Fermion Mediated Pairing in the Ruderman-Kittel-Kasuya-Yosida to Efimov Transition Regime

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The Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction and Efimov physics are two distinct quantum phenomena in condensed matter and nuclear physics, respectively. The RKKY interaction describes correlations between impurities mediated by an electron gas, while Efimov physics describes universal bound states of three particles with resonant interactions. Recently, both effects have been observed in Bose-Fermi mixtures in the weak and resonant interaction regimes, respectively. Intriguing conjectures exist to elucidate how the two phenomena meet in the transition regime where the mixture is strongly interacting. In this Letter, we explore the RKKY-Efimov transition in a mixture of bosonic ^{133}Cs and fermionic ^{6}Li near a tunable interspecies Feshbach resonance. From dispersion and relaxation measurements, we find that the transition is highlighted by a fermion-mediated scattering resonance between Cs atoms and a weaker resonance on Li atoms. These resonances represent reactive scattering of Cs and Li atoms in the many-body regime, which reduce to an Efimov resonance in the thermal gas regime. Our observation demonstrates the intriguing interplay of two-, three-, and many-body physics in a Bose-Fermi mixture that connects condensed matter physics, nuclear physics, and quantum many-body chemistry.

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Ultracold atoms are a versatile platform to explore exotic quantum phenomena across condensed matter, nuclear, and cosmological physics [1]. A key strength of cold atom systems is the precise tunability of their interactions, e.g., via Feshbach resonances [2], which enables the simulation of interactions governing other quantum systems.

A new class of mediated interactions, where particles of one species induce a force between particles of another species, have recently been realized in mixtures of atomic gases [3–8]. With tunable strength and functional form [9–12], these interactions open opportunities to simulate long-range forces in nature [13], including those underlying fundamental particles [14], superconductivity [15], and magnetic orders in materials [16–18].

Mixtures of particles with a large mass imbalance are particularly favorable for studying mediated interactions. The large mass ratio validates the Born-Oppenheimer approximation such that the light, fast moving particles induce an effective potential $V(r)$ between two heavy, slowly moving particles separated by a distance r. Light bosons and heavy fermions, for example, are best for simulating a phonon-mediated Cooper pairing in superconductors [19–24]. Meanwhile, a heavy-boson light-fermion mixture can enhance the fermion-mediated interaction. This leads to a strong Efimov potential for boson-boson-fermion three-body systems [25,26] and RKKY interactions for bosonic impurities in a degenerate Fermi gas [11].

The mixture of bosonic ^{133}Cs and fermionic ^{6}Li atoms is an excellent platform to probe the above physics. The combination has a large mass ratio of $m_{\mathrm{Cs}}/m_{\mathrm{Li}} \approx 22.1$ and features an interspecies Feshbach resonance allowing for tuning of the interspecies scattering length a_{BF} at a magnetic field where stable Cs Bose-Einstein condensates (BECs) can be created [27–29]. Because of the mass ratio enhancement, multiple Efimov states are observed near Feshbach resonances $|a_{\mathrm{BF}}| \to \infty$ [30,31]. In the weak coupling regime with $|a_{\mathrm{BF}}| \ll 1/k_{\mathrm{F}}$, where k_{F} is the Fermi wave number, RKKY-type fermion-mediated interactions between Cs atoms are observed to impact the condensate radius [3] and sound speed [7]. These works demonstrate the Efimov and RKKY effects in the resonant- and weak-interaction limits, respectively; see Fig. 1.

In the transition regime where RKKY and Efimov physics meet, the Bose-Fermi mixture is strongly interacting with the scattering length comparable to the Fermi length scale $|a_{\mathrm{BF}}| \approx 1/k_{\mathrm{F}}$. Novel quantum phenomena are

