Universal three-body parameter in ultracold 4He*

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I. INTRODUCTION

When the short-range interaction between particles gives rise to (near-)resonant scattering, few-body properties are expected to become universal, i.e., irrespective of the precise nature of the interaction and therefore applicable to nucleons, atoms, or molecules [1]. Within universal few-body physics a hallmark prediction is the Efimov effect, in which three particles that interact via a resonant short-range attractive interaction exhibit an infinite series of three-body bound states, even in the regime where the two-body interaction does not support a bound state [2]. The first experimental evidence of Efimov trimers came from an ultracold trapped gas of atoms [3] by tuning the strength of the interaction via a Feshbach resonance [4]. In the context of ultracold atoms, the universal regime is realized when the s-wave scattering length $a$, characterizing the two-body interaction in the zero-energy limit, is much larger than the characteristic range of the interaction potential. Signatures of Efimov states are imprinted on trap loss caused by three-body recombination, which typically determines the lifetime of an ultracold trapped atomic gas or Bose-Einstein condensate. So far, observations of Efimov features have been made in ultracold quantum gases of bosons: $^7$Li [5–7], $^{39}$K [8], $^{85}$Rb [9], Cs [3,10,11], a three-spin component mixture of fermionic $^6$Li [12–14], and the Bose-Bose mixture $^4$K + $^8$Rb [15].

In addition to the scattering length, a three-body parameter (3BP) is needed to fully describe the spectrum of Efimov trimers. The 3BP accounts for all the short-range information that is not contained in the scattering length, including a true three-body interaction. It can be parametrized as the location of the first Efimov resonance, $a_\ast$, on the $a < 0$ side of a Feshbach resonance. Initially, the 3BP was thought to be very sensitive to details of the short-range interaction and therefore different for each (atomic) system [16]. However, experiments around different Feshbach resonances and with different alkali-metal atoms found the ratio $a_\ast$/$r_{vdW}$ in a narrow range between 8 and 10 [5,9,11], where $r_{vdW}$ = $(mC_6/h^2)^{1/4}$ is the range of the tail of the two-body potential (also called the van der Waals length), with $m$ the atomic mass and $C_6$ the long-range coefficient. There is a vivid theoretical debate on the physical origin of this universal 3BP [17–22]. Most work points towards a three-body repulsive barrier that prevents the three atoms from probing the short-range interaction. An important question is how general the universal 3BP is. Experimental data outside the group of alkali-metal atoms could shed light on this issue.

In this paper we investigate the possibility of extracting the 3BP from our recently measured three-body loss rate coefficient in a Bose-Einstein condensate (BEC) of metastable triplet helium-4 (denoted as $^4$He$^*$) [23]. We will show that its value is consistent with those measured in alkali-metal systems, providing further experimental evidence of a universal 3BP. We will also discuss other atomic systems that can be analyzed in a similar fashion. The common feature is that in the absence of a Feshbach resonance, these atomic systems already have a scattering length that is much larger than the range of the potential. The mechanism for this is an almost resonant interaction potential, i.e., a bound state is almost degenerate with the collision threshold. This potential resonance is a simple single-channel effect. In contrast, a Feshbach resonance is a multichannel effect, where the width of the resonance introduces another length scale [4], which may give rise to nonuniversal physics. Therefore, potential resonances are more directly related to the universal description connected to a large scattering length than Feshbach resonances.

