Exploiting Universality
in Atoms with Large Scattering Lengths

Final Progress Report

for a grant from the

US Department of Energy

August 1 2005 – July 31 2010

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The focus of this research project was atoms with scattering lengths that are large compared to the range of their interactions and which therefore exhibit universal behavior at sufficiently low energies. Recent dramatic advances in cooling atoms and in manipulating their scattering lengths have made this phenomenon of practical importance for controlling ultracold atoms and molecules. This research project was aimed at developing a systematically improvable method for calculating few-body observables for atoms with large scattering lengths starting from the universal results as a first approximation. Significant progress towards this goal was made during the five years of the project.

I published 3 review articles describing research supported by this project. In 2006, Hammer and I published a review article in Physics Reports entitled *Universality in Few-body Systems with Large Scattering Length*. It was a thorough review of universality in such systems in atomic and molecular physics and in nuclear and particle physics. This 132-page review has had a large impact, having already been cited more than 200 times. In 2007, Hammer and I wrote an abridged version (44 pages) entitled *Efimov Physics in Cold Atoms*, which was published in Annals of Physics and focused on applications to atomic physics systems consisting of three identical bosons. In 2008, I wrote another review article with Kusunoki and Zhang entitled *Scattering Models for Ultracold Atoms*, which was also published in Annals of Physics.

I published 3 papers in Physical Review Letters describing research supported by this project. These papers were all related to ultracold atoms with large scattering lengths. In a 2008 paper, Platter and I showed how some universal relations for fermionic atoms with two spin states that were discovered by Shina Tan could be rederived using the operator product expansion of quantum field theory. In a 2009 paper, Hammer, Kang, Platter and I presented the first universal predictions for the 3-body recombination rate of fermionic atoms with three spin states. In a 2010 paper, Kang, Platter, and I used the operator product expansion to derive universal relations for the rf spectroscopy of fermionic atoms with two spin states.

I published 7 papers in Physical Review A describing research supported by this project. I will only describe three of these papers, all of which were related to ultracold atoms with large scattering lengths. In a 2006 paper with Hammer, we introduced the Efimov parameters a_* (or a_- or a_+, which differ from a_* by universal numerical constants) and η_*. These parameters have been universally adopted by experimentalists to analyse atom loss features related to Efimov physics. In a 2008 paper with Hammer, Kang, and Platter, we calculated the universal 3-body recombination rate for identical bosons with a large positive scattering length at temperatures up to 100 times the binding energy of the shallow dimer. This paper demonstrated that universal predictions need not be limited to phenomena near threshold. In a 2010 paper with Hammer, Kang, and Platter, we carried out a thorough analysis of Efimov physics for fermionic ^{6}Li atoms with three spin states. Our results played an instrumental

role in the first direct production of Efimov trimers through rf spectroscopy.

One postdoc and two students were supported by this grant. Lucas Platter was supported as a postdoc from 2007 to 2009. He was a coauthor on 6 of the published papers listed below. He moved on to a postdoc position at the University of Washington and is now an Assistant Physicist at Argonne National Laboratory. Dongqing Zhang was supported as a graduate research assistant from 2005 to 2007. He was a coauthor on 3 of the published papers listed below. The title of his Ph.D. thesis was *Aspects of cold bosonic atoms with a large scattering length*. After receiving his Ph.D. in fall 2007, Zhang moved on to a postdoc position in the medical school at Ohio State University and is now on the faculty at Colorado State University. Daekyang Kang was supported as a graduate research assistant from 2007 to 2010. He was a coauthor on 5 of the published papers listed below. Kang received his Ph.D. in fall 2011 and is now a postdoc at MIT.

Students and postdocs supported by the grant

- **Lucas Platter**, postdoc
  supported December 2007 – August 2009
- **Dongqing Zhang**, graduate student
  supported January 2005 – March 2007
  Ph.D. in fall 2007
- **Daekyang Kang**, graduate student
  supported October 2007 – November 2010
  Ph.D. in fall 2011

Publications resulting from the grant

- *Universality in Few-body Systems with Large Scattering Length*, E. Braaten and H.-W. Hammer, Physics Reports **428**, 259 (2006) [arXiv:cond-mat/0410417].
- *Factorization in Break-up and Recombination Processes for Atoms with a Large Scattering Length*, E. Braaten and D. Zhang, Physical Review A **73**, 042707 (2006) [arXiv:cond-mat/0501510].
- *Resonant Dimer Relaxation in Cold Atoms with a Large Scattering Length*, E. Braaten and H.-W. Hammer, Physical Review A **75**, 052710 (2007) [arXiv:cond-mat/0610116].
- *Efimov Physics in Cold Atoms*, E. Braaten and H.-W. Hammer, Annals of Physics **322**, 120-163 (2007) [arXiv:cond-mat/0612123].

- *Universality Constraints on Three-Body Recombination for Cold Atoms: from ^4He to ^{133}Cs*, E. Braaten, D. Kang, and L. Platter, Physical Review A **75**, 052714 (2007) [arXiv:cond-mat/0612601].

- *Condensates of Strongly-interacting Atoms and Dynamically Generated Dimers*, E. Braaten and D. Zhang, Physical Review A **75**, 063624 (2007) [arXiv:cond-mat/0703308].

- *Scattering Models for Ultracold Atoms*, E. Braaten, M. Kusunoki, and D. Zhang, Annals of Physics **323**, 1770 (2008) [arXiv:0709.0499 [cond-mat]].

- *Three-Body Recombination of Identical Bosons with a Large Positive Scattering Length at Nonzero Temperature*, E. Braaten, H.-W. Hammer, D. Kang, and L. Platter, Physical Review A **78**, 043605 (2008) [arXiv:0801.1732 [cond-mat]].

- *Exact Relations for a Strongly-interacting Fermi Gas from the Operator Product Expansion*, E. Braaten and L. Platter, Physical Review Letters **100**, 205301 (2008) [arXiv:0803.1125 [cond-mat]].

- *Universal Relations for a Strongly-interacting Fermi Gas near a Feshbach Resonance*, E. Braaten, D. Kang, and L. Platter, Physical Review A **78**, 053606 (2008) [arXiv:0806.2277 [cond-mat]].

- *Three-body Recombination of Fermionic Atoms with Large Scattering Lengths*, E. Braaten, H. W. Hammer, D. Kang, and L. Platter, Physical Review Letters **103**, 073202 (2009) [arXiv:0811.3578 [cond-mat]].

- *How the Tail Wags the Dog in Ultracold Atoms*, E. Braaten, Physics **2**, 9 (2009).

- *Efimov Physics in ^6Li Atoms*, E. Braaten, H. W. Hammer, D. Kang, and L. Platter, Physical Review A **81**, 013605 (2010) [arXiv:0908.4046 [cond-mat.quant-gas]].

- *Short-Time Operator Product Expansion for rf Spectroscopy of a Strongly-* interacting Fermi Gas, E. Braaten, D. Kang, and L. Platter, Physical Review Letters **104**, 223004 (2010) [arXiv:1001.4518 [cond-mat.quant-gas]].