# Topical Group on Few-Body Systems and Multiparticle Dynamics

FEW-BODY TOPICAL GROUP

## 25th Anniversary Newsletter

*June 2009*

**TABLE OF CONTENTS**



## GFB's Inception

**Frank S. Levin**

Professor Emeritus of Physics
Brown University

This year, 2009, is a special one in the history of the Topical Group on Few Body Systems and Multiparticle Dynamics: it is the silver anniversary of the Group's founding. As with other Topical Groups, the GFB was created via a petition, signed by the attendees at the 1984 Gordon Conference on Few Body Problems, which I had sent to the American Physical Society. The Society's approval established the Group, which came into being on January 1, 1985. I was its founding Chairman, with David Micha as its vice-Chairman, and Teck-Kah Lim as its Secretary/Treasurer.

It is probably unknown to most current members of the GFB that its founding was partly a response to an action that some members of the then few-body nuclear physics community regarded as a major insult. It was, of course, an action whose consequences we are happily still living with, and it seems appropriate in this silver jubilee year to recount those times and the relevant events. What follows is a summary that I hope will be of interest to the members of the Group, not least for the role likely played by physics politics.

The International Conferences on the three-body problem began with a meeting in London in 1965 and, apart from a one-year gap (1971 and 1972) and an 18 month one (1974 and

1975-76) were subsequently held at two year intervals. The 1974 Quebec Conference marked a small but important development: areas other than nuclear physics were included in the program, a move that was to prove influential.

A related and very significant development occurred after the Delhi Conference. Don Kouri, a theoretical chemist, and Yeong Kim, a nuclear theorist, each on leave in Germany, met and decided to submit a proposal to the Gordon Research Foundation, seeking their sponsorship of a conference on few body problems in physics and chemistry. The idea was that by bringing together persons active in each of the disciplines, in the informal but often intense setting of a Gordon Conference, useful cross-fertilizations might result.

The Kouri-Kim proposal was approved, and the first of these Gordon Conferences was held in 1977. It was the first truly inter-disciplinary meeting on few-body problems, and as hoped, it marked the beginning of fruitful cross-fertilizations. Two extremely important principles were established in 1977. One was the requirement of avoiding specialized talks and instead presenting ideas in a form simple enough that members of the other discipline could grasp the basic ideas -- a colloquium rather than a seminar presentation. This was a direct consequence of the very first talk, on the current status of the two-nucleon interaction. It began with a slide showing a Feynman-type diagram. But the meaning of that diagram was so unclear to most of the chemists in the audience that it provoked a huge outcry, with them demanding a degree of clarity that became the goal of all future talks (the speaker hardly knew what had hit him!). The other principle was to annually rotate the chairmanship between persons from each of the two disciplines by selecting a vice-Chairman from the area opposite to that of the chairman. I had long favored interdisciplinary activities, and the latter principle became an important feature for me when I founded the GFB.

Interdisciplinarity was featured in the Ninth International Conference on the Few Body Problem, which I co-organized with Mike Moravcsik in 1980. The next Conference was planned for Karlsruhe in 1982, and it was here that the "insulting" bombshell exploded. All previous Conferences had received approval from the International Union of Pure and Applied Physics (IUPAP), under whose auspices they had been held. In general, IUPAP sought the advice of the APS, in particular that of the Nuclear Physics Division when considering international few body meetings, since few body problems were then regarded as an area of nuclear physics, despite the increasing emphasis on its interdisciplinary nature. This time around, the NP Division did not support the proposed 1982 Conference, claiming that there had been too many such! Instead, they advised a three-year interval, which IUPAP accepted. Without IUPAP approval, the proposed 1982 Conference could not take place, and so we, the Organizing Committee, were forced into an undesired and unwelcome three-year interval. (Among the strong but futile responses were: How dare they? Who could know better than we, the few-body community, what interval was appropriate? etc.)

Though one might guess, we never found out what the politics were that had provoked the NP Division's reaction, but it was uppermost in my mind when the APS announced in 1984 that it was creating Topical Groups. The response of the attendees at the 1984 Gordon Conference was overwhelmingly positive -- I think everyone signed the petition urging formation of the GFB -- and of course, the rest is history.

My congratulations to the current members for keeping the GFB going after all these years: long may it flourish!

