaquark and stable strange nuclear matter", April 8, 2004.
- Michael Ramsey-Musolf (California Institute of Technology), "Sub-Z supersymmetry", March 9, 2004.
- Ubirajara van Kolck (University of Arizona), "The up-down quark mass difference in pion production", February 10, 2004.
- Boris Gelman (University of Arizona), "Exotic hadrons", September 23, 2003.
- Roy Frieden (University of Arizona), "Fisher information and physics", May 12, 2003.
- Richard Lebed (Arizona State University), "Baryons in $1/N_c$: the classic and the nouveau", May 7, 2003.
- Romas Kalinauskas (Institute of Physics, Vilnius), "Techniques for nuclear structure calculations", April 7, 2003.
- Kirill Tuchin (INT, Seattle), "QCD at high energies at work: DIS and heavy-ion collisions", April 2, 2003.
- Shmuel Nussinov (Tel-Aviv University), "A simple physicist approach to complex problems", April 1, 2003.
- Ionel Stetcu (Louisiana State University), "Can we trust the random phase approximation?", March 27, 2003.
- Matthias Burkardt (New Mexico State University), "Hadron tomography", March 26, 2003.
- Simon Catterall (Syracuse University), "Lattice supersymmetry and topological field theory", March 12, 2003.

- Christian Forssén (Chalmers University of Technology), "On the few-body character of light exotic nuclei", March 6, 2003.
- Giorgio Torrieri (University of Arizona), "Hadron freeze-out and particle spectra", March 5, 2003.
- Marco Huertas (College of William & Mary), "Applications of effective field theory/density functional theory approach to properties of nuclei far from stability", February 28, 2003.
- Tom Luu (INT, Seattle), "Perturbative effective theory within an oscillator basis", January 28, 2003.
- Urs Heller (APS & BNL), "Thermodynamics simulations with improved staggered quarks", January 21, 2003.
- David Cardamone (University of Arizona), "Two-state model for the decay of superdeformed nuclei", December 11, 2002.
- Aron Soha (Stanford University/SLAC), "Branching fraction and CP asymmetry in $B^0 \to J/\psi\,\pi^0$", December 4, 2002.
- Yasushi Nara (University of Arizona), "Non-perturbative computation of gluon production from the color glass condensate in high-energy heavy-ion collisions", November 20, 2002.
- Xavier Calmet (California Institute of Technology), "Non-constant fine-structure constant and grand unified theories", November 13, 2002.
- Ubirajara van Kolck (University of Arizona), "EFT of halo nuclei", October 30, 2002.
- Irina Mocioiu (University of Arizona), "Neutrino oscillations and matter effects", October 16, 2002.
- Boris Gelman (University of Arizona), "Heavy baryons in the combined large-N and heavy-quark expansion", October 2, 2002.
- Hans-Werner Hammer (Ohio State University), "Effective field theory: from nuclear physics to cold atoms", April 24, 2002.

Other activities

- U. van Kolck, member of the Committee on International Scientific Affairs of the American Physical Society, January 2004–present.
- U. van Kolck, member of Committees of the APS Division of Nuclear Physics: Home Page, Summer 2003–present; National Nuclear Physics Summer School Steering, Spring 2002–present; Program, Spring 2001–Fall 2002.

- U. van Kolck, member of the International Advisory Committee, 17th International IUPAP Conference on Few-Body Problems in Physics, TUNL, Durham, June 2003.
- B.A. Gelman, participant in the Fall Meeting of the Division of Nuclear Physics of the APS, Tucson, October 2003.
- B.A. Gelman, participant in the Gordon Conference on Nuclear Physics, Waterville, July 2003.
- W. Hockings, participant in the 2004 National Nuclear Physics Summer School, Bar Harbor, June 2004.
- W. Hockings, participant in the Program on Theories of Nuclear Forces and Nuclear Systems, INT, Seattle, October/November 2003.
- W. Hockings, participant in the 2003 National Nuclear Physics Summer School, Tennessee, June 2003.