Measurement of an Efimov trimer binding energy in a three-component mixture of $^6\text{Li}$

Shuta Nakajima, Munekazu Horikoshi, Takashi Mukaiyama, Pascal Naidon, and Masahito Ueda
1Department of Physics, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
2ERATO Macroscopic Quantum Control Project, JST, 2-11-16 Yayoi, Bunkyo-ku, Tokyo 113-8656, Japan
3Center for Frontier Science and Engineering and Institute for Laser Science, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan.

(Dated: June 13, 2018)

The binding energy of an Efimov trimer state was precisely determined via radio-frequency association. It is found that the measurement results significantly shift with temperature, but that the shift can be made negligible at the lowest temperature in our experiment. The obtained trimer binding energy reveals a significant deviation from the nonuniversal theory prediction based on a three-body parameter with a monotonic energy dependence.

About forty years ago, V. Efimov predicted that the existence of universal trimer states known as the Efimov states, in a three-body system with resonant short-range interactions [1]. Such universal states are characterized only by the two-body scattering lengths for each pair of particles and a three-body parameter fixed by short-range physics. Owing to magnetic Feshbach resonances [2], ultracold atomic systems turned out to be the first systems where the Efimov effect was observed conclusively. Since the first experimental evidence in an ultracold cesium gas [3], the two-body scattering lengths for each pair of particles and the notable discrepancies in properties of the Efimov trimers not only at particular points, but also over a continuous range of the magnetic field. The measured energies reported in [16] are seemingly in very good agreement with the predictions of our phenomenological model [13]. However, their measurement was done at a temperature of $1 \mu K$ which can shift the resonance of the RF spectroscopy on the order of 30 kHz [16]. To precisely determine the three-body parameter from the binding energy measurement, it is important to take into account the temperature effect in the RF spectroscopy.

In this Letter, we report on the measurements of the binding energy of the Efimov trimer state and the precise determination of the three-body parameter. In particular, we observed the temperature dependence of the RF spectrum, and found a resonance shift with temperature. Operating at lower temperature to eliminate this shift, we found that the measured energies significantly deviate from those of Ref. [16] and the previous predictions [13]. Refining the model to fit these measurements, we obtain a non-monotonic energy dependence of the three-body parameter $\Lambda$.

We use a mixture of fermionic $^6\text{Li}$ atoms in the lowest three 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. Because of their fermionic nature, only distinguishable particles interact via s-wave scattering, i.e., pair interactions are described by three different two-body scattering lengths $a_{12}$, $a_{23}$ and $a_{31}$, which diverge at 834 G, 811 G, and 690 G respectively due to Feshbach resonances. These three broad and overlapping Feshbach resonances allow us to precisely tune all three scattering lengths simultaneously via magnetic field. At first, we create a degenerate Fermi gas of $^6\text{Li}$ atoms in the two lowest hyperfine states $|1\rangle$ and $|2\rangle$ as described in detail in [17]. Then we

The binding energy of an Efimov trimer state was precisely determined via radio-frequency association. It is found that the measurement results significantly shift with temperature, but that the shift can be made negligible at the lowest temperature in our experiment. The obtained trimer binding energy reveals a significant deviation from the nonuniversal theory prediction based on a three-body parameter with a monotonic energy dependence.

About forty years ago, V. Efimov predicted that the existence of universal trimer states known as the Efimov states, in a three-body system with resonant short-range interactions [1]. Such universal states are characterized only by the two-body scattering lengths for each pair of particles and a three-body parameter fixed by short-range physics. Owing to magnetic Feshbach resonances [2], ultracold atomic systems turned out to be the first systems where the Efimov effect was observed conclusively. Since the first experimental evidence in an ultracold cesium gas [3], the two-body scattering lengths for each pair of particles and the notable discrepancies in properties of the Efimov trimers not only at particular points, but also over a continuous range of the magnetic field. The measured energies reported in [16] are seemingly in very good agreement with the predictions of our phenomenological model [13]. However, their measurement was done at a temperature of $1 \mu K$ which can shift the resonance of the RF spectroscopy on the order of 30 kHz [16]. To precisely determine the three-body parameter from the binding energy measurement, it is important to take into account the temperature effect in the RF spectroscopy.

In this Letter, we report on the measurements of the binding energy of the Efimov trimer state and the precise determination of the three-body parameter. In particular, we observed the temperature dependence of the RF spectrum, and found a resonance shift with temperature. Operating at lower temperature to eliminate this shift, we found that the measured energies significantly deviate from those of Ref. [16] and the previous predictions [13]. Refining the model to fit these measurements, we obtain a non-monotonic energy dependence of the three-body parameter $\Lambda$.