Return to top

## GFB through the Years

**Wayne N. Polyzou**

Professor of Physics
University of Iowa

The birth of modern few-body physics in the nuclear physics community can be traced to L.D. Faddeev's doctoral dissertation on ``*Mathematical questions in the quantum theory of scattering for a system of three particles*'' [1]. While this work addressed mathematical questions, the practical significance, which was soon realized by the physics community, was that Faddeev's reformulation of the three-body scattering problem also provided a convergent algorithm that reduced the solution of the problem to finite-dimensional matrix algebra. Nucleon-nucleon interactions, because of their short range, are largely determined by their ability to reproduce bound-state observables and two-body scattering cross sections. Because of this the three-nucleon system is simplest system where it is possible to make non-trivial predictions based on these interactions that can be compared to experiment.

Like most problems in quantum mechanics, there is a large difference between what is in principle possible and what is practically possible. I remember a preprint by Gyula Bencze [2], who worked out the combinatorial analysis to count the number of Yakubovsky equations [3], which generalized the Faddeev equations for system of more than three particles. For the case of non-identical particles he determined that the number of coupled equations that had to be solved for an 8 particle system was 1,587,600 in 21 variables. At that time it was apparent to all that progress would come slowly. It was only after roughly 30 years of many different advances that accurate solutions of the three-nucleon problem with realistic interactions were obtained.

Modern calculations can now treat bound systems of more than eight particles with realistic interactions. Today, thanks largely to advances by many few-body nuclear physicists, we are very close to realizing the goal of having a microscopic theory of low-energy nuclear physics that can be reliably used to treat systems of many more nucleons.

In this anniversary article I would like to chronicle some of the advances that have led us to where we are today. It would be impossible to acknowledge everyone who has made important contributions to this program; the list would include a very large fraction of the few-body physics community, as well as others who have gone on to make important contributions in other disciplines, so I apologize in advance.

A number of important advances have moved the field to the point that it is at today. These include developing a skill set to solve the Faddeev equations. Most of the programs used today took many years to develop. The only way to reliably test these complex calculations was to compare solutions based on the same benchmark Hamiltonian using different representations of the Faddeev equations [4-6]. Initially there were small disagreements, which eventually led some of the competing groups to refine their programs. Now there is a great deal of confidence in the accuracy of the computational methods, and the same quantities can be accurately calculated using very different computational methods.

A second important advance was improvements in the nucleon-nucleon interaction. The original nucleon-nucleon interactions had hard cores, which caused computational difficulties in the momentum space calculations. The long-range part of these interactions is motivated by pion-exchange, while the parameters of short-range part are adjusted to fit nucleon-nucleon scattering data. The original data used to constrain these interactions was limited. Experiments at LAMPF and the Indiana University Cyclotron significantly improved the quality of the world data set which led several groups to construct realistic model nucleon-nucleon interactions [7-9] that provide a precise description of nucleon-nucleon scattering phenomena, including spin observables. These modern interactions have much milder momentum dependence than the original hard-core interactions and provide a realistic description of the two-nucleon system.

A third important advance was purely technological. Computational power has increased to the point that it is now possible to perform calculations that could not be conceived thirty years ago.

Accurate three-body calculations with realistic two-body interactions led to the disappointing result that Hamiltonians having only realistic two-body interactions did not predict the experimental triton binding energy [10]. This led to the investigation of the need for three-body interactions [11-12] or the replacement of two-body interactions by ``phase equivalent'' non-local two-body interactions [13-14]. Nevertheless, the solution of the Faddeev equations for scattering problems using realistic interactions led to a very good understanding of most measured experimental observables for energies up to 200 MeV [15-16]. These observables include cross sections for breakup reactions and reactions involving and polarized targets and beams. For most observables these results are in good quantitative agreement with experiment, indicating that the resulting few-body Hamiltonians provide a good model of few-nucleon systems. I recall early in the three-body program, in part because progress on such difficult problems was slow, hearing criticism that these rather complicated calculations tended to obscure the underlying physics. One no longer hears these criticisms now that it is possible to perform essentially exact calculations with realistic interactions. In fact, the combination of both the precision of the calculations and the experimental data has led to a detailed understanding of the underlying dynamics.

These advances in the few-body problem have provided the seeds for contemporary nuclear few-body research. Open questions that are under investigation include

1. the inclusion of the Coulomb force in nuclear few-body calculations
2. understanding the nature of three and four body interactions

3. developing new methods that build on the success of the few-body models to provide a quantitative treatment of larger systems
4. understanding the connection of nuclear forces with QCD
5. developing methods that can be used at higher energies.

