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Juris Ulmanis

Heteronuclear Efimov Scenario in Ultracold Quantum Gases

Universality in Systems with Large Mass Imbalance

Doctoral Thesis accepted by
Heidelberg University, Heidelberg, Germany

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"Everything must be made as simple as possible. But not simpler."

— Albert Einstein

Supervisor's Foreword

One, two, three,..., many. This naïve extrapolation trying to deduce the properties of complex systems from the well-known structure of their fundamental constituents is every reductionist's nightmare. Any attempt to construct the world from its fundamental pieces fails already at the simplest level, namely systems consisting of more than two mutually interacting particles. Prime examples of our limited understanding of three-body systems are the celestial dynamics of three massive objects, which elude a practically applicable analytical solution of the seemingly simple Newtonian equations of motion, as shown by Poincaré in the late 19th century, or the magnetic moment of the proton, consisting of only three quarks, the value of which still cannot be predicted from first principles despite its first accurate determination by Stern and Frisch more than eighty years ago.

Given the difficulties of properly describing the structure and dynamics of systems of three particles, it came as a surprise when, in 1970, the young Russian nuclear scientist Vitalii Efimov claimed that he had analytically solved the quantum mechanical three-body problem for particles interacting via pairwise resonant forces. Not only did he find an infinite series of bound states for the three particles, even for effectively repulsive interactions where two particles would not bear a single bound state—a rather counterintuitive feat, but he also predicted that all properties of this system, e.g., energy levels, wavefunctions etc., were governed by simple geometric relations independent of the specific nature of the particles involved. Due to its universal assumptions, his model could be applied to any system of three particles, be it nucleons, atoms, or other resonantly interacting particles. In a recent publication, Efimov himself characterizes the developments following his theoretical discovery as "from questionable to pathological to exotic to a hot topic," thus describing probably every theorist's dream for the fate of their prediction. In fact, soon after the first seminal papers by Efimov had been published, other theorists tried hard to prove Efimov wrong, but instead, they had to finally admit that his findings appeared to be right. Over decades, scientists sought appropriate systems to experimentally realize Efimov's scenario, ranging from halo states of atomic nuclei to molecular trimers such as He_3. Despite heroic efforts by many groups, no evidence of the predicted universal scaling could actually be found in any of these systems.

With the development of advanced techniques to cool and trap atoms at ultralow temperatures, combined with the exquisite control over their mutual interactions, resonances following Efimov's predicted universal behavior were finally observed at the University of Innsbruck ten years ago. In their experiment Rudi Grimm and coworkers used a gas of cesium atoms at temperatures in the sub-microkelvin range in combination with magnetically tuned interactions via so-called Feshbach resonances. This first discovery was followed by a plethora of experimental confirmations by several groups worldwide, accompanied by theoretical investigations of an ever increasing level of sophistication. It is fair to say that, due to these breathtaking developments within the last decade, "Efimov Physics" has been established as a emerging new field of modern quantum physics, as confirmed by series of conferences and the still rising number of publications on this topic.

However, observing an entire series of Efimov resonances, with the universal, purely geometric scaling as predicted by Efimov, was considered impossible because the size of the first excited Efimov trimer spans micrometer distances with a binding energy corresponding to only nanokelvin temperatures. Among the many theoretical predictions following the first discovery, however, was the anticipation that the universal scaling, and thus the size of the Efimov trimer and its vulnerability to thermal collisions, would be strongly reduced by choosing a three-body system consisting of two different atomic species with a large mass difference. The only condition was that these atoms had to also interact via resonant two-body forces. In his thesis work presented here, Juris Ulmanis actually observed such an entire series of Efimov states using an ultracold mixture of lithium and cesium, which happens to provide two Feshbach resonances with favorable complementary properties. This lucky situation, combined with Juris Ulmanis' exceptional scientific skills, allowed him to directly deduce the universal scaling factor, a major hallmark of Efimov Physics, and to investigate in great detail the interplay between universal and microscopic system-specific behavior in the Efimov scenario for systems with large mass imbalance.

Juris Ulmanis' thesis is truly remarkable, not only due to its outstanding scientific outcomes, but also in the clarity and pedagogical quality of its presentation. The first chapter provides a concise introduction to the field by placing Efimov Physics into a wider scientific context, thus being easily accessible to a nonspecialist. The second chapter is devoted to the discussion of tunable two-body interactions, using the specific example of lithium and cesium to explain the fundamental features of Feshbach resonances and their characterization. In the third chapter, the general concept of the Efimov scenario is introduced and then applied to the specific lithium–cesium case. The highlight of this chapter is the first observation of subsequent Efimov resonances in the mixed ultracold lithium–cesium gas. The fourth chapter addresses deviations from universality due to short-range effects. The key element here is the application of a Born–Oppenheimer approximation, well known from basic molecular physics, to the three-body problem of two heavy atoms and one light atom, which provides a particularly clear and intuitive picture of the heteronuclear Efimov Physics for systems with large mass imbalance. The favorable features of the Feshbach resonances then allowed a study of the influence of the effective cesium interactions on the Efimov resonances.

