Summary of Research Interests

Ubirajara van Kolck

My main research interests involve applications of effective field theories (EFTs) to problems at the intersection of particle, nuclear, atomic/molecular and astrophysics. The main goal is to achieve a quantitative understanding of nuclear structure (including nuclear matter at finite temperature) and reactions that is fully consistent with the Standard Model.

I have aimed at establishing a bridge between QCD and nuclear physics along two complementary lines: *(i)* development of a systematic approach to low– and intermediate–energy nuclear processes based on EFT, and *(ii)* attempts to derive a chiral EFT from QCD. Along the first line, I have explored an EFT with pion fields ("pionful" EFT) —a generalization of chiral perturbation theory (ChPT)— and an EFT where pion fields are integrated out ("pionless" EFT). Among the ideas to account for QCD dynamics in the prediction of chiral–Lagrangian parameters, I have investigated the large–N_c limit and sum rules in the chiral quark model, and the constraints imposed on effective chiral theories by Regge asymptotic behavior.

Some of the accomplishments of this research program —for reviews, see Ref. [1]— are [1]:

- Discovery of the correct power counting in the pionless EFT [2] and its first non–trivial application, nuclear and molecular three–body systems [3, 4]. These results have established the pionless nuclear EFT as a precise tool for the study of few–nucleon systems at low energies. They have also generated a new approach to trapped dilute gases near Feshbach resonances.

- Renormalization–group analysis of the three–body system with short–range interactions, discovery of the limit–cycle behavior of the three–body force, and explanation of certain universal properties (such as the Philips line) [4]. As a consequence, limit cycles are now being actively studied in various contexts.

- Renormalization–group analysis of singular potentials [5]. The generalization to the one–pion exchange potential has shown that the pionful EFT represents an expansion around the chiral limit [6], allowing for the formulation of the correct power counting (a modification of Weinberg's original proposal) [7].

- Derivation of the nuclear potential to third order (in Weinberg's power counting) in the pionful EFT [8, 9], including the first two–pion–exchange two– and three–nucleon potentials with correct chiral–symmetry transformation properties. The two–nucleon two–pion–exchange force has been incorporated in the Nijmegen phase shift-analysis and verified. The three–nucleon two–pion–exchange potential has been called TM' and is now used in most phenomenological calculations. Also calculated for the first time were various isospin–violating components of the potential [10], demonstrating the observed class hierarchy of isospin–dependent forces [11].

- First EFT fit to two–nucleon phase shifts [8], which demonstrated the viability of the EFT approach in nuclear physics. Several other groups have subsequently shown that fits can be achieved with accuracy comparable to those of phenomenological potentials.

[1] A full list of my publications can be found in my CV.

- Model–independent, consistent determination of proton and neutron polarizabilities [12] from low–energy proton and deuteron Compton scattering data.
- Prediction of the amplitude for neutral–pion photoproduction on the deuteron [13], later confirmed at SAL and MAMI [14]. This was the first example of a prediction in nuclear EFT that was substantially different from existing model predictions.
- Generalization of power counting to pion production in NN collisions [15].
- Prediction of the sign of the charge–symmetry–breaking asymmetry in $pn \to d\pi^0$ [16], later confirmed at TRIUMF [17]. This work demonstrated that it is possible to separate quark-mass and electromagnetic contributions to the nucleon mass difference through the pion interactions they generate via chiral symmetry, and re-ignited interest on charge–symmetry breaking.
- Proposal of, and theoretical support for, the first experiment to measure the charge–symmetry–forbidden reaction $dd \to \alpha\pi^0$, at IUCF [18]. This successful experiment has stimulated experimental programs elsewhere, in particular more extensive measurements at COSY.
- Calculation of the anapole and electric dipole form factors of the nucleon in ChPT [19].
- Formulation of a broad framework for the analysis of parity violation in nuclear systems, including the derivation of the parity–violating two–nucleon potential in EFT [20].
- Development of the EFT for shallow resonances and halo nuclei [21].
- Formulation of the No-Core Shell Model as an EFT in a harmonic-oscillator basis, and first calculation of the pionless EFT beyond the four-body system [22].
- Proof–of–principle calculation of thermal properties of nuclear matter using EFT in a finite spatial lattice [23]. Several groups are now attempting lattice solutions of EFTs for nuclear matter and trapped gases.

My future research is likely to follow the growth of my interests in the direction of the structure and reactions of heavier nuclei. It might include:

(1) **The EFT in few–nucleon systems**. Despite all the progress, several open issues — particularly regarding the ordering of interactions, known as power counting— still plague the formulation of the pionful EFT, and demand further study in the context of few–nucleon systems. For example, the renormalization of both two– and three–nucleon amplitudes is being examined in subleading orders in the new power counting, with A. Nogga (Jülich) and R. Timmermans (KVI). In addition, the role of the Delta isobar is being studied with graduate student B. Long (Arizona). There are issues of power counting in reactions as well, which were unearthed in our work on Compton scattering. Moreover, a quantitative understanding of pion production in nuclear collisions remains elusive. Currently, a theoretical collaboration put together by G. Miller (Washington) and myself is trying to improve our description of the IUCF data on $dd \to \alpha\pi^0$.

