論文内容の要旨

論文題目：Few-body physics in ultracold ^{6}Li gases with tunable interactions

（相互作用可変な冷却 ^{6}Li 原子気体を用いた少数多体系の研究）

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1 Background

The strength of two-body interaction in ultracold atoms, which is characterized by scattering length a, can be tuned by means of Feshbach resonances. This tunability of the interactions provides numerous experimental applications not only in two-body physics but also in many-body physics such as the so called BEC-BCS crossover physics and unitary Fermi gases. Recently, researchers in the field of ultracold atomic physics have found that the ultracold atoms with tunable interactions also offer an excellent testing ground to investigate few-body physics, especially the so-called Efimov physics. The Efimov states are universal trimer states in a three-body system with resonant short-range interactions and characterized only by the two-body scattering lengths for each pair of particles and a three-body parameter fixed by short-range physics. Since the first experimental evidence of the Efimov state was observed in an ultracold cesium gas, general properties of few-body systems near unitarity such as the universal scaling laws were confirmed in many ultracold atomic systems, and the ultracold atomic systems have been attracting attention as the first systems in which the Efimov effect was unambiguously observed.

2 Motivation

We focus on an ultracold mixture of Fermionic ^{6}Li atoms in the three lowest hyperfine states $|F, m_F\rangle = |1/2, 1/2\rangle$, $|1/2, -1/2\rangle$ and $|3/2, -3/2\rangle$, which we label as $|1\rangle$, $|2\rangle$, and $|3\rangle$, respectively. The interaction strengths in all three two-body scattering channels in these three hyperfine states can be widely tuned by applying an external magnetic field owing to the Feshbach resonances. Some previous experiments indirectly indicate the existence of the Efimov trimer states in the three-component mixture of ^{6}Li and the magnetic-field dependence of the Efimov trimer binding energy spectrum was predicted by the Efimov's universal theory. Inspired by these theoretical and experimental works, we have pursued to determine the Efimov spectrum in this system experimentally.

3 Atom-dimer recombination in a three-component mixture of ^{6}Li

To evaluate the theoretical prediction of the Efimov spectrum based on the universal theory, we measured the recombination loss in an ultracold atom-dimer mixture of atoms $|1\rangle$ and dimers $|23\rangle$. In our setup, degenerate Fermi gases of ^{6}Li atoms in the two lowest hyperfine states $|1\rangle$ and $|2\rangle$ were prepared by employing an all-optical production method. The atom-dimer mixtures were prepared by using multiple stages of adiabatic rapid passage and magnetic field sweep. From the recombination loss measurement at the various magnetic field values, we found two loss maxima near 602 G and 685 G (Fig.1). They can be attributed to the crossings between the atom-dimer threshold and two (ground and first excited) Efimov states. The observed loss peak positions show considerable deviations from the universal predictions, which cannot be explained by finite-temperature effects or finite-range corrections to the two-body physics. To explain the observed loss spectrum, a phenomenological non-universal model with an energy-dependent three-body parameter was needed (red solid curve in Fig.1).

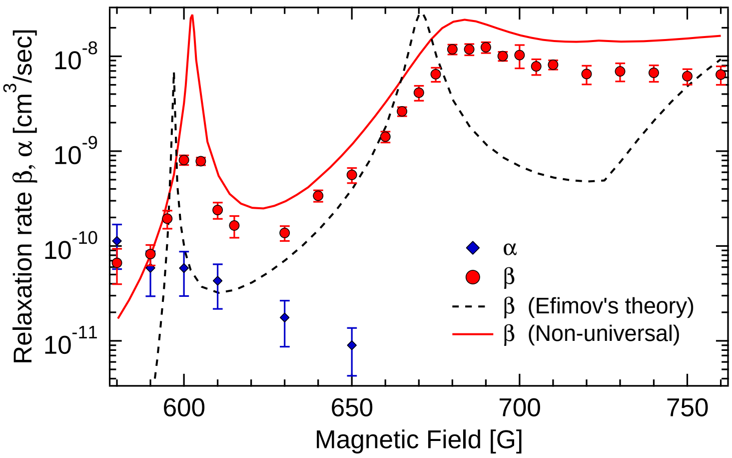

Fig. 1 Magnetic-field dependence of the atom-dimer loss rate β (red circles) and dimer-dimer loss rate α (blue diamonds) in a mixture of atoms $|1\rangle$ and dimers $|23\rangle$. The black dashed and the red solid curves show calculated β based on Efimov's universal theory and our non-universal model, respectively.