II. THREE-BODY LOSS IN ALKALI METALS

To relate our work to the alkali-metal experiments, we first summarize how the 3BP is extracted from three-body loss measurements around a Feshbach resonance [1,3]. In the limit of $|a| \gg r_{vdW}$ the three-body loss rate coefficient $L_3$ for identical bosons is given by

$$L_3 = 3C_\pm(a) \frac{\hbar a^4}{m},$$  

(1)

where $C_\pm(a)$ are dimensionless prefactors that depend on $a$. Here we assume that three atoms are lost from the trap in the event of three-body recombination. The scattering length $a$ is tuned by a magnetic field from $a > 0$ to $a < 0$ through...
resonance. The prefactors are given by

$$C_+(a) = 67.1 e^{2 \eta_+} \left[ \cos^2 \left( s_0 \ln a/a_+ \right) + \sin^2 \eta_+ \right] + 16.8 \left( 1 - e^{-4 a_+} \right)$$

(2)

and

$$C_-(a) = \frac{4590 \sin(2 \eta_-)}{\sin^2 \left( s_0 \ln a/a_- \right) + \sin^2 \eta_-},$$

(3)

respectively. On top of a strong $a^2$ scaling, $L_3$ shows, as a function of $a$, a series of resonances for $a < 0$ and minima for $a > 0$, and the locations of these Efimov features are determined by $a_+$ and $a_-$. The parameters $\eta_\pm$ are related to the decay of the trimers into atom-dimer pairs and provide a width to the Efimov features. Experimentally $a_\pm$ and $\eta_\pm$ are obtained by fitting Eqs. (2) and (3) to the measured $L_3$ spectrum as a function of $a$. For identical bosons $s_0 = 1.06624$, such that $C_+(a) = C_+(22.7a)$, and therefore $a_+$ and $a_-$ are defined only within a factor 22.7, $n$ being an integer. Universal theory requires a single 3BP and therefore the Efimov features for $a > 0$ and $a < 0$ are related, namely, via the relation $a_+/a_- = 0.96(3)$ [1]. A nonuniversal 3BP would manifest itself as random scatter of $|a_\pm|$ values in a range between 1 and 22.7 for different systems. However, the ratio $|a_-|/r_{vdW}$ was found in a narrow range between 8 and 10 for experiments with different alkali-metal atoms [5,9,11,18], indicating a universal 3BP [24].

III. ANALYSIS OF THREE-BODY LOSS IN $^4$He$^*$

Recently we have measured the three-body loss rate coefficient in a $^4$He$^*$ BEC, prepared in the high-field-seeking $m = -1$ Zeeman substate, and obtained the value $L_3 = 6.5(0.4)\text{stat}(0.6)_{\text{sys}} \times 10^{-27} \text{cm}^6 \text{s}^{-1}$ [23]. For spin-polarized He$^*$ Penning ionization is strongly suppressed [25] and three-body loss dominates the lifetime of a $^4$He$^*$ BEC. Scattering of spin-polarized He$^*$ is given by the $2\Sigma^+_g$ potential, for which high-accuracy $ab\; initio$ electronic structure calculations are available [26]. For $^4$He$^*$ the $2\Sigma^+_g$ + $^4$He$^*$ this potential supports 15 vibrational states. The highest excited vibrational state is weakly bound, which gives rise to a narrow potential resonance. Its binding energy is $h \times 91.35(6) \text{ MHz}$, measured by two-photon spectroscopy [27], from which a quintet scattering length of $141.96(9) a_0$ ($a_0 = 0.05292 \text{ nm}$) was deduced, consistent with the $ab\; initio$ theoretical value of $144(4)a_0$ [26]. It is indeed much larger than the range of the potential, as $r_{vdW} = 35a_0$ [28], such that $a/r_{vdW} = 4.1$. The binding energy of this weakly bound two-body state corresponds to 4.4 mK, which is much larger than the trap depth of about 10 $\mu$K and therefore both the formed dimer and the free atom leave the trap after three-body recombination. There are no broad Feshbach resonances in $^4$He$^*$ because of the absence of nuclear spin [29].

We now consider Eq. (2) to find the set of $a_\pm$ and $\eta_\pm$ values that explains our observed value of $L_3$. Following the current convention, we present the 3BP in the form $|a_-|/r_{vdW}$ by using the universal relation $a_+/a_- = 0.96$. In the alkali-metal experiments typically $\eta_\pm \approx \eta_0$ and therefore in the following we will only use $\eta$. In Fig. 1 we show two sets of solutions of Eq. (2) that match our measured $L_3$ value, namely, $|a_-|/r_{vdW} = 2.3$ (dashed lines) and 7.7 (solid lines), for different values of $\eta$. In both cases our data point is located far outside an Efimov minimum, giving rise to a weak dependence of $\eta$ on $L_3$. That is the reason why our $L_3$ value, obtained for a single scattering length, provides information about $a_\pm$.