It is fair to conclude that our understanding of the Efimov scenario has been promoted to a new level through this work. Supervising students like Juris Ulmanis makes life as a scientist really enjoyable, and I hope that readers of this book experience a similar pleasure in being introduced to the realm of Efimov Physics.

Heidelberg, Germany
November 2016

Prof. Matthias Weidemüller

Abstract

The quantum mechanical three-body problem is of fundamental importance in many areas of atomic, molecular, and nuclear physics. It is a central building block in theories describing strongly interacting many-body systems and indispensable for our understanding of one of the oldest questions in quantum mechanics, namely, to what extent microscopically different physical systems can be described by the same fundamental laws of quantum mechanics. Universal and nonuniversal aspects of three-body physics in a system consisting of two heavy and one light particles that interact via resonant forces is the main topic of this thesis. The obtained results for the first time reveal that a class of atomic and nuclear three-body systems behave identically, marking an important step toward our understanding of fundamental few-body theories, as well as enabling future studies of exotic quantum matter in extreme conditions.

In order to explore the properties of the quantum mechanical three-body problem under well-controlled conditions, we used a mass-imbalanced mixture of ultracold bosonic ^{133}Cs and fermionic ^{6}Li atoms as a prototypical system. An experimental apparatus for the creation of quantum degenerate gases was constructed. Using radio frequency association of weakly bound LiCs molecules and additional atom-loss spectroscopy, we precisely determined two-body interaction properties between Li and Cs atoms at low collision energies. The analysis with a coupled channels calculation yielded precise singlet and triplet electronic ground state molecular potential curves, from which scattering lengths and positions of Fano–Feshbach resonances were extracted. These results represent almost a tenfold improvement over the previous determination, and can be used as a starting point for any future endeavor that builds on precise understanding of Li-Cs microscopic interactions. The achieved precision is also important for modeling and interpretation of three-body physics in the Li-Cs-Cs system.

The Efimov scenario is a quintessential quantum three-body effect of three resonantly interacting particles. By exploring its bizarre and sometimes counter-intuitive properties, we strived to understand the essence of universal three-body physics. In this scenario, three particles, for our system one Li atom and two Cs atoms, bind together in an infinite number of different bound states even though none of the individual pairs can be bound. Its further hallmark is universal, purely geometric scaling of all the relevant system's parameters, such as binding energies and wavefunctions, independent of the specific nature that governs the underlying pairwise interactions. During this thesis, we observed a series of three consecutive Efimov resonances for the first time in any system studied so far, using a Li-Cs Feshbach resonance to tune the Li-Cs scattering length via external magnetic field. The experimentally measured scaling confirmed the predictions from the universal theory, but also showed minor deviations from it. In the following experiments the unbound Cs pair was replaced with a bound one, which had not been done previously. Surprisingly, the resulting Efimov scenario was independent of molecular forces that govern chemical binding of atoms into molecules—the binding of the three atoms was purely quantum mechanical and the three-body system became truly universal. In this regime it would not matter if one used atoms or nucleons with the same mass ratios and interactions. Furthermore, these experiments showed that the Efimov scenario itself is severely modified by the same change of the fundamental nature of the Cs-Cs bond. Careful comparison with two theoretical models, which used either pairwise zero-range or Lennard-Jones model potentials to describe the binary interactions, quantified the regimes in which the Li-Cs-Cs system obeyed universal three-body physics and identified van der Waals interaction between the Cs atoms as a significant source of the observed departures from universality.

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A special thanks goes to Selim Jochim for becoming my thesis referee and being my advisor. His persistent and adhesive enthusiasm for physics and the habit of asking tricky questions about the nature and our research was invaluable during all the stages of my work in Heidelberg.

My studies and research were immensely enhanced by the interconnected academic framework, in which I was proud to participate. I thank DAAD for providing me with a stipend and excellent opportunities to meet and connect with great people from all over the world, and HGSFP and IMPRS-QD for their financial support and for outstanding seminars and various kinds of events, which altogether made my time as a graduate student in Heidelberg and Germany remarkable.

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Juris Ulmanis

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