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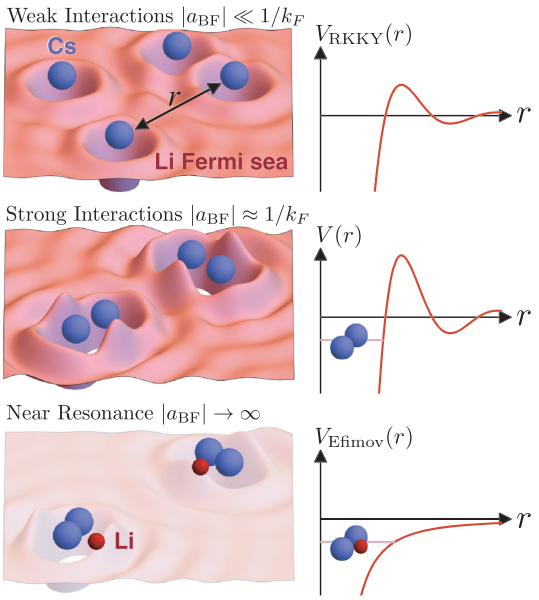


FIG. 1. Quantum mixtures of heavy bosonic ^{133}Cs atoms (blue) and light fermionic ^{6}Li atoms (red) in different interaction regimes. In the weak coupling regime with small interspecies scattering length $|a_{BF}| \ll 1/k_F$ (top panel), fermionic scattering leads to interactions between Cs atoms through the Ruderman–Kittel–Kasuya–Yosida (RKKY) mechanism. The RKKY potential $V_{RKKY}(r)$ shows Friedel oscillations due to fermion scattering (ripples in the Fermi sea) at the Fermi length scale $1/k_F$. In the strong coupling regime $|a_{BF}| \sim 1/k_F$ (middle panel), this Letter reports binding of Cs atoms due to enhanced mediated interactions $V(r)$. Near the interspecies Feshbach resonance $|a_{BF}| \to \infty$ (bottom panel), the effective potential supports Efimov Cs_2Li states. Because of the large boson-fermion mass ratio, the effective potentials in all three panels can be expressed as a function of the bosonic separation r [11,32].

conjectured in this regime, including fermionic zero sound [33], p-wave fermionic superfluidity [10,23], and Bose-Fermi droplets [34]. Relevant to this Letter, the effect of a Fermi sea on few-body physics has been investigated theoretically [10,35–40].

In this Letter, we investigate the Cs-Li quantum mixture in the "RKKY-Efimov" transition regime by tuning the interspecies interactions across a Feshbach resonance. We show that the transition physics is highlighted by a fermion mediated resonance between Cs atoms. Resonance structure manifests in both the dynamical response of collective excitations as well as the decay and heating of the Cs condensate. The resonance position can be compared with theoretical models that incorporate both RKKY and Efimov physics [38,41]. When temperature increases, we observe a transition of the mediated resonances into the well-known Efimov resonance. This reveals the intriguing impact of many-body physics on two- and three-body binding in the strong coupling regime.

Our experiments begin with a BEC of 30,000 ^{133}Cs atoms fully immersed in a larger single component degenerate Fermi gas of up to 20,000 ^{6}Li atoms. The mixture is prepared in a single beam dipole trap with a weak axial (x) and tight transverse (y and z) confinement. The trap frequencies are $\omega_{Cs} = (\omega_x, \omega_y, \omega_z) = 2\pi \times (6.53, 153, 114)$ Hz for Cs and $\omega_{Li} = 2\pi \times (36, 330, 330)$ Hz for Li. Both species are spin-polarized in their lowest hyperfine ground state, where the interspecies scattering length a_{BF} can be tuned near a Feshbach resonance at 892.65 G [27,30]. Over this range, a bare Cs BEC is stable with a moderate boson-boson scattering length $a_{BB} = 270a_0$ [52], where a_0 is the Bohr radius. A bare Fermi gas is also stable and noninteracting.

The mixture is initially prepared in the weak-coupling regime. The BEC chemical potential is $\mu = k_B \times 35$ nK, where k_B is the Boltzmann constant. The Fermi energy is up to $E_F = \hbar^2 k_F^2/2m = k_B \times 370$ nK, where $2\pi\hbar$ is the Planck constant and m is the fermion mass. This corresponds to $k_F = 3$ μm^{-1}. The mixture initially has temperature $T \approx 30$ nK, corresponding to a very pure BEC and a deeply degenerate Fermi gas. See Ref. [7] for details on the sample preparation.