In Fig. 2 we show the set of solutions to Eq. (2) in $(|a_-|/r_{vdW}, \eta)$ parameter space for our value of $L_3$, represented by the black solid line, with the gray shaded area reflecting the experimental uncertainty in our measured $L_3$ value. Within the range of 1 to 22.7 for $|a_-|/r_{vdW}$, we indeed find two narrow regions of $|a_-|/r_{vdW}$ around 2 and 8, provided that $\eta$ is not too large. For $\eta = 0.1$ we find $|a_-|/r_{vdW} = 7.7(7)$ and 2.3(2). If $\eta$ becomes larger than 0.5 the Efimov minima are washed out and their location becomes undefined, giving rise to a broad range of possible $|a_-|/r_{vdW}$ values. For comparison, the 3BPs obtained from the different alkali-metal experiments are depicted by the colored symbols, with their numerical values.

FIG. 1. (Color online) Universal three-body loss curves [Eq. (2)] for $^4$He$^*$ with $|a_-|/r_{vdW} = 2.3$ (dashed lines) and $|a_-|/r_{vdW} = 7.7$ (solid lines), for different values of $\eta$, that match our measured $L_3$ value (see inset).

FIG. 2. (Color online) Graphic representation of the set of $(|a_-|/r_{vdW}, \eta)$ and $\eta$ values for which Eq. (2) matches our observed value of $L_3$, given by the black solid line, where the gray band corresponds to possible values based on our $L_3$ error bar. Also indicated are the $|a_-|/r_{vdW}$ values for the alkali-metal experiments: Cs, 8.6(2),10.2(6),9.5(8),9.5(3) [11] (red diamonds), $^7$Li 8.1(3) [5], 9.2(3) [6], 8.3(4) [7] (blue squares), $^6$Li 9.3 [30] (green circle), $^{85}$Rb 9.23(7) [9] (orange triangle), showing at the same time the observed $\eta$ parameters.
given in the caption. We expect the value of \( \eta \) for \(^4\text{He}^*\) to be similar to those found in the alkali-metal systems, since Penning ionization will play no important role in the decay mechanism of the Efimov trimers. Figure 2 shows that our value is consistent with the 3BPs found in the alkali-metal system, considering the scatter shown in the available data and our uncertainty in \( L_3 \).

In our analysis we rely on two assumptions. The first assumption is that \( a/r_{vdW} = 4.1 \) is sufficiently large for application of Eq. (2). Here we notice that the three-body loss data around a Feshbach resonance fit well for \( |a| \) larger than a few \( r_{vdW} \). Effects beyond universal theory [31–33] may be present, but are small enough not to alter our conclusion. The second assumption is that three atoms are lost for each three-body recombination event. For \( a > 0 \) additional resonances on top of the \( a^4 \) scaling have been observed in three-body loss spectra [6,8,34]. Those features are explained by secondary atom-dimer collisions that are resonantly enhanced near \( a = a_s \), where \( a_s \) is the atom-dimer Efimov resonance position [1], which effectively leads to an enhancement of the number of atoms lost in a three-body recombination event. The precise underlying mechanism, and therefore what to extract from these additional resonances, is still under debate [35–37]. Here we note that if we take \( |a|/r_{vdW} = 8 \), then \( a_s = 300a_0 \), which is far away from the actual value 142\(a_0\), such that secondary atom-dimer collisions are expected not to play a role for \(^4\text{He}^*\).

