Three-body collisions for alkali atoms near Feshbach resonances

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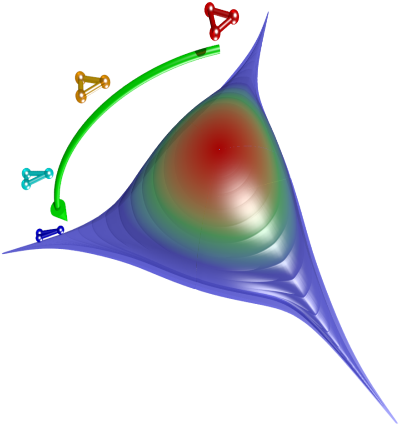


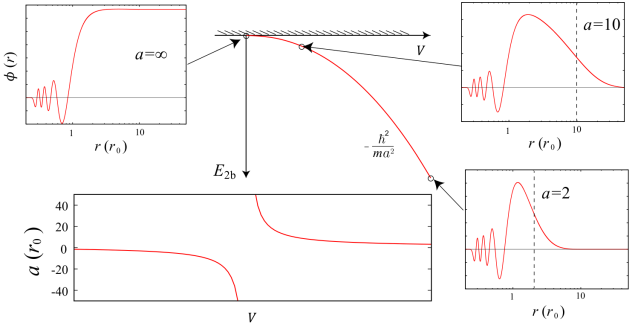
Outline

In this section

Few-body problem near unitarity

A quantum criticality → unitarity limit ($a \to \infty$)

scattering length $a = \lim_{k \to 0} - \tan \delta(k)/k$



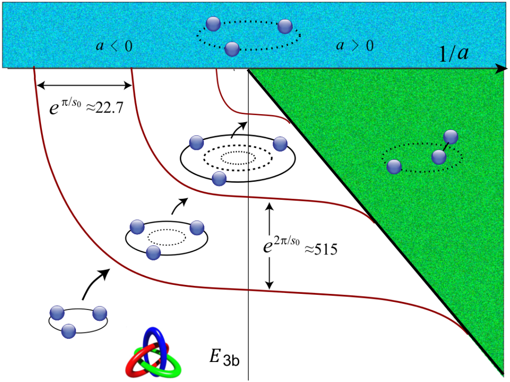
- Halo state: ^{6}He, ^{11}Li nuclei, He_3 molecule
- **Three-body Efimov effect**

The Efimov effect: if two do not bind, three would

Vitaly Efimov, 1970

Three particles with ***isotropic, short-range*** interactions form an ***infinite*** series of three-body bound states with $E_n = E_0 e^{-2n\pi/s_0}$ when $a \to \infty$ ($s_0 \approx 1.00624$) [1].

Three-body energy spectrum

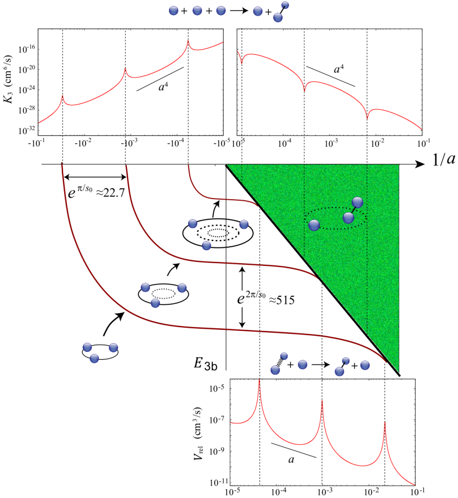


- Borromean: one leaves, all fall apart ($a < 0$)
- ∞ large state with short-range interactions
- Less states with stronger interactions ($a > 0$)

[1] Efimov, Phys. Lett. B 33, 563 (1970).

Efimov states: manifestations

Ultracold atoms ✔



First experimental observation in Cs atoms
Kraemer, *et al.* Nature (2006)

Efimov states: manifestations

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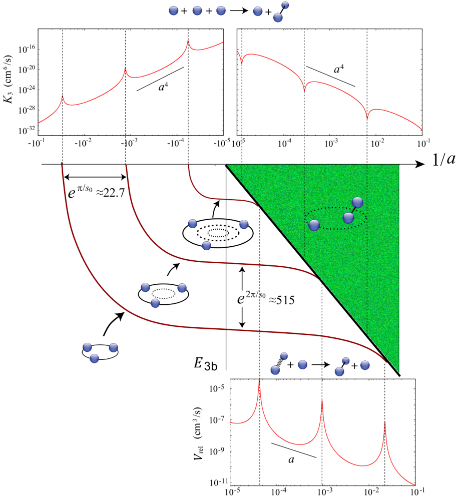

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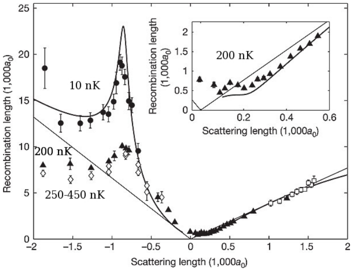

Efimov states: manifestations

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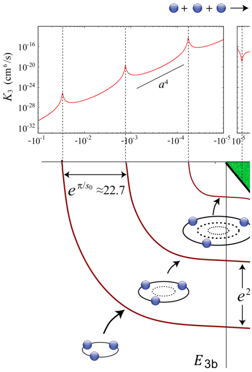