(2) **The EFT of heavier nuclei**. The solution of the EFT at a given order becomes complicated as the number of nucleons increase. One promising possibility is to adapt Shell–Model methods

to the solution of the EFT, whose parameters are, to high order, determined by the $A = 2, 3, 4$ systems. With I. Stetcu (LANL) and B. Barrett (Arizona), I am working on formulating EFTs within the No–Core Shell Model. A preliminary calculation with J. Vary (Iowa State) of ^{48}Ca using a toy delta–function model yields surprisingly good results. However, even such a powerful method will not handle heavy nuclei. An alternative is to develop a lower–energy EFT for the interactions of outer nucleons with a core. (This new EFT is not unrelated to traditional single–particle models.) A first application was the description of $n\alpha$ scattering near its shallowest resonance. I am working with C. Bertulani (Arizona) and R. Higa (Bonn) on the inclusion of Coulomb (and the description of $p\alpha$ scattering), and with H. Hammer (Bonn) on Borromean systems, in particular ^{6}He (using $n\alpha$ data as input). The intention is not only to develop a theory for nuclear structure, but also to apply it in the analysis of low–energy processes of astrophysical interest, in particular radiative capture reactions such as $^4\text{He}(2n, \gamma)^6\text{He}$ (for supernovae nucleosynthesis) or $^7\text{Be}(p, \gamma)^8\text{B}$ (for the solar neutrino flux, recently re-measured at CENPA-UW).

(3) **The EFT of nuclear matter**. We are attempting to solve the EFT in nuclear matter at finite temperature, using Monte–Carlo methods to calculate the grand–canonical partition function on a spatial lattice. In a first paper we investigated a toy model with Skyrme–like interactions, and with R. Seki (California State) I am taking the first steps toward using EFT interactions. We are currently examining neutron matter at low density. Since the method will provide information about the equation of state of matter with any desired proton fraction, we hope to be able to eventually attack several issues of experimental and astrophysical interest, for example: the liquid–gas transition (important in the collapse of a supernova core), nuclear correlations in neutrino scattering (relevant to neutrino transport in supernova and neutron stars), and the approach to the chiral–restoring phase transition (studied at RHIC).

(4) **Weak (and other) interactions in the nuclear environment**. Weak and beyond–the–Standard-Model interactions can be incorporated in the EFT, allowing for a comprehensive description of rare nuclear processes that is consistent with QCD. I have already examined some of the constraints of chiral symmetry on parity–violating hadronic interactions. A future topic of study, with J. Friar (LANL), is second–class currents, where our experience with isospin violation will play an important role. I also intend to consider time–reversal–violating interactions. The nucleon electric dipole form factor from the QCD θ–term is isovector at leading order in ChPT, so the proposed storage–ring measurement (by the EDM Collaboration) of the deuteron electric dipole moment would be sensitive to the sub-leading terms in the nucleon electric dipole form factor, to pion–exchange currents, and to the time–reversal–violating two–nucleon potential, which I am calculating with my former graduate student W. Hockings (Blue Mountain) and C. Maekawa (Rio Grande). Eventually, I would like to tackle rare processes in more complex nuclei —*e.g.*, the β–decay of halo nuclei such as ^{11}Li, measured at TRIUMF— with the tools described above.

I expect that this work will cement the basis of a description of nuclear physics within the SM, enhancing our understanding of EFTs in a non-perturbative context and of the role of nuclei as a laboratory for tests of fundamental symmetries.

References

[1] U. van Kolck, *Nucl. Phys. A* **752** (2005) 145c; P.F. Bedaque and U. van Kolck, *Ann. Rev. Nucl. Part. Sci.* **52** (2002) 339; U. van Kolck, *Prog. Part. Nucl. Phys.* **43** (1999) 337.

[2] U. van Kolck, in *Chiral Dynamics: Theory and Experiment*, A. Bernstein, D. Drechsel, and T. Walcher (editors), Springer, Berlin (1998), hep-ph/9711222; in *Nuclear Physics with Effective Field Theory*, R. Seki, U. van Kolck, and M.J. Savage (editors), World Scientific, Singapore (1998); *Nucl. Phys. A* **645** (1999) 273.

[3] P.F. Bedaque and U. van Kolck, *Phys. Lett. B* **428** (1998) 221; P.F. Bedaque, H.-W. Hammer, and U. van Kolck, *Phys. Rev. C* **58** (1998) R641.

[4] P.F. Bedaque, H.-W. Hammer, and U. van Kolck, *Phys. Rev. Lett.* **82** (1999) 463; *Nucl. Phys. A* **646** (1999) 444; *Nucl. Phys. A* **676** (2000) 357.

[5] S.R. Beane, P.F. Bedaque, L. Childress, A. Kryjevski, J. McGuire, and U. van Kolck, *Phys. Rev. A* **64** (2001) 042103.