IV. OTHER SYSTEMS

There are more atomic systems with a nearby potential resonance, for which a similar analysis as that performed for \(^4\text{He}^*\) can be done once a precise measurement of \( L_3 \) becomes available. Alkali-metal atoms prepared in a spin-stretched state (i.e., electron and nuclear spin maximally aligned) scatter only in the triplet potential. Therefore alkali metals with a large triplet scattering length provide the opportunity to extract the 3BP obtained from three-body loss in the presence of a potential resonance. Two candidates are \(^{85}\text{Rb} \) \( |\alpha_T = -388(3)a_0|, r_{vdW} = 82a_0 \) and \(^{133}\text{Cs} \) \( |\alpha_T = 2440(24)a_0|, r_{vdW} = 101a_0 \). An experimental challenge is to distinguish three-body loss from two-body loss processes, such as spin relaxation and hyperfine-changing collisions, especially in the case of Cs [40].

Another group of atoms that do not possess Feshbach resonances are the alkaline-earth-metal elements and Yb. In the electronic ground state the atoms have zero electron spin and therefore there is only a single two-body potential, which is of singlet character. Furthermore, the bosonic isotopes have zero nuclear spin and two-body loss processes are completely absent. An interesting example is Ca, for which potential resonances show up for all the bosonic isotopes [41]. In the following we will discuss two isotopes of Sr and Yb, for which \( a \) is accurately known, \( a \gg r_{vdW} \), and the first three-body loss measurements in BECs have already been reported.

For \(^{86}\text{Sr} \) \( a = 798(12)a_0 \) [42], \( r_{vdW} = 75a_0 \), Stellmer et al. [43] report an upper limit of \( L_3 = 6(3) \times 10^{-24} \text{ cm}^6 \text{ s}^{-1} \), which is one order of magnitude larger than maximally allowed by Eq. (2). The authors indicate that secondary collisions, possibly enhanced by a resonance in the atom-dimer cross section, may explain this discrepancy. We note that if one tentatively assumes that the scattering length is indeed near the atom-dimer resonance, i.e., \( a_s \approx 800a_0 \), then \( a_{\ast} \approx -750a_0 \) and thus \( |a_{\ast}|/r_{vdW} \approx 10 \). This is a hint that three-body loss in \(^{86}\text{Sr} \) is consistent with the universal 3BP.

For \(^{168}\text{Yb} \) \( a = 252(3)a_0 \) [44], \( r_{vdW} = 78a_0 \), Sugawa et al. [45] report an upper limit of \( L_3 = 8.6(1.5) \times 10^{-28} \text{ cm}^6 \text{ s}^{-1} \). If we perform a similar analysis as for \(^4\text{He}^*\) we find again two solutions of \( |a_{\ast}|/r_{vdW} \). Taking the upper limit, one of the two solutions lies in a narrow range between 8 and 9. Here a smaller \( L_3 \) leads to a larger \( |a_{\ast}|/r_{vdW} \), and a value between 10 and 11 is reached when the reported \( L_3 \) value is reduced by a factor of 2. This is a strong indication that three-body loss in \(^{168}\text{Yb} \) is also consistent with the universal 3BP.

V. CONCLUSIONS

We find our measured \( L_3 \) coefficient in spin-polarized \(^4\text{He}^*\) to be consistent with the 3BP that was recently found in comparing measurements using alkali-metal atoms. We give further examples of atomic systems without a Feshbach resonance but in the presence of a nearby potential resonance for which the 3BP can be extracted from an accurately measured \( L_3 \), such as alkali-metal atoms in spin-stretched states and alkaline-earth-metal atoms. We find that the three-body loss measured in \(^{168}\text{Yb} \) strongly indicates consistency with the universal 3BP.

We provide experimental evidence for a universal 3BP, outside the alkali-metal group and in the absence of a Feshbach resonance. A universal 3BP means that short-range three-body physics is not relevant for the Efimov spectrum. This implies that not only three-body observables in the universal regime are fully determined by two-body physics, but four-body [46–48] and \( N \)-body \( (N > 4) \) [49,50] observables as well.

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