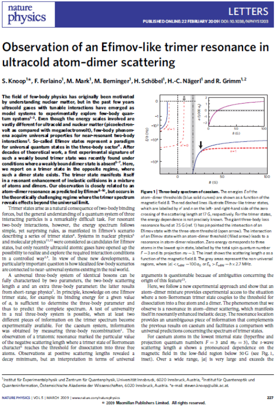

Observation of an Efimov-like trimer resonance in ultracold atom–dimer scattering

S. Knoop[1*], F. Ferlaino[1], M. Mark[1], M. Berninger[1], H. Schöbel[1], H.-C. Nägerl[1] and R. Grimm[1,2]

The field of few-body physics has originally been motivated by understanding nuclear matter, but in the past few years ultracold gases with tunable interactions have emerged as model systems to experimentally explore few-body quantum systems[1–3]. Even though the energy scales involved are vastly different for ultracold and nuclear matter (picoelectronvolt as compared with megaelectronvolt), few-body phenomena acquire universal properties for near-resonant two-body interactions[2]. So-called Efimov states represent a paradigm for universal quantum states in the three-body sector[4]. After decades of theoretical work, a first experimental signature of such a weakly bound trimer state was recently found under conditions where a weakly bound dimer state is absent[5–7]. Here, we report on a trimer state in the opposite regime, where such a dimer state exists. The trimer state manifests itself in a resonant enhancement of inelastic collisions in a mixture of atoms and dimers. Our observation is closely related to an atom–dimer resonance as predicted by Efimov[8–10], but occurs in the theoretically challenging regime where the trimer spectrum reveals effects beyond the universal limit.

Trimer states arise as a natural consequence of two-body binding forces, but the general understanding of a quantum system of three interacting particles is a remarkably difficult task. For resonant two-body interactions, however, the energy spectrum follows simple, yet surprising rules, as manifested in Efimov's scenario describing a series of trimer states[4]. Systems in nuclear physics[5] and molecular physics[11,12] were considered as candidates for Efimov states, but only recently ultracold atomic gases have opened up the possibility to realize and explore the required interaction conditions in a controlled way[1,3]. In view of these new developments, a particularly important question is how idealized few-body scenarios are connected to near-universal systems existing in the real world.

A universal three-body system of identical bosons can be fully characterized by two parameters, the two-body scattering length a and an extra three-body parameter; the latter results from short-range physics[2]. In principle, knowledge on one Efimov trimer state, for example its binding energy for a given value of a, is sufficient to determine the three-body parameter and thus to predict the complete spectrum. A test of universality in a real three-body system is possible, when at least two different pieces of information on the trimer spectrum become experimentally available. For the caesium system, information was obtained by measuring three-body recombination[1]. The observation of a triatomic resonance marked the particular value of the negative scattering length where a trimer state of Borromean character[5] reaches the threshold for dissociation into three free atoms. Observations at positive scattering lengths revealed a decay minimum, but an interpretation in terms of universal arguments is questionable because of ambiguities concerning the origin of this feature[13].

Figure 1 | Three-body spectrum of caesium. The energies E of the atom–dimer thresholds (blue solid curves) are shown as a function of the magnetic field B. The red dashed lines illustrate Efimov-like trimer states, which are labelled by n' and n on the left- and right-hand side of the zero crossing of the scattering length at 17 G, respectively. For the trimer states, the energy dependence is not precisely known. The giant three-body loss resonance found at 7.5 G (ref. 1) has pinpointed the intersection of an Efimov state with the three-atom threshold (open arrow). The intersection of an Efimov state with an atom–dimer threshold (filled arrow) leads to a resonance in atom–dimer relaxation. Zero energy corresponds to three atoms in the lowest spin state, labelled by the total spin quantum number $F=3$ and its projection $m_F=3$. The inset shows the scattering length a as a function of the magnetic field B. The grey areas represent the non-universal regions, where $|a| < r_{vdW} = 100a_0$ or $E_b > E_{vdW} = h \times 2.7$ MHz.

Here, we follow a new experimental approach and show that an atom–dimer mixture provides experimental access to the situation where a non-Borromean trimer state couples to the threshold for dissociation into a free atom and a dimer. The phenomenon that we observe is a resonance in atom–dimer scattering, which manifests itself in resonantly enhanced inelastic decay. The resonance location provides an unambiguous piece of information that complements the previous results on caesium and facilitates a comparison with universal predictions concerning the spectrum of trimer states.

For caesium atoms in the lowest internal state (hyperfine and projection quantum numbers $F=3$ and $m_F=3$), the s-wave scattering length a shows a pronounced dependence on the magnetic field in the low-field region below 50 G (see Fig. 1, inset). Over a wide range, $|a|$ is very large and exceeds the

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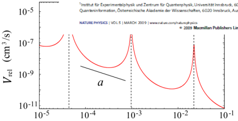

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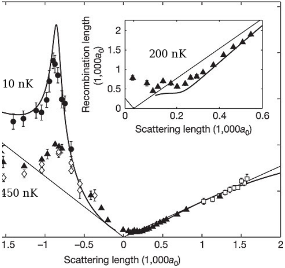
mer, *et al.* Nature (2006)