Most of the world scattering data is for proton deuteron-scattering while most of the calculations were done for the neutron-deuteron scattering. The treatment of the Coulomb interaction, particularly in the momentum space formulations, was an important topic of discussion and disagreement at many meetings. Even though the Coulomb force in nuclear physics is repulsive, the scattering asymptotic conditions are only really well-understood in the time-dependent formulation of scattering [17]. Methods using screened Coulomb interactions were proposed by Taylor [18] and initially developed by Alt, Sandhas and Ziegelmann [19] to treat three-body problems with two charged particles. An important computational breakthrough involving this method was to use smooth but very sharp cutoff functions, which led to converged calculations [20-21] for systems of two charged particles using realistic potentials. These methods have been compared to configuration space calculations [22], tested in benchmark calculations [23] and used in realistic calculations for the three and four-body systems with two charged particles. The treatment of systems of three or more charged nucleons is still an open problem.

The problem of constructing three-nucleon interactions is more difficult than the corresponding problem of constructing nucleon-nucleon interactions. The interactions involve more degrees of freedom and the additional degrees of freedom are constrained by less data. Low-energy theorems identified important contributions to three-body interactions [11], however the group of transformations that generate phase equivalent two-body interactions [24] also change the three-body interaction [25], so it has become clear that one should construct two and three-body interactions ``consistently''. New methods based on effective field theory [26-29] have provided important insight into this problem. They provide a systematic framework for understanding the low-energy structure of the two and three-nucleon interactions and they also provide practical insight into what is meant by a consistent treatment of two and three-body interactions.

One of the most useful benefits of having accurate solutions of the Faddeev equation for realistic systems is that they can be used to test and improve computational methods that can be applied to larger systems of interacting nucleons. Methods such as variational Monte Carlo [30], Green function Monte Carlo [31], and no-core shell model calculations [32] allow one to treat bound systems of more than three nucleons based on nuclear Hamiltonians with realistic interactions. Other methods [33-34] have the potential to treat even larger systems. The reliability of the computational algorithms has been tested by comparing solutions based on these methods to Faddeev solutions, leading to a great deal of confidence in these methods. These methods in turn, have been used to test the reliability of methods that can treat larger systems.

A part of this success is due to the freedom to construct equivalent two and three-body interactions by transforming them to a form that improves the convergence of these methods. These interactions have been constructed by direct solutions of the inverse scattering problem

[35] or by applying renormalization group methods to high precision interactions [36].

Given a set of realistic nucleon-nucleon interactions there remains the challenge of understanding how they are related to more fundamental degrees of freedom. Lattice QCD methods have advanced to the point where it is now possible to begin exploring properties of the nucleon-nucleon interaction [37-38] based on quark and gluon degrees of freedom.

Finally, Faddeev methods are beginning to be applied directly at higher energies, where subnuclear degrees of freedom may be relevant. The dynamics of these systems is determined by a few-body Hamiltonian from an exactly Poincaré invariant three-body model [39-40]. These energies lead to a new set of challenges as additional degrees of freedom become important.

In looking back at the initial beginnings of few-body physics, it would have been difficult to predict the amount of progress made during the last 40 years. Unlike many advances in physics, this took the collective effort of many physicists working together for many years on different aspects of a challenging problem. The Few-Body Topical Group has played an important role in this progress by providing a forum to facilitate communication between physicists in the few-body community. Now, during this 25-th Anniversary of Few-Body Topical Group, is good time for all members of the few-body nuclear physics community to reflect on and celebrate the success of this collective enterprise.