We use a mixture of fermionic $^6\text{Li}$ atoms in the lowest three 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. Because of their fermionic nature, only distinguishable particles interact via s-wave scattering, i.e., pair interactions are described by three different two-body scattering lengths $a_{12}$, $a_{23}$ and $a_{31}$, which diverge at 834 G, 811 G, and 690 G respectively due to Feshbach resonances. These three broad and overlapping Feshbach resonances allow us to precisely tune all three scattering lengths simultaneously via magnetic field. At first, we create a degenerate Fermi gas of $^6\text{Li}$ atoms in the two lowest hyperfine states $|1\rangle$ and $|2\rangle$ as described in detail in [17]. Then we
evaporatively cooled the atoms with a population ratio of \(|1⟩ : |2⟩ = 1 : 2 \sim 1 : 4\) at 834 G, and adiabatically ramped down the magnetic field to 685 G-740 G in 300 ms. At this field ramp, |12⟩ dimers, which were formed from associating states |1⟩ and |2⟩, were adiabatically formed and excess atoms in |2⟩ still remained in the trap. In this way, we obtained a mixture of |2⟩ atoms and |12⟩ dimers.

In our experiment, temperature was controlled by changing the depth of the optical trap. For the measurement at high temperatures (\(T > 500\) nK), we used a single-beam optical trap with a beam waist of 33 µm (we call this a “tight trap”). For measurements at lower temperatures (\(T < 500\) nK), we used a large-volume hybrid magnetic/optical trap with an effective beam waist of 300 µm (“shallow trap”). The trap frequencies for the tight (shallow) trap were approximately given by \(\omega_x/2\pi = 67\sqrt{P}\) Hz (54 Hz), \(\omega_y/2\pi = 52\sqrt{P}\) Hz (44 Hz) and \(\omega_z/2\pi = \sqrt{0.26B + 0.20P}\) Hz (\(\sqrt{0.31B}\) Hz) in the \(x, y\) and \(z\) directions, respectively, where \(P\) is the power of the optical dipole trap in mW and \(B\) is the strength of the magnetic field in Gauss. The laser power for the tight trap was varied between 80 and 660 mW, which corresponds to a temperature from 500 nK to 2 \(\mu\)K. The total number of atoms in state |2⟩ before creating dimers was \(10^6 - 10^8\) depending on the final temperature.

Figure 1 (a) represents the energy levels and transitions related to the RF association of trimers. We started from a mixture of |2⟩ atoms and |12⟩ dimers at the fields of interest and applied an RF field at frequencies around the transition from |2⟩ to |3⟩. We applied the RF fields to the atom-dimer mixture for 30 ms (highest temperature) – 300 ms (lowest temperature) using an antenna designed to be resonant at 80 MHz. The Rabi frequency was 7 kHz for the \(|2⟩-|3⟩\) transition at 705 G. After RF-pulse we performed state-selective absorption imaging at 834 G, and counted the number of atoms in |2⟩ after dissociating |12⟩ dimers.

Figure 1 (b) shows a typical RF spectrum taken at 700 G at the temperature of 70 nK. The central dip (B) at \(\nu_t\) corresponds to the bare atomic transition between |2⟩ and |3⟩. The width of the transition reflects the inelastic collision rate between |3⟩ atoms and |12⟩ dimers. The left dip (A) at \(\nu_t\) corresponds to the association to Efimov trimers. Association occurs when the detuning from the bare atomic transition \(\Delta\nu = \nu_0 - \nu_t\) matches to the difference between the |12⟩ dimer binding energy \(E_b^{12}\) and the trimer binding energy \(E_f^{123}\), i.e. \(\nu_t = \nu_0 - E_f^{123}/h + E_b^{12}/\tau\), where \(h\) is Planck’s constant. The right dip (C) is the signal from the dissociation of |12⟩ dimers. The location of the bare atomic transition and the dip of the Efimov association were determined by fitting the data with a double-Lorentzian function, \(N(\nu) = N_0 - A_0/[1+(\nu-\nu_0)^2/(G_0/2)^2] - A_1/[1+(\nu-\nu_1)^2/(G_1/2)^2]\). The free parameters are amplitude, position and width of the free-free transition \((A_0, \nu_0, G_0)\) and those of trimmer association dips \((A_1, \nu_1, G_1)\), and offset \(N_0\).