Efimov states: manifestations

Ultracold atoms ✔

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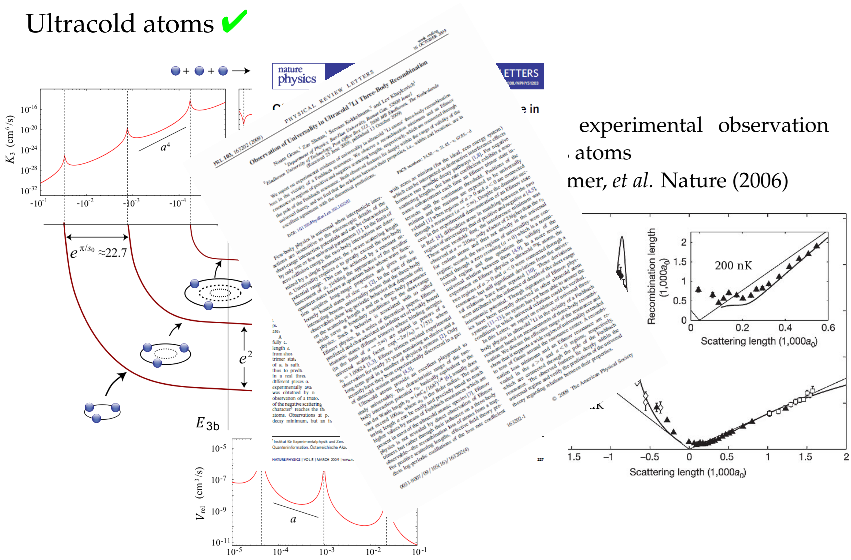

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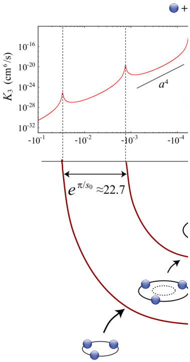

PRL 102, 165302 (2009) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2009

Three-Body Recombination in a Three-State Fermi Gas with Widely Tunable Interactions

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We investigate the stability of a three spin state mixture of ultracold fermionic ^{6}Li atoms over a range of magnetic fields encompassing three Feshbach resonances. For most field values, we attribute decay of the atomic population to three-body processes involving one atom from each spin state and find that the three-body loss coefficient varies by over 4 orders of magnitude. We observe high stability when at least two of the three scattering lengths are small, rapid loss near the Feshbach resonances, and two unexpected resonant loss features. At our highest fields, where all pairwise scattering lengths are approaching $a_t \simeq -2140a_0$, we measure a three-body loss coefficient $L_3 \simeq 5 \times 10^{-22}$ cm^6/s and a trend toward lower decay rates for higher fields indicating that future studies of color superfluidity and trion formation in a SU(3) symmetric Fermi gas may be feasible.

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Multicomponent Fermi gases with tunable interactions are exceptionally well suited to the study of few- and many-body quantum physics. Ultracold two-state Fermi gases near a Feshbach resonance have been used to characterize the crossover from Bardeen-Cooper-Schreiffer superfluidity to Bose-Einstein condensation of diatomic molecules [1]. Further, a normal to superfluid transition and phase separation have been observed in imbalanced two-state spin mixtures [2]. The stability of the two-state mixtures against two- and three-body loss processes was critically important to the success of these experiments.

Recently, there has been considerable interest in the study of three-state Fermi gases with tunable interactions [3–8]. Whereas three-body interactions in ultracold two-state Fermi gases are suppressed by the exclusion principle, the addition of a third spin component allows for the study of three-body phenomena such as the Efimov effect [7]. Further, with this additional spin state there may be competition between multiple pairing states and trion formation [3,4,6]. For example, if pairwise interactions are all attractive and of equal magnitude, the system is expected to exhibit a novel superfluid phase analogous to color superconductivity in quantum chromodynamics (QCD) [5]. A quantum phase transition to a Fermi liquid of trimers (analogous to baryons) may be observed if the ratio of the interaction energy to the kinetic energy is increased (e.g., by an optical lattice) [5].

Future studies of the above phenomena critically depend on the magnitude of two- and three-body loss rates, particularly when two or more scattering lengths are resonantly enhanced. Two- and three-body loss and heating processes can impose stringent limits on the maximum achievable phase space density. Further, the unambiguous observation of three-body resonances requires negligible two-body loss [9].

Most investigations of Fermi gases with tunable interactions have focused on two-state mixtures. A small admixture of a third spin component has been used for thermometry [10] and recently the rapid decay of a three-state Fermi gas near a Feshbach resonance was noted during an investigation of Cooper pair size by radio-frequency (rf) spectroscopy in a two-state Fermi gas [11]. Very recently our group reported measurements of three-body loss in thermal and degenerate three-state Fermi gases of ^{6}Li for magnetic fields between 400 and 960 G which included three Feshbach resonances [12]. Independently, Ottenstein *et al.* observed loss in a three-state ^{6}Li gas for field values between 0 and 750 G (including a single Feshbach resonance) and reported three-body loss rate coefficients for field values up to 600 G (excluding any pairwise scattering resonances) [13].