1. L. D. Faddeev, "Mathematical aspects of the three body problem in quantum scattering theory ", Israel Program for Scientific Translations, 1965.
2. Gy. Bencze, Volume Physics Letters **72B**, 19 (1977).
3. O. A. Yakubovsky, Sov. J. Nucl. Phys. **5**, 937 (1967).
4. J. L. Friar, B. F. Gibson, G. Berthold, W. Glöckle, Th. Cornelius, and H. Witała, J. Haidenbauer, Y. Koike, G. L. Payne, J. A. Tjon, and W. M. Kloet, Phys. Rev. C**42**, 1838 (1990).
5. J. L. Friar, G.L. Payne, W. Glöckle, D. Hüber, H. Witała Phys. Rev. C**51**, 2356 (1995).
6. A. Kievsky, M. Viviani, S. Rosati, D. Hüber, W. Glöckle, H. Kamada, H. Witała and J. Golak, Phys. Rev. C**58**, 3085 (1998).
7. V. G. J. Stoks, R. A. M. Klomp, C.P.F. Terheggen, and J.J. de Swart, Phys. Rev. C**49**, 2950 (1994).
8. R. B. Wiringa, V. G. J. Stoks, R. Schiavilla, Phys. Rev. C**51**, 38 (1995).
9. R. Machleidt, Phys. Rev. C**63**, 024001 (2001).
10. A. Nogga, D. Hüber, H. Kamada, W. Glöckle, Phys. Lett. **B409**, 19 (1997).
11. S. A. Coon et. al., Nucl. Phys. **A317**, 242 (1979).
12. B. S. Pudliner et. al., Phys. Rev. Lett **74**, 4396 (1995).
13. R. Lazauskas, J. Carbonell, Phys. Rev. C**70**, 044002 (2004).
14. P. Doleschall, Z. Papp, Phys. Rev. C**72**, 044003 (2005).
15. W. Glöckle, H. Witała, D. Hüber, H. Kamada and J. Golak, Phys. Rep. **274**, 107 (1996).
16. A. Kievsky, M. Viviani, and S. Rosati, Phys. Rev. C**64**, 024002 (2001).
17. J. D. Dollard, J. Math. Phys. **5**, 729 (1964).
18. J. R. Taylor, Nuovo Cimento **B23**, 313 (1974).

19. E. O. Alt, W. Sandhas, and H. Ziegelmann, Phys. Rev. C**17**, 1981 (1978); E. O. Alt and W. Sandhas, ibid. **21**, 1733 (1980).
20. A. Deltuva, A. C. Fonseca, P. U. Sauer, Phys. Rev. C**71**, 054005 (2005).
21. M. Viviani, S. Rosati, A. Kievski, Phys. Rev. Lett. **81**, 1580 (1998).
22. A. Kievsky, J. L. Friar, G. L. Payne, S. Rosati, and M. Viviani, Phys. Rev. C**63**, 064004 (2001).
23. A. Deltuva, A.C. Fonseca, A. Kievsky, S. Rosati, P.U. Sauer, M. Viviani Phys. Rev. C**71**, 064003 (2005).
24. H. Ekstein Phys. Rev. **117**, 1590 (1960).
25. W. Glöckle and W. Polyzou, Few-Body Systems **9**, 97 (1990).
26. U. van Kolck, Phys. Rev. C**49**, 2932 (1994).
27. J.L. Friar, G.L. Payne, U. van Kolck, Phys. Rev. C**71**, 024003 (2005).
28. E. Epelbaum, W. Glöckle, H. Kamada, U.G. Meißner, H. Witała, Phys. Rev. C**66**, 064001 (2002).
29. D. R. Entem R. Machleidt, Phys. Rev. C**68**, 041001 (2003).
30. Steven C. Pieper and R. B. Wiringa, Annu. Rev. Nucl. Part. Sci. **51**, 53-90 (2001).
31. J. Carlson, Nuclear Physics **A508**, 141 (1990).
32. R. P. Navrátil, J.P. Vary, B.R.Barrett., Phys. Rev. C**62**, 054311 (2000).
33. S. Fantoni, A. Sarsa, and K. E. Schmidt, Phys. Rev. Lett. **87**, 181101 (2001).
34. F. Coester, Nucl. Phys. **7**, 421 (1958); F. Coester and H. Kümmel, Nucl. Phys. **17**, 477 (1960).
35. A. M. Shirokov, J. P. Vary, A. I. Mazur, S. A. Zaytsev and T. A. Weber, J. Phys. **G31**, S1283 (2005).
36. S. K. Bogner, R. J. Furnstahl, R. J. Perry, Phys. Rev. C**75**, 061001 (2007).
37. S.R. Beane, P.F. Bedaque, K. Orginos, M.J. Savage, Phys. Rev. Lett.**97**, 012001,(2006).
38. N. Ishii, S. Aoki and T. Hatsuda Phys. Rev. Lett. **99**, 022001 (2007).
39. T. Lin, Ch. Elster, W. N. Polyzou, H. Witała, W. Glöckle, Phys. Rev. C**78**, 024002 (2008).
40. H. Witała, J. Golak, R. Skibínski, W. Glöckle, W. N. Polyzou, H. Kamada, Phys. Rev. C**77**, 034004 (2008).