To probe the mixture in the transition regime, we quickly switch the magnetic field to quench the interspecies scattering length a_{BF} from its initial value of $a_{BF} = -300a_0$ to a target value [41]. We introduce an interaction parameter $g = 1000a_0/a_{BF}$ to interpolate the weak coupling RKKY regime $g \ll -1$ and the resonant Efimov regime $g \to 0$. The RKKY-Efimov transition occurs in our system with $-1 < g < 0$, where the mixtures become strongly interacting.

Our first experiment to probe the transition regime is to study the dispersion of the Cs BEC immersed in a Fermi gas. Soon after the magnetic field settles, we imprint a weak periodic phase pattern at spatial frequency k on the sample, leading to the emergence of an oscillatory density wave; see Fig. 2. From *in situ* images of the Cs BEC, see Figs. 2(b) and 2(c), we obtain the real and imaginary part of the dispersion $\omega(k)$ from the frequency ω and damping Γ of the density wave response [53]. We perform the experiment for different k, interaction parameters g, and Li atom numbers.

In the weak interaction regime $g < -2$, the density wave oscillates with low damping. The measured dispersion $\omega(k)$ can be described by the Bogoliubov dispersion of the BEC with an effective bosonic interaction a_{eff} [3,7]; see Fig. 2(d). The extracted a_{eff} is consistent with the RKKY prediction [3] and sound speed measurements [7].

For greater attractions $g > -2$, the extracted frequencies and damping rates follow a characteristic dispersive and absorptive response across a resonance; see Figs. 2(e) and 2(f): the frequency first reaches a minimum, indicating enhanced attraction, and then returns to the background value when the interaction strength reaches $g = -1$, where the damping peaks, indicating a resonance. For even stronger interaction $g > -1$, the frequencies deviate from our dispersion model, which we attribute to excitations of the