In this Letter, we report the first measurements of three-body loss coefficients for a three-state Fermi gas over a range of magnetic fields where pairwise interactions are resonantly enhanced. This enhancement is due to three overlapping Feshbach resonances and a zero-energy resonance in the ^{6}Li triplet molecular potential. Further, we demonstrate that all two-state mixtures of the three lowest energy hyperfine states of ^{6}Li are stable against two-body loss processes for almost the entire range of field values between 15 and 953 G, making this three-state mixture well suited to studies of three-body physics. We observe a narrow loss feature at 127 G [14] which may be due to a three-body resonance and an additional state-dependent loss feature at 504 G. Finally, we measure the three-body loss rate coefficient at high fields where all three scattering lengths are asymptoting to the triplet scattering length $a_t = -2140a_0$. This measurement and an observed trend toward lower loss at higher fields has important implications for realizing cold atom analogs of color superfluid and baryon phases in QCD.

We study a ^{6}Li Fermi gas with equal populations in the three lowest energy hyperfine states. At zero field, the three states correspond to $|1\rangle = |\frac{1}{2}, +\frac{1}{2}\rangle$, $|2\rangle = |\frac{1}{2}, -\frac{1}{2}\rangle$, and $|3\rangle = |\frac{3}{2}, -\frac{3}{2}\rangle$ in the $|f, m_f\rangle$ basis. For fields above $\simeq$200 G, these states become increasingly electron-spin

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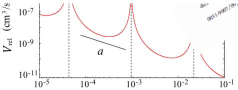

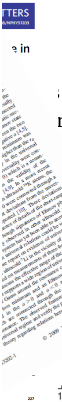

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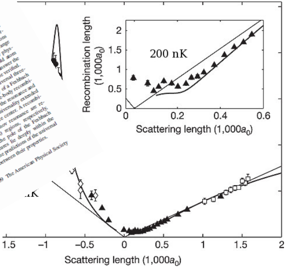
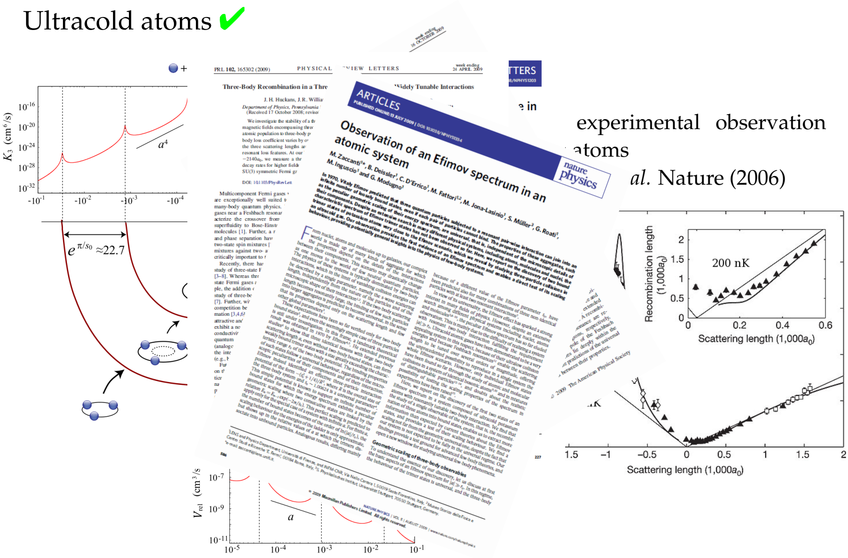


Efimov states: manifestations

Ultracold atoms ✔



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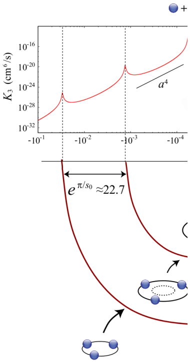
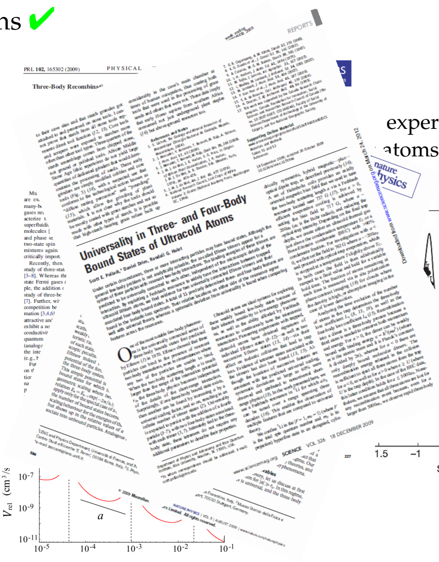
Efimov states: manifestations

Ultracold atoms ✔





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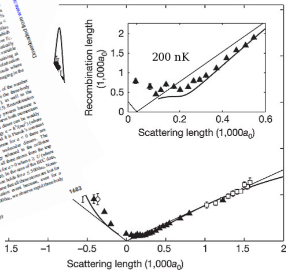