Return to top

## A Perspective from Atomic Physics

**B.D. Esry, D. Blume, and A.R.P. Rau**

The 25th anniversary of the GFB finds few-body AMO physics a very active area, with strong ties to nuclear physics, chemistry, and computational physics. The danger of writing any highlight article, though, is its subjectivity and the possibility of leaving out someone's work. On the flip side, the fact that there is so much work to choose from is just one further indication of how healthy AMO few-body physics is these days.

One force driving AMO few-body physics is a seemingly unlikely one, without immediately obvious ties to few-body systems: ultracold quantum gases. In ultracold quantum gases, AMO physics converges with nuclear physics in the Efimov effect, which is the appearance of an infinite series of three-body bound states when a two-body bound state is exactly at the dissociation threshold [1]. Further theoretical work by a number of groups has shown that the Efimov effect and related physics underlies nearly all collisions of three atoms at very low energies. In fact, the first really convincing experimental evidence of an Efimov state came in 2006 from a measurement of three-body recombination in ultracold Cs atoms by Rudi Grimm's group [2] which confirmed in rather spectacular fashion a theoretical curve published in a 1999 PRL by Esry, Greene, and Burke [3]. Ultracold quantum gases were crucial for this observation since the key parameter for the Efimov effect, the two-body *s*-wave scattering length, can be controlled experimentally and tuned to nearly any value. An equally important property of ultracold gases is the availability of relatively unambiguous diagnostic probes.

The 1999 PRL by Esry, Greene, and Burke -- along with a PRL published one week earlier by Nielsen and Macek [4] -- marked the beginning of a still-growing effort to understand ultracold three- and four-body collisions and Efimov physics. Particularly notable among the theoretical work that has come out is the 2004 prediction by Petrov, Salomon, and Shlyapnikov [5] that relaxation of diatomic molecules $FF'$ ($F$ and $F'$ are fermionic atoms) in collisions with an $F$ or $F'$ atom or another $FF'$ molecule is suppressed near a pole of the $F$-$F'$ scattering length. Since relaxation had been expected to be a substantial source of molecular loss, this result was welcome news to a large number of experimentalists who wanted to make, and have since made, $FF'$ molecules and explore the BEC-BCS crossover in ultracold atoms. And, the story is not over yet. D'Incao, Rittenhouse, Mehta, and Greene [6] have recently carried out a full four-body calculation for $FF'$+$FF'$ collisions, showing that the degree of suppression depends sensitively on collision energy, resolving some discrepancies between the Petrov *et al*. predictions and experiment.

Even though we have focused here on the AMO developments in few-body Efimov physics related to ultracold gases, the topic does draw a diverse crowd of physicists. For example, the review from Braaten and Hammer [7] gives a different, but complementary, point of view on Efimov physics and universality in ultracold three-body systems. Moreover, having started in nuclear physics, there has been more work on Efimov states and universality by nuclear physicists than can be listed here. Some of the similarities between atomic resonances and Efimov resonances in neutron-rich nuclei have been explored by Mazumdar, Rau, and Bhasin [8].

While the number of theory papers on ultracold few-body physics still outnumber experimental papers by far, the work from Grimm's group [2] showed that ultracold gases are a feasible way to study these interesting systems, and other groups are starting to take notice. The group of Minardi and Inguscio, for instance, has recently reported the first observation of an Efimov resonance in a heteronuclear system [9]. The Grimm group has also continued its work along these lines with their recent observation of an Efimov atom-dimer resonance [10]. The grapevine has several other groups working to make Efimov physics an experimental reality as well. In many ways, three-body -- and even four-body! -- physics is only becoming *more* relevant to ultracold experiments.

Of course, AMO physicists have also made substantial progress on their more traditional focus: the few-body Coulomb problem. In particular, the dynamics of three charged particles has seen considerable progress both experimentally and theoretically. The breakthrough in accuracy for low-energy electron impact ionization of H by Rescigno, Baertschy, Isaacs, and McCurdy in 1999 [11] received considerable attention and renewed interest in this benchmark system. They followed up with several other developments as have other groups. Williams, Bartlett, and Stelbovics, for instance, published a paper in 2004 [12] comparing state-of-the-art experiment and theory that showed excellent agreement. Experimentalists have really taken advantage of their kinematically complete measurement capability to image the fragments in four-body Coulomb systems [13], including in the delicate regime just above threshold [14].