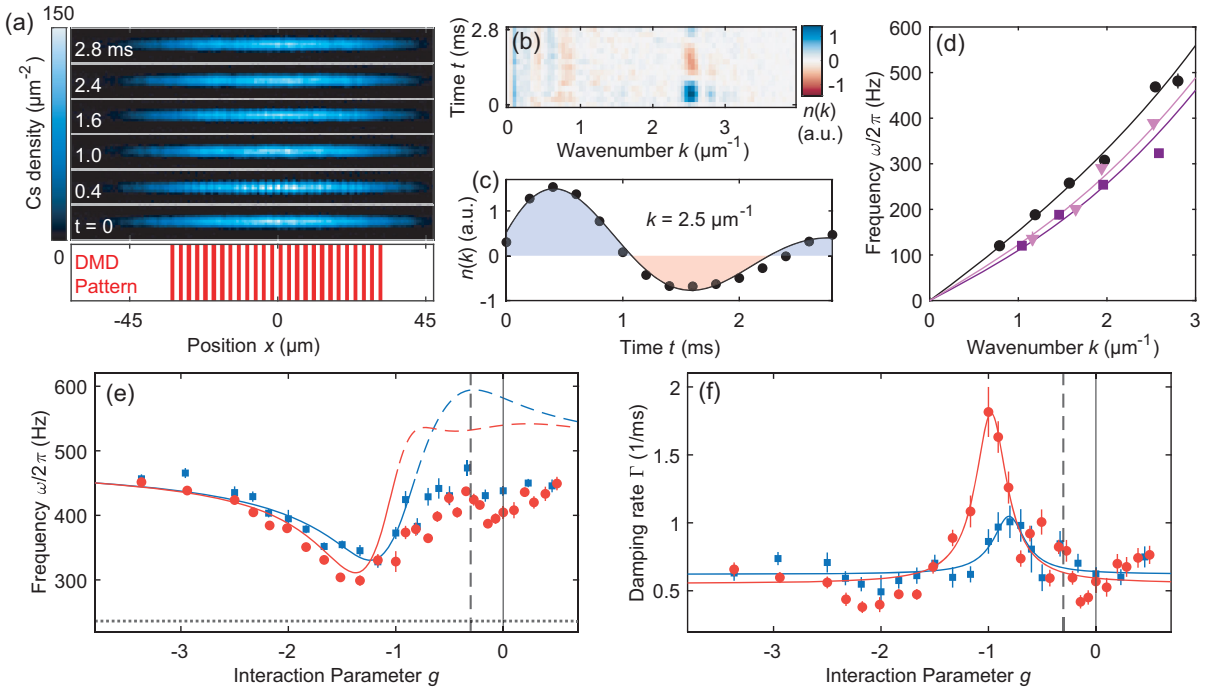


FIG. 2. Dispersion of Cs BEC embedded in a Li degenerate Fermi gas. (a) We imprint a periodic phase on the Cs condensate with a short 80 μs pulse of a periodic optical potential, generated by a digital micromirror device (lower panel). The phase modulation at wave number $k = 2.5\ \mu\text{m}^{-1}$ leads to an oscillating density wave order, shown in *in situ* images of the BECs (upper panel) at an example interaction parameter $g = -2.5$, where $g \equiv 1000a_0/a_{\text{BF}}$. (b) Fourier transform of the density profiles $n(k)$. (c) Real part of $n(k)$ is fit to $n = Ae^{-\Gamma t}\sin\omega t$ (solid line), from which we extract the damping Γ and frequency ω. (d) Measured frequencies ω for $g = -2.5$ (black circles), $g = -1.45$ (purple squares), and $g = 0$ (pink triangles). Solid lines are fits to the data based on the Bogoliubov model. (e) Excitation frequency ω and (f) damping Γ at $k = 2.5\ \mu\text{m}^{-1}$ show a resonant dispersive and absorptive behavior for samples with 20,000 (red circles) and 10,000 Li atoms (blue squares) when the interaction parameter g reaches -1. Fits based on an empirical model (solid lines) yield resonance positions at $a_{\text{BF}} = -1030(20)a_0$ for 20,000 Li atoms and $-1230(50)a_0$ for 10,000 Li atoms. Dashed colored lines in (e) indicate the extension of the fit prediction beyond the fitting region; see Supplemental Material [41] for more data and analysis. In all panels, error bars are 1-σ standard deviations of the mean. In (e), (f), the black solid line and dashed line indicate the Feshbach resonance and Efimov resonance, respectively. In (e), the black dotted line indicates the Cs free particle energy at $k = 2.5\ \mu\text{m}^{-1}$.

Cs BEC and reduction of fermion number within the BEC. For $g > 0$, the mixture phase separates, and the dispersion returns to its background value. The resonance feature weakens for lower fermion numbers and vanishes without fermions.

To further understand the nature of the resonance, we investigate the decay and heating dynamics of Cs BECs embedded in the Fermi gas. Immediately after the magnetic field quench, we monitor the BEC and thermal fractions from the transverse density distribution; see Figs. 3(a) and 3(b). In the weak coupling regime $g < -2$, the BEC remains stable. Near the mediated resonance, however, fast decay of the BEC occurs within milliseconds, accompanied by fast generation of excited atoms. Beyond the mediated resonance, the decay and heating quickly reduce. No discernible resonance features are observed at the positions of Efimov and Feshbach resonances. The fitted resonance positions from Figs. 3(c) and 3(d) are consistent with the collective excitation measurement in Fig. 2. The weighted average of the resonance positions from these measurements is $a_1 = -1100(100)a_0$ [41].

The resonant behavior of the dispersion and the BEC relaxation offers strong evidence that the observed feature at $a_1 = -1100(100)a_0$ is a fermion-mediated resonance of Cs atoms. This is fully consistent with the previous sound propagation measurement that the sound speed is quenched on one side of the resonance and restored on the other side [7], which is the expected behavior of atomic interactions across a Feshbach resonance. As the resonance only emerges in the presence of Li, the resonance at $a_1 = -1100(100)a_0$ can be regarded as a fermion-mediated collision resonance of Cs atoms.