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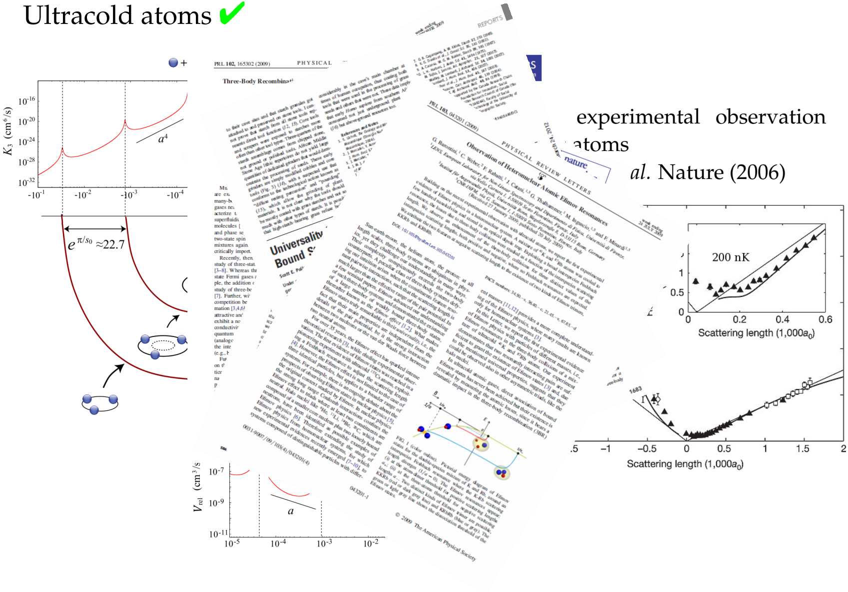

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Efimov states: manifestations

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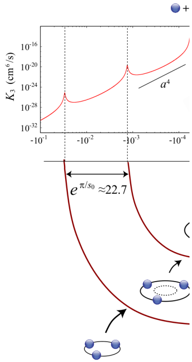

PRL 107, 120401 (2011) PHYSICAL REVIEW LETTERS week ending 16 SEPTEMBER 2011

Universality of the Three-Body Parameter for Efimov States in Ultracold Cesium

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We report on the observation of triatomic Efimov resonances in an ultracold gas of cesium atoms. Exploiting the wide tunability of interactions resulting from three broad Feshbach resonances in the same spin channel, we measure magnetic-field dependent three-body recombination loss. The positions of the loss resonances yield corresponding values for the three-body parameter, which in universal few-body physics is required to describe three-body phenomena and, in particular, to fix the spectrum of Efimov states. Our observations show a robust universal behavior with a three-body parameter that stays essentially constant.

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The concept of universality manifests itself in the fact that different physical systems can exhibit basically the same behavior, even if the relevant energy and length scales differ by many orders of magnitude [1]. Universality thus allows us to understand in the same theoretical framework physical situations that at first glance seem completely different. In ultracold atomic collisions, 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. Then the essential properties of the two-body system such as the binding energy of the most weakly bound dimer state and the dominating part of the two-body wave function can simply be described in terms of a, independent of any other system-dependent parameters. In the three-body sector, the description of a universal system requires an additional parameter, which incorporates all relevant short-range interactions not already included in a. In few-body physics, this important quantity is commonly referred to as the three-body parameter (3BP).

In Efimov's famous scenario [1,2], the infinite ladder of three-body bound states follows a discrete scaling invariance, which determines the relative energy spectrum of the states. The 3BP fixes the starting point of the ladder and thus the absolute energies of all states. The parameter enters the theoretical description as a short-range boundary condition for the three-body wave function in real space or as a high-frequency cutoff in momentum space. To determine the 3BP from theory would require precise knowledge of both the two-body interactions and the genuine three-body interactions at short range. In real systems, this is extremely difficult and the 3BP needs to be determined experimentally through the observation of few-body features such as Efimov resonances.

In the past few years, ultracold atomic systems have opened up the possibility to explore Efimov's scenario experimentally and to test further predictions of universal theory [3–14]. The key ingredient of such experiments is the possibility to control a by an external magnetic field B via the Feshbach resonance phenomenon [15]. This naturally leads to the important question whether the 3BP remains constant or whether it is affected by the magnetic tuning, in particular, when different Feshbach resonances are involved.

The current status of theoretical and experimental research does not provide a conclusive picture on possible variations of the 3BP. A theoretical study [16] points to strong possible variations when different two-body resonances are exploited in the same system, and even suggests a change of the 3BP on the two sides of a zero crossing of the scattering length. Other theoretical papers point to the importance of the particular character of the Feshbach resonance [15]. While closed-channel dominated ("narrow") resonances involve an additional length scale that may fix the 3BP [17–19], the case of entrance-channel dominated ("broad") resonances leaves the 3BP in principle open. However, predictions based on two-body scattering properties exist that apparently fix the 3BP for broad resonances as well [20–22]. The available experimental observations provide only fragmentary information. The first observation of Efimov physics in an ultracold Cs gas [3] is consistent with the assumption of a constant 3BP on both sides of a zero crossing. A later observation on ^{39}K [5] indicated different values of the 3BP on both sides of a Feshbach resonance. A similar conclusion was drawn from experiments on ^{7}Li [6], but other experiments on ^{7}Li showed universal behavior with a constant 3BP for the whole tuning range of a single resonance [7] and for another spin channel [12]. Besides these observations on

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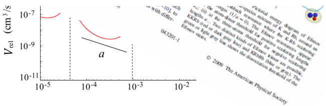