In addition to studying few-body Coulomb systems via collisions, AMO physicists utilize novel light sources to interrogate these system with photons. The single photon, double ionization of He or $H_2$ is a pretty stringent test for the theoretical treatment of electron correlation. The latter especially is challenging due its two-center nature. Nevertheless, progress has been made for EUV and soft x-ray photons by Vanroose, Martin, Rescigno, and McCurdy [15] and by Colgan, Pindzola, and Robicheaux [16]. These calculations are matched by synchroton experiments that show, among other things, double slit-like interference patterns [17]. The opposite limit of multiphoton ionization by visible or IR photons is also studied. The interaction with the laser field is then very nonperturbative and can involve the exchange of tens to hundreds of photons. Even for this demanding problem, numerical solutions for He have been obtained and compared with experiment by Parker, Doherty, Taylor, Schultz, Blaga, and DiMauro [18]. Such solutions, however, are at the limit of our current capabilities.

The few-body problem is alive and well in AMO physics, with more people appreciating the unique challenges they present as well as the rich physics they contain.

1. "Energy levels arising from resonant two-body forces in a three-body system," V. Efimov, Phys. Lett. B **33**, 563 (1970).
2. "Evidence for Efimov quantum states in an ultracold gas of caesium atoms," T. Kraemer, M. Mark, P. Waldburger, J. G. Danzl, C. Chin, B. Engeser, A. D. Lange, K. Pilch, A. Jaakkola, H.-C. Nägerl, and R. Grimm, Nature **440**, 315-318 (2006).
3. "Recombination of three atoms in the ultracold limit," B.D. Esry, C.H. Greene, and J.P. Burke, Jr., Phys. Rev. Lett. **83**, 1751 (1999).
4. "Low-Energy Recombination of Identical Bosons by Three-Body Collisions," E. Nielsen and J.H. Macek, Phys. Rev. Lett. **83**, 1566 (1999).
5. "Weakly Bound Dimers of Fermionic Atoms," D. S. Petrov, C. Salomon, and G. V. Shlyapnikov, Phys. Rev. Lett. **93**, 090404 (2004).
6. "Dimer-dimer collisions at finite energies in two-component Fermi gases," J. P. D'Incao, S. T. Rittenhouse, N. P. Mehta, and C. H. Greene, arXiv:0806.3062 (2008).
7. "Universality in few-body systems with large scattering length," E. Braaten and H. W. Hammer, Phys. Rep. **428**, 259 (2006).
8. "Efimov States and their Fano Resonances in a Neutron-Rich Nucleus," I. Mazumdar, A.R.P. Rau, and V.S. Bhasin, Phys. Rev. Lett. **97**, 062503 (2006).

9. "Observation of heteronuclear atomic Efimov resonances," G. Barontini, C. Weber, F. Rabatti, J. Catani, G. Thalhammer, M. Inguscio, and F. Minardi, arXiv:0901.4584 (2009).
10. "Observation of an Efimov-like trimer resonance in ultracold atom-dimer scattering," S. Knoop, F. Ferlaino, M. Mark, M. Berninger, H. Schöbel, H.-C. Nägerl, and R. Grimm, Nature Phys. **5**, 227 (2009).
11. "Collisional Breakup in a Quantum System of Three Charged Particles," T. N. Rescigno, M. Baertschy, W. A. Isaacs, and C. W. McCurdy, Science **286**, 2474 (1999).
12. "Threshold Electron-Impact Ionization Mechanism for Hydrogen Atoms," J. F. Williams, P. L. Bartlett, and A. T. Stelbovics, Phys. Rev. Lett. **96**, 123201 (2006).
13. "Three-dimensional imaging of atomic four-body processes," M. Schulz, R. Moshammer, D. Fischer, H. Kollmus, D. H. Madison, S. Jones and J. Ullrich, Nature **422**, 48-50 (2003).
14. "Coulomb Four-Body Problem: Electron-Impact Double Ionization of Helium in the Threshold Regime," X. Ren, A. Dorn, and J. Ullrich, Phys. Rev. Lett. **101**, 093201 (2008).
15. "Complete Photo-Induced Breakup of the $H_2$ Molecule as a Probe of Molecular Electron Correlation," W. Vanroose, F. Martin, T. N. Rescigno, and C. W. McCurdy, Science **310**, 1787 (2005).
16. "Triple Differential Cross Sections for the Double Photoionization of $H_2$," J. Colgan, M.S. Pindzola, and F. Robicheaux, Phys. Rev. Lett. **98**, 153001 (2007).
17. "Interference in the Collective Electron Momentum in Double Photoionization of $H_2$," K. Kreidi, D. Akoury, T. Jahnke, Th. Weber, A. Staudte, M. Schöffler, N. Neumann, J. Titze, L. Ph. H. Schmidt, A. Czasch, O. Jagutzki, R. A. Costa Fraga, R. E. Grisenti, M. Smolarski, P. Ranitovic, C. L. Cocke, T. Osipov, H. Adaniya, J. C. Thompson, M. H. Prior, A. Belkacem, A. L. Landers, H. Schmidt-Böcking, and R. Dörner, Phys. Rev. Lett. **100**, 133005 (2008).
18. "High-Energy Cutoff in the Spectrum of Strong-Field Nonsequential Double Ionization," J. S. Parker, B. J. S. Doherty, K. T. Taylor, K. D. Schultz, C. I. Blaga, and L. F. DiMauro, Phys. Rev. Lett. **96**, 133001 (2006).

