mgr Jacek Gębala
j.gebala@uw.edu.pl

Warsaw, 02.06.2026

Rada Naukowa Dyscypliny Nauki Fizyczne
Uniwersytetu Warszawskiego

Three-body physics of ultracold gases: theory of weakly bound quantum states in strongly interacting systems

Summary

The thesis "Three-body physics of ultracold gases: theory of weakly bound quantum states in strongly interacting systems" investigates few-body quantum physics in ultracold atomic gases and atom-ion mixtures, with a particular focus on the role of finite-range interactions and the breakdown of universal Efimov physics in the presence of realistic interparticle potentials.

The first part of this thesis comprises four chapters that introduce the few-body physics of ultracold gases. The first chapter reviews significant experimental and theoretical developments in ultracold physics over the past 25 years. The second chapter examines the emergence of ultracold three-body systems as a fundamental platform for addressing a wide range of physical problems. Chapter three presents a theoretical overview of the quantum three-body problem. The fourth chapter expands upon this discussion by emphasizing universal behavior in quantum phenomena, such as the Efimov effect and the universal properties of three-body observables.

The second part of the thesis, in the fifth chapter, describes ion-atom systems near Feshbach resonances. By calculating the bound and scattering properties of a three-body system, the thesis shows that long-range atom-ion interactions cause strong deviations from universal predictions based on short-range or van der Waals models. In these ionic systems, inelastic decay channels are suppressed, which leads to lower recombination rates and longer lifetimes of Efimov states than in neutral systems. The results also reveal a dense spectrum of long-lived triatomic molecular ion states, showing that atom-ion mixtures are a promising platform for studying non-universal few-body physics driven by long-range forces.

The third part of the thesis, in the sixth chapter, examines neutral three-body systems near Feshbach resonances with varying widths. By studying homonuclear bosonic systems, it is shown that the Efimov spectrum exhibits non-universal behavior for narrow resonances ($s_{\mathrm{res}} < 1$). This happens because an effective repulsive interaction appears in the atom-dimer channel, changing both the ground and excited Efimov states. The results highlight that short-range physics, exchange interactions, and van der Waals forces all play important roles in whether universal Efimov scaling applies. As an example, ^{7}Li in the $|F = 1, m_F = 0\rangle$ state is studied showing how a smaller resonance width increases non-universal effects.

The seventh chapter describes in detail the constraints on numerical calculations of three-body observables. Some of these limitations can be attributed to two-body physics, while others stem from intrinsic numerical effects, which influence the convergence of three-body potentials. The final chapter presents a summary of the results along with an outlook for future research.

In summary, this thesis demonstrates that deviations from universality in Efimov physics occur naturally in real systems due to finite interaction ranges and resonance properties. Both ion-atom and narrow-resonance atomic systems provide distinct opportunities to investigate the boundaries of universal three-body theory, revealing a more intricate structure of few-body quantum states than predicted by idealized models.