When the kinetic energies of the atoms and dimers are on the same order as the resolution of the RF spectroscopy, we need to take into account the resonance shift due to finite temperature effects. Figures 2 (a)-(c) show the temperature dependent RF spectra taken at 705 G. We can clearly see that the dip of the Efimov resonance shifts to the left as the temperature increases. Here we estimate the temperature of the cloud from the time-of-flight images of |2⟩ atoms at zero magnetic field. The magnetic field was turned off simultaneously with the optical trap to suddenly eliminate the interaction between atoms and dimers, and the expansion of |2⟩ atoms reflects the temperature of the cloud. Although \(T/T_F\) is around 0.5 at the lowest \(T_F\) is the Fermi temperature of the trapped system, the collisional energy distribution remains close to a Boltzmann distribution.

Figure 2 (d) shows the temperature dependence of the Efimov resonance location measured from the bare atomic transition \(\nu_0 - \nu_t\) at 695 G, 705 G and 715 G. We found that
the shift due to temperature below 1.5 μK is well described by 1.5k_BT (dashed lines) as expected from the Boltzmann distribution [20]. It is also expected that the slope of the temperature dependence becomes smaller when \( k_BT/\hbar \) is comparable with the transition linewidth. A change in the slope can be seen at around 1.5 μK in Fig. 2(d), which seems to suggest that the linewidth of the Efimov trimer state in this magnetic field region is roughly 1.5 μK/30 kHz, which is consistent with the fitting result of \( \Gamma_r \). The density of the |2⟩ atoms is \( 1 \times 10^{11} \text{ cm}^{-3} \) for the shallow trap (data point for \( T < 0.5 \mu K \)) and \( 2 \times 10^{12} \text{ cm}^{-3} \) for the tight trap. We estimate that the resonance shifts due to collisions between trimers and atoms or dimers are negligible in the shallow trap corresponding to the low temperature measurements. In the tight trap, we noticed a shift of the bare atomic transition resonance on the order of 10(2) kHz, which is within the accuracy of our measurement.

Note that the measurement in [16] and our data points around 1 μK in Fig. 2(d) are consistent. However, since there is a non-negligible shift due to the temperature effect as shown in the present measurement, we need to extrapolate the plot in Fig. 2(d) toward zero temperature to extract the actual binding energy from the RF spectra.

Figure 3(a) shows the magnetic-field dependence of the binding energy divided by \( \hbar \). All data points were taken at 70 nK. The binding energy of the trimer is given by \( E_{123} = E_{12}^{|2⟩} + (\hbar \nu_0 - \hbar \nu_1) \), where \( E_{12}^{|2⟩} \) is the binding energy of the |12⟩ dimer from coupled-channel equations using singlet and triplet potentials for \(^6\text{Li} \) [21]. The separation between the Efimov association dip and atom resonance become smaller as the magnetic field increases. To resolve these two resonances, we made the bare atomic transition narrower by reducing the number of dimers. Since the linewidth of the bare atomic transition is determined by the inelastic collision rate of \( |3⟩ \) atoms with |12⟩ dimers, reducing the number of |12⟩ dimers makes the atomic resonance narrower and helps separate the Efimov resonance from the atomic resonance. Above 715 G where the Efimov resonance frequency gets closer to the atomic resonance, we used unbalanced atom-dimer mixtures whose population ratio is about |12⟩ : |2⟩ \( \sim 1 : 3 \). We confirmed that changing the population ratio does not change the position of the association dips. In this way, we were able to determine the binding energy of Efimov trimers up to 740 G [23]. We could not observe an association dip at and below 685 G. This is consistent with the previous atom-dimer loss experiments [13, 14] in which the dimer-trimer meeting point was observed at 685 G.

In previous works [13, 15], we showed that the universal model cannot accurately describe the trimer because the dimer binding energy is already off by 8 % from its universal behaviour. Taking into account the non-universal two-body behaviour using energy-dependent scattering lengths, we determined the two values of the three-body parameter \( \Lambda_{685} \) and \( \Lambda_{895} \) which reproduce the observed dimer-trimer meeting point at 685 G [13, 14], and the trimer dissociation point at 895 G [12], respectively. These two values are not consistent and lead to two different trimer energy curves indicated by the blue dotted and green dashed curves in Fig. 3. This lead us to the conclusion that the three-body parameter \( \Lambda \) must vary, presumably with energy. We made an interpolation of \( \Lambda \), leading to the trimer energy curve indicated by the red solid curve in Fig. 3. Fortuitously, the trimer energy reported in [16] from 1 μK measurements agree with this interpolated curve. However, our new data do not follow this curve, and suggest a more complicated variation of \( \Lambda \).