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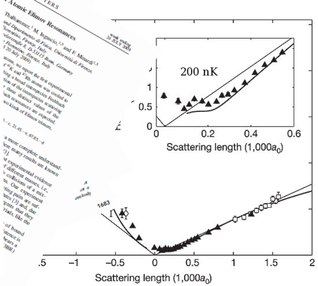
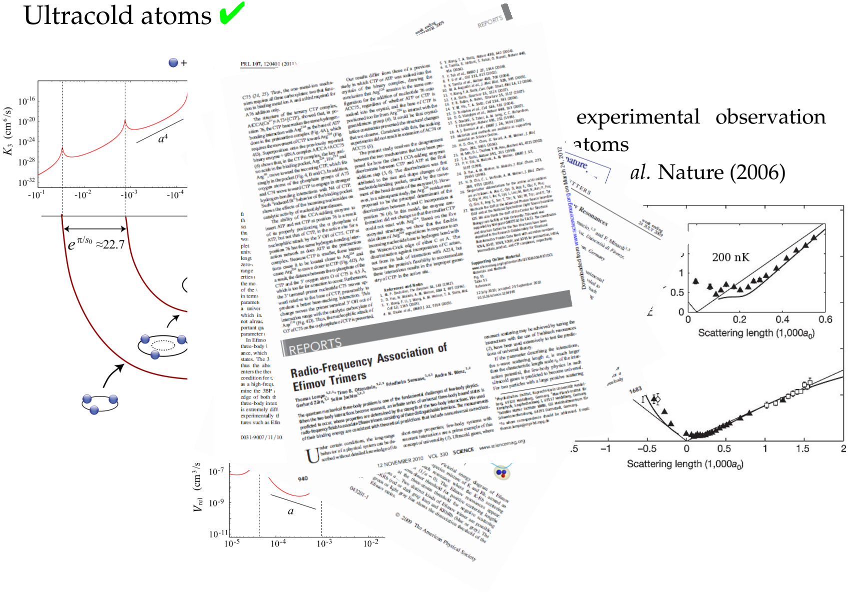


Efimov states: manifestations

Ultracold atoms ✔



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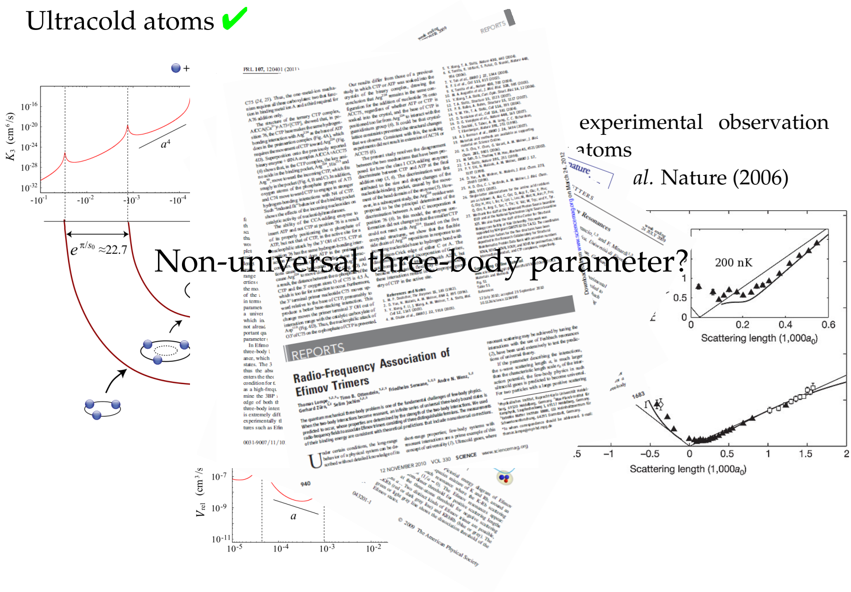
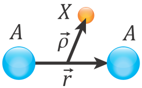


Non-universal three-body parameter?

In this section

Efimov effect in Born-Oppenheimer picture

Hyperspherical vs Born-Oppenheimer (BO)



$$\left[-\frac{1}{m_A}\nabla^2_{\boldsymbol{r}} - \frac{2m_A+m_X}{2m_Am_X}\nabla^2_{\boldsymbol{\rho}} + V_{AA}(r) + V_{AX}\left(\left|\boldsymbol{\rho}+\frac{\boldsymbol{r}}{2}\right|\right) + V_{AX}\left(\left|\boldsymbol{\rho}-\frac{\boldsymbol{r}}{2}\right|\right)\right]\Psi = E\Psi$$

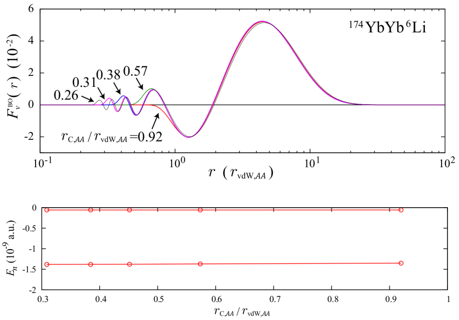
In adiabatic hyperspherical representation $\Psi = \sum_\nu F_{\nu,E}(R)\Phi_\nu(R;\Omega)$:

- Exact solution by coupling hyperradial equations for solving $F_{\nu,E}$. $(\mu R^2 = \frac{1}{2}m_Ar^2 + \frac{2m_Am_X}{2m_A+m_X}\rho^2)$

In BO approximation $\Psi = F^{\rm BO}_{\nu,E}(\boldsymbol{r})\Phi^{\rm BO}_\nu(\boldsymbol{r};\boldsymbol{\rho})$:

- Long-range Efimov behavior $U^{BO}_\nu(r) \simeq -\chi_0^2/2m_Xr^2$ ($\chi_0 \approx 0.57$).
- Short-range van der Waals behavior $U^{BO}_\nu(r) \simeq V_{AA}(r) = -C_{6,AA}/r^6$.