[6] S.R. Beane, P.F. Bedaque, M.J. Savage, and U. van Kolck, *Nucl. Phys. A* **700** (2002) 377.

[7] A. Nogga, R.G.E. Timmermans, and U. van Kolck, *Phys. Rev. C* **72** (2005) 054006

[8] C. Ordóñez and U. van Kolck, *Phys. Lett. B* **291** (1992) 459; C. Ordóñez, L. Ray, and U. van Kolck, *Phys. Rev. Lett.* **72** (1994) 1982; *Phys. Rev. C* **53** (1996) 2086.

[9] U. van Kolck, *Phys. Rev. C* **49** (1994) 2932; J.L. Friar, D. Hüber, and U. van Kolck, *Phys. Rev. C* **59** (1999) 53; D. Hüber, J.L. Friar, A. Nogga, H. Witała, and U. van Kolck, *Few–Body Syst.* **30** (2001) 95; V.R. Pandharipande, D.R. Phillips, and U. van Kolck, *Phys. Rev. C* **71** (2005) 064002.

[10] U. van Kolck, J.L. Friar, and T. Goldman, *Phys. Lett. B* **371** (1996) 169; U. van Kolck, M.C.M. Rentmeester, J.L. Friar, T. Goldman, and J.J. de Swart, *Phys. Rev. Lett.* **80** (1998) 4386; J.L. Friar and U. van Kolck, *Phys. Rev. C* **60** (1999) 034006; J.L. Friar, U. van Kolck, G.L. Payne, and S.A. Coon, *Phys. Rev. C* **68** (2003) 024003; J.L. Friar, U. van Kolck, M.C.M. Rentmeester, and R.G.E. Timmermans, *Phys. Rev. C* **70** (2004) 044001; J.L. Friar, G.L. Payne, and U. van Kolck, *Phys. Rev. C* **71** (2005) 024003.

[11] U. van Kolck, *Few–Body Syst. Suppl.* **9** (1995) 444.

[12] S.R. Beane, M. Malheiro, D.R. Phillips, and U. van Kolck, *Nucl. Phys. A* **656** (1999) 367; S.R. Beane, M. Malheiro, J.A. McGovern, D.R. Phillips, and U. van Kolck, *Phys. Lett. B* **567** (2003) 200; (E) **607** (2005) 320; *Nucl. Phys. A* **747** (2005) 311.

[13] S.R. Beane, C.Y. Lee, and U. van Kolck, *Phys. Rev. C* **52** (1995) 2914; S.R. Beane, V. Bernard, T.-S.H. Lee, U.-G. Meißner, and U. van Kolck, *Nucl. Phys. A* **618** (1997) 381.

[14] J.C. Bergstrom *et al.*, *Phys. Rev. C* **57** (1998) 3203; I. Ewald *et al.*, *Phys. Lett. B* **499** (2001) 238.

[15] T.D. Cohen, J.L. Friar, G.A. Miller, and U. van Kolck, *Phys. Rev. C* **53** (1996) 2661; U. van Kolck, G.A. Miller, and D.O. Riska, *Phys. Lett. B* **388** (1996) 679; C.A. da Rocha, G.A. Miller, and U. van Kolck, *Phys. Rev. C* **61** (2000) 034613; C. Hanhart, U. van Kolck, and G.A. Miller, *Phys. Rev. Lett.* **85** (2000) 2905.

[16] U. van Kolck, J. Niskanen and G.A. Miller, *Phys. Lett. B* **493** (2000) 65.

[17] A.K. Opper *et al.*, *Phys. Rev. Lett.* **91** (2003) 212302.

[18] E.J. Stephenson, A.D. Bacher, C.E. Allgower, A. Gårdestig, C.M. Lavelle, G.A. Miller, H. Nann, J. Olmsted, P.V. Pancella, M.A. Pickar, J. Rapaport, T. Rinckel, A. Smith, H.M. Spinka, and U. van Kolck, *Phys. Rev. Lett.* **91** (2003) 142302.

[19] C.M. Maekawa and U. van Kolck, *Phys. Lett. B* **478** (2000) 73; C.M. Maekawa, J.S. Veiga, and U. van Kolck,. *Phys. Lett. B* **488** (2000) 167; W.H. Hockings and U. van Kolck, *Phys. Lett. B* **605** (2005) 273.

[20] S.-L. Zhu, C.M. Maekawa, B.R. Holstein, M.J. Ramsey-Musolf, and U. van Kolck, *Nucl. Phys. A* **748** (2005) 435.

[21] C.A. Bertulani, H.-W. Hammer, and U. van Kolck, *Nucl. Phys. A* **712** (2002) 37; P.F. Bedaque, H.-W. Hammer, and U. van Kolck, *Phys. Lett. B* **569** (2003) 159.

[22] I. Stetcu, B.R. Barrett, and U. van Kolck, `nucl-th/0609023`.

[23] H.-M. Müller, S.E. Koonin, R. Seki, and U. van Kolck, *Phys. Rev. C* **61** (2000) 044320; R. Seki and U. van Kolck, *Phys. Rev. C* **73** (2006) 044006.