It should be noted that the value of \( \Lambda \) is very sensitive to the two-body model, in particular the uncertainty of the scattering length. For example, the experimental uncertainties of dimer binding energy of \( \sim2 \text{ kHz} \) at 720 G reported in [22] gives an uncertainty of at most \( \sim 0.7 \% \) in the scattering length, but it can cause a 5 % variation of \( \Lambda \). As such, the value of \( \Lambda \) per se is not so meaningful. As long as the deviation of the scattering length in our model from the real one is a smooth nearly-constant shift, the energy dependence of the three-body parameter shows the same behavior. Therefore we can investigate the variation of \( \Lambda \).
temperature measurements reveal that the binding energy physics of three-component models. This new information on the non-universal Efimov parameter which sets the trimer binding energy in zero-range interactions of such as the observations of loss minima in atom-dimer mix-
sociation at very low temperature (\(\leq 70\) nK). Our lowest temperature measurements reveal that the binding energy of the Efimov states is smaller than expected. Our results suggest a 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. A full understanding of the Efimov spectrum will provide quantitative explanations for other experiments on the three component mixtures of \(^6\)Li such as the observations of loss minima in atom-dimer mix-
tures of \([12]\) and \([3]\) \([14]\), which have received so far only qualitative \([25]\) or phenomenological \([15]\) explanations.

We thank A. Wenz, T. Lompe, Y. Castin and L. Pricoupenko, P. S. Julienne, E. Tiesinga and A. Simoni for useful discussions. This work was supported by KAKENHI (22340114, 22103005), Global COE Program “the Physical Sciences Frontier” and the Photon Frontier Network Program, MEXT, Japan. S.N. acknowledges support from the Japan Society for the Promotion of Science.

\[\begin{align*}
\Lambda &\text{ Three-body parameter} \\
\text{Energy/h [kHz]} &\text{dependence of } \Lambda \text{ to reproduce the trimer energy for each experimental point. The resulting variation of } \Lambda \text{ is indicated by black diamonds in Fig. 4. Curiously enough, the vari-}
\end{align*}\]

In summary, we have measured the binding energy of an Efimov state by RF association in a three-component mixture of \(^6\)Li atoms. We found that the observed RF association dip shifts with temperature and performed our as-
mixture of \(^6\)Li constitutes a new chal-
genge for few-body theories. A full understanding of the Efimov spectrum will provide quantitative explanations for other experiments on the three component mixtures of \(^6\)Li such as the observations of loss minima in atom-dimer mix-
tures of \([12]\) and \([3]\) \([14]\), which have received so far only qualitative \([25]\) or phenomenological \([15]\) explanations.

We thank A. Wenz, T. Lompe, Y. Castin and L. Pricoupenko, P. S. Julienne, E. Tiesinga and A. Simoni for useful discussions. This work was supported by KAKENHI (22340114, 22103005), Global COE Program “the Physical Sciences Frontier” and the Photon Frontier Network Program, MEXT, Japan. S.N. acknowledges support from the Japan Society for the Promotion of Science.

\[\begin{align*}
\Lambda &\text{ Three-body parameter} \\
\text{Energy/h [kHz]} &\text{dependence of } \Lambda \text{ to reproduce the trimer energy for each experimental point. The resulting variation of } \Lambda \text{ is indicated by black diamonds in Fig. 4. Curiously enough, the vari-}
\end{align*}\]

In summary, we have measured the binding energy of an Efimov state by RF association in a three-component mixture of \(^6\)Li atoms. We found that the observed RF association dip shifts with temperature and performed our as-
mixture of \(^6\)Li constitutes a new chal-
genge for few-body theories. A full understanding of the Efimov spectrum will provide quantitative explanations for other experiments on the three component mixtures of \(^6\)Li such as the observations of loss minima in atom-dimer mix-
tures of \([12]\) and \([3]\) \([14]\), which have received so far only qualitative \([25]\) or phenomenological \([15]\) explanations.

We thank A. Wenz, T. Lompe, Y. Castin and L. Pricoupenko, P. S. Julienne, E. Tiesinga and A. Simoni for useful discussions. This work was supported by KAKENHI (22340114, 22103005), Global COE Program “the Physical Sciences Frontier” and the Photon Frontier Network Program, MEXT, Japan. S.N. acknowledges support from the Japan Society for the Promotion of Science.

\[\begin{align*}
\Lambda &\text{ Three-body parameter} \\
\text{Energy/h [kHz]} &\text{dependence of } \Lambda \text{ to reproduce the trimer energy for each experimental point. The resulting variation of } \Lambda \text{ is indicated by black diamonds in Fig. 4. Curiously enough, the vari-}
\end{align*}\]