Efimov-favored AAX systems — universal three-body parameter



- Nodal positions in the van der Waals region are determined by a_{AA} and $r_{vdW,AA}$.
- Universal Efimov state energies independent of r_c

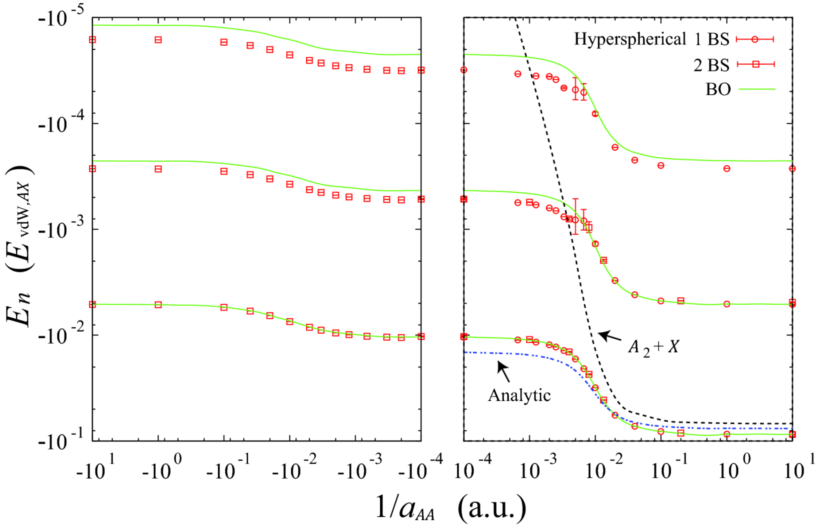
r_+ determines the ground Efimov state energy:

$E_{0,\text{analytic}} = -\frac{4}{Mr_+^2}\exp\left(-\frac{2}{s_0}\{\text{Arg}[\Gamma(1-is_0)]-\pi\}\right)$, r_+ can be found by

$$J_{-\frac{i\alpha s_0}{2}}\left(2\frac{r_{vdW,AA}^2}{r_+^2}\right)N_{-\frac{i\alpha s_0}{2}}\left(2\frac{r_{vdW,AA}^2}{r_-^2}\right)=N_{-\frac{i\alpha s_0}{2}}\left(2\frac{r_{vdW,AA}^2}{r_+^2}\right)J_{-\frac{i\alpha s_0}{2}}\left(2\frac{r_{vdW,AA}^2}{r_-^2}\right),$$

$$N_{\frac{1}{4}}\left(2\frac{r_{vdW,AA}^2}{r_-^2}\right)=\left[1-\sqrt{2}\frac{a_{AA}}{r_{vdW,AA}}\frac{\Gamma(5/4)}{\Gamma(3/4)}\right]J_{\frac{1}{4}}\left(2\frac{r_{vdW,AA}^2}{r_-^2}\right).\ (\alpha\approx 2)$$

Efimov-favored *AAX* systems — universal three-body parameter



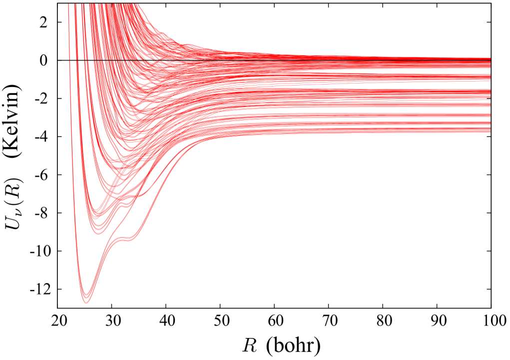
Universal Efimov spectrum for YbYbLi [1]

[1] Wang, Wang, D'Incao, and Greene, PRL (2012).

In this section

Hyperspherical potentials with nuclear spins

$$\psi = \sum_{\nu} F_\nu(R) \sum_{K,J} \phi_\nu^{J,K,\lambda}(R;\theta,\varphi) D^J_{MK}(\alpha,\beta,\gamma) \sum_{\lambda=m_{s_i},m_{i_i}} |m_{s_1} m_{s_2} m_{s_3} m_{i_1} m_{i_2} m_{i_3}\rangle$$



Hyperspherical potentials for three ^{7}Li atoms

^{7}Li atom:

- $s = 1/2, i = 3/2$
- 8 hyperfine levels $f = 1, 2$
- $\Delta E_{\text{hf}} \approx 20\text{mK}$

In the calculation:

- $|f = 1, m_f = 1\rangle$, $|f = 2, m_f = 1\rangle$
- $J = 0, 2$
- $B = 200G$

More work needs to be done for $>$ 50 spin channels.