4 Measurement of an Efimov trimer binding energy in a ^{6}Li mixture

In order to assess the validity of our phenomenological non-universal model, we measured the binding energy of an Efimov state via radio-frequency (RF) association in the three-component mixture of ^{6}Li atoms. We prepared an atom-dimer mixture of atoms $|2\rangle$ and dimers $|12\rangle$, and then associate them to Efimov trimers by applying an RF magnetic field pulse. By taking the RF spectra at varying temperature, it is found that the observed RF association dip shifts with temperature (Fig.2) and the temperature shift can be made negligible at the lowest temperature in our experiment ($\sim$70 nK). Our lowest temperature measurements reveal that the binding energy of the Efimov states is smaller than both of the universal theory predictions and our phenomenological non-universal model (Fig.3). Our results suggest a

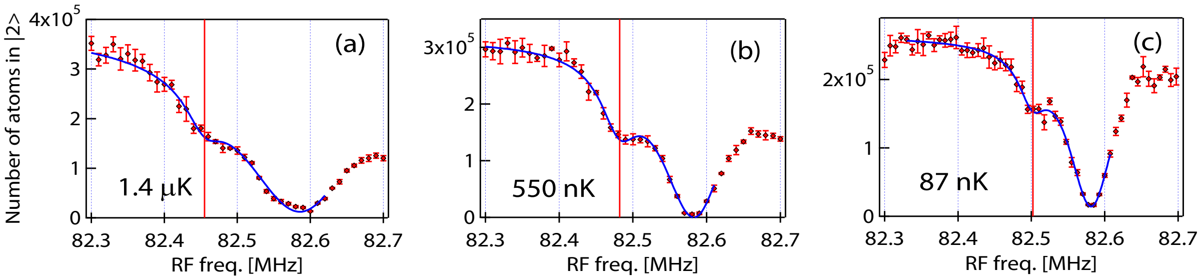

Fig. 2 A typical temperature dependence of the RF association spectra. The data were taken at 705 G at the temperature of (a) 1.4 μK, (b) 550 nK, and (c) 87 nK. The Efimov association peak position (vertical red line) shifts as temperature changes due to the thermal energy distribution.

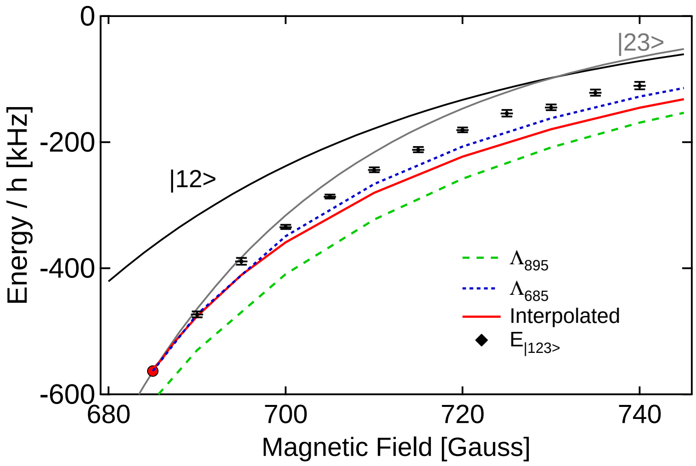

Fig. 3 Magnetic-field dependence of the measured binding energies of Efimov trimer states (black diamond). The blue dotted, the green dashed, and the red solid curves indicate the calculated binding energy based on constant three-body parameters Λ_{685}, Λ_{895}, and a monotonic energy-dependent three-body parameter, respectively.

peculiar variation of the effective three-body parameter which sets the trimer binding energy in zero-range models. This new information on the non-universal Efimov physics of three-component ^{6}Li constitutes a new challenge for few-body theories.

5 Conclusion

In this thesis, we determined the binding energy of the Efimov states in the three-component mixture of ^{6}Li atoms at two magnetic field values via atom-dimer loss measurement. We also measured the binding energy of an excited-state Efimov trimer by RF association over a range of magnetic field of 50 G. Since our spectroscopic data are expanded from two points to a continuous range, we can now clearly discuss the deviations from the universal theory. Thus this work provided not only another evidence of the Efimov states in ultracold atomic systems, but also the first conclusive evidence of the non-universal behavior of the atomic Efimov states near the Feshbach resonances.