Return to top

## Some Hot Topics in Nuclear Physics

**Ch. Elster, R.J. Furnstahl, and U. van Kolck**

Few-body physics is experiencing a resurgence in nuclear physics as well as atomic physics, generated by a combination of new ideas and methods that exploit increased computational capabilities. Here we mention a few of the topics that have excited the nuclear community. We do not attempt to give a complete list but rather pick out some highlights.

There is now an enhanced appreciation of the role a large scattering length plays in few nucleon systems. Of special interest is its connection to the more general Efimov physics that manifests itself also in atomic systems (e.g. near Feshbach resonances) and in particle physics (hidden charm systems like the X(3872)) [see contributions above]. These ideas are currently being extended to halo nuclei, in which a subset of nucleons behaves as a coherent core, and only a few nucleons "orbiting" this core at anomalously large radii. Thus, the problem reduces effectively to a few-body system with unequal mass particles.

Halo/cluster nuclei like $^6$He and the Hoyle state of carbon, which can be viewed as a system of three alpha clusters, are of general interest because they test the limits of our understanding of nuclear binding. These nuclei have astrophysical implications and are targets of many experimental programs worldwide. The lightest of these nuclei can be calculated with ab initio methods, which can then be in principle matched to the effective few-body methods.

Ab initio methods for calculating structure and reactions of nuclei (stable as well as unstable) are in fact one of the current main thrusts of the nuclear theory community. Exact few-body calculations, traditionally performed by solving Faddeev- or Faddeev-Yakubovsky-type equations, have been extended to nuclei with about twelve nucleons (and even beyond for closed-shell nuclei) with various methods based on Monte Carlo techniques, diagonalization in a harmonic oscillator basis, or coupled cluster methods. Realistic two-nucleon interactions fail to give the right spectroscopy at the 10% level, and the frontier is now on the incorporation of consistent three-body forces, which can be constructed using effective field theory (EFT).

An EFT provides systematic, model-independent approximations to the underlying dynamics that are valid in a well-defined but limited regime. Its predictions are organized in terms of an expansion parameter that is typically the ratio of two physical scales. For large scattering systems, an EFT with fermions and contact interactions is particularly powerful in highlighting universal aspects of the physics. Thus for nuclear phenomena at very low energies, where the pion is a heavy degree of freedom, the EFT is the same as for dilute gases of cold atoms.

For more general applications to nuclear physics, the pion is a long-distance degree of freedom. The associated chiral EFT is manifestly consistent with the underlying theory of strong interactions, and can be used to extrapolate lattice QCD data to a realistic pion mass. We have witnessed extraordinary success in the calculation of nuclear observables in lattice simulations, and this method holds the promise of determining low-energy parameters that cannot easily be isolated experimentally, such as the isospin 3/2 component of the three-nucleon force present in the unbound three-neutron system and the lambda-nucleon force that governs the structure of hyper-nuclei. We are thus on the verge of understanding the structure of light nuclei directly from QCD, one of the fundamental goals of nuclear physics.

Return to top