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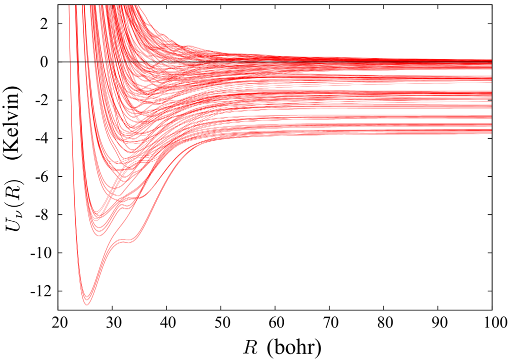

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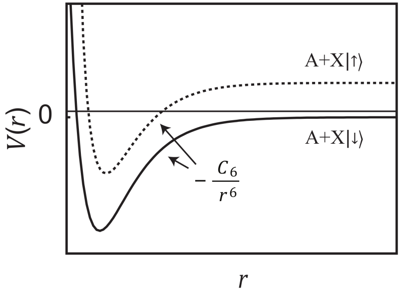
A two-channel model for $A + A + X$ two-body interactions

Two-channel model for isolated Feshbach resonances:



$$s_{res} = 2\mu_2 \delta\mu \delta B a_{\rm bg} r_{\rm vdW} / \hbar^2$$

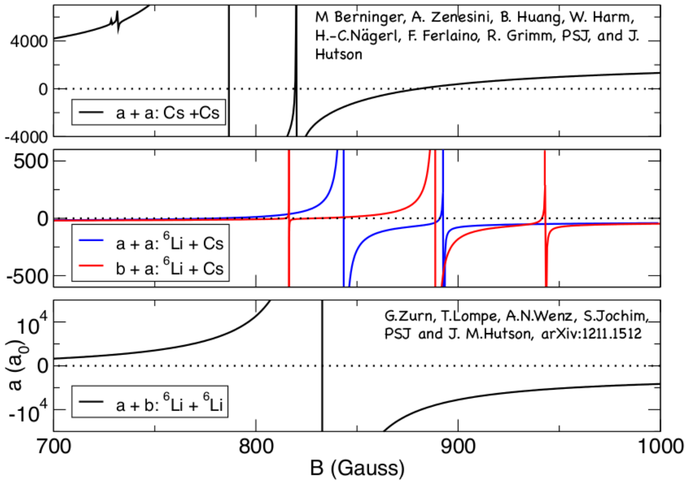
$s_{res} \gg 1$: broad resonances

$s_{res} \ll 1$: narrow resonances

Three-body in two-channel representation:

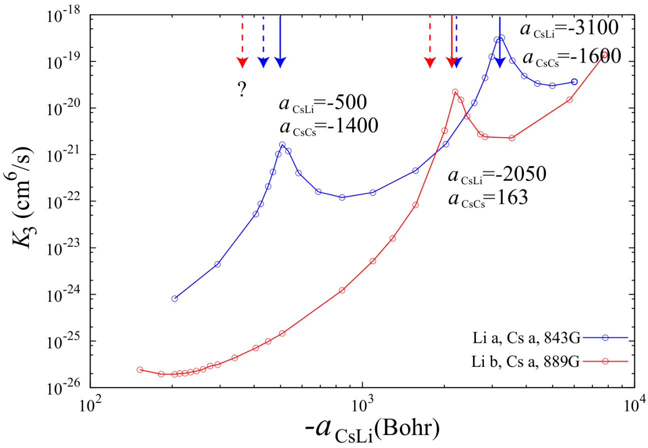
$$\left(-\frac{1}{2\mu}\frac{\partial^2}{\partial R^2} + \frac{\Lambda^2}{2\mu R^2} + V_{AA}(r_{31})\right)\psi_\alpha + \sum_{\beta=g,e;i<j} V_{\alpha\beta}(r_{ij})\psi_\beta \qquad = (E - \epsilon_\alpha)\psi_\alpha$$

Feshbach resonances in Cs+Li systems



Cs-Li broad resonances: $a_{\mathrm{bg}} \approx -29$ bohr, $\Delta_B \approx 60$G, $s_{\mathrm{res}} \approx 0.7$

Efimov resonances in Cs+Cs+Li recombination ($e^{\pi/s_0} \approx 4.9$)



No Efimov resonance is found for $|a_{\rm CsLi}| < 10^4$ near 893G (aa) and 943G (ba) narrow Cs+Li Feshbach resonances.

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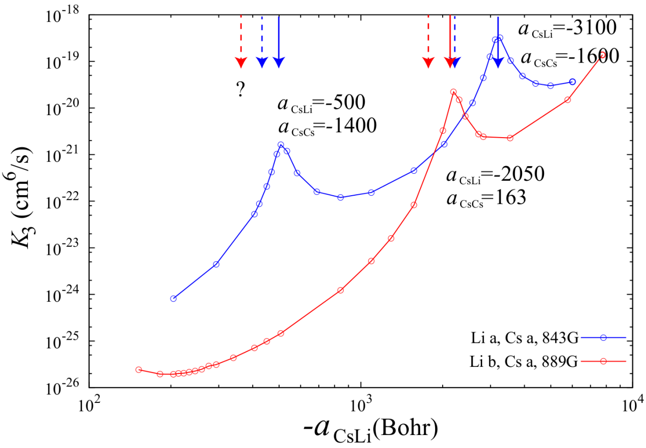

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In this section

Summary

- The three-body parameter is universal for atoms near broad Feshbach resonances.
- Three-body hyperspherical potentials are calculated by including hyperfine interactions.
- The positions of Efimov resonances are predicted in Cs-Li ultracold admixture.