We compare the measured resonance position with theoretical models. A calculation based on the RKKY potential shows that the mediated interactions can support a bound state of two impurities at [41]

$$a_{\text{th}} = \frac{\alpha}{k_{\text{F}}^*}\sqrt{\frac{m}{M}} = -1440a_0, \tag{1}$$

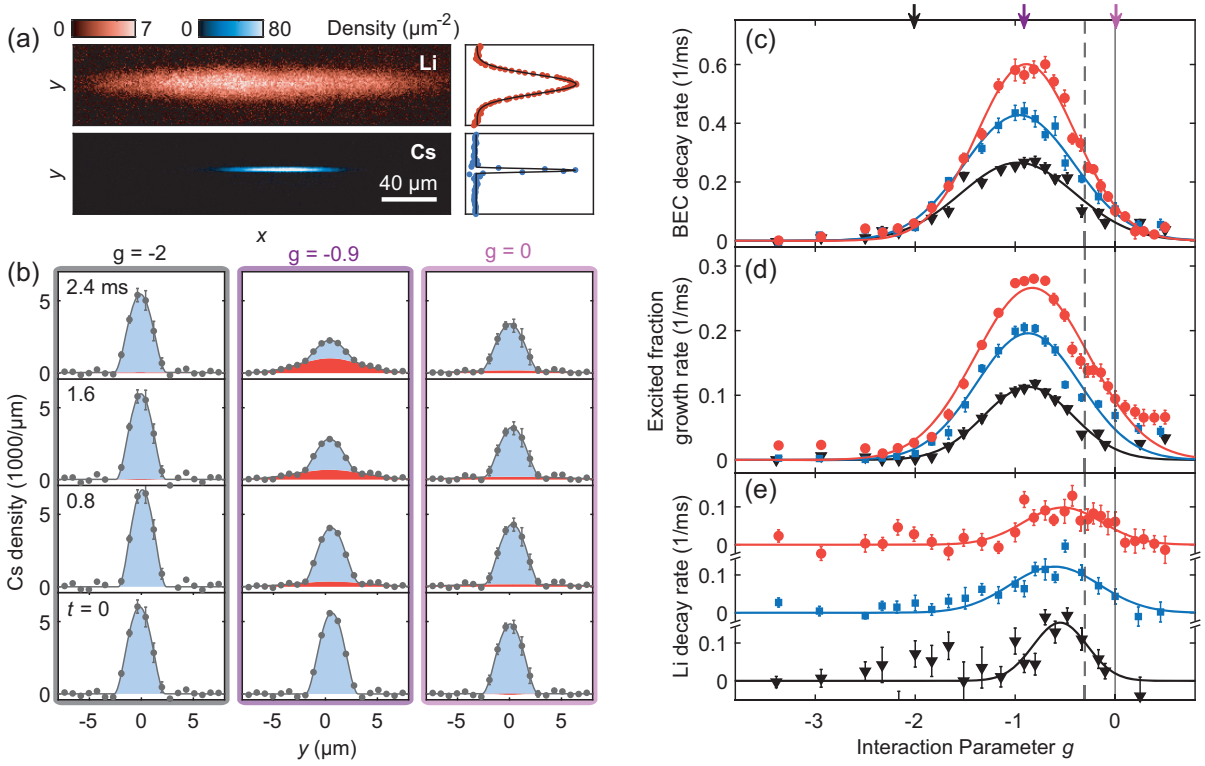


FIG. 3. Resonant decay and excitation Cs BECs induced by the Li degenerate Fermi gas. (a) Example *in situ* images of Li and Cs. Right panels show axially integrated density profiles. (b) Evolution of Cs density profile below (left), at (middle), and above (right) the mediated resonance at $g = -0.9$. Bimodal fits to the density profile show the condensed (blue) and Gaussian (red) parts of the sample. The Gaussian fraction has an effective temperature of 130–180 nK. (c) Cs BEC number decay rate, (d) Cs excited fraction growth rate, and (e) Li number decay rate show resonances for samples with 20,000 (red circles), 10,000 (blue squares), and 5,000 (black triangles) Li atoms. Gaussian fits yield average resonance positions at $a_{\mathrm{BF}} = -1090(50)a_0$ for the BEC decay, $-1170(30)a_0$ for the excitation growth, and $-1800(100)a_0$ for the Li decay. In all panels, error bars are 1-σ standard deviations of the mean. In (c)–(e), the Feshbach resonance (vertical solid line) and Efimov resonance (vertical dashed line) are shown for comparison.

where m is the mass of the fermion, M is the mass of the impurity, $\alpha = -2.40\ldots$ is a constant, and the wave number of the Fermi gas $k_{\mathrm{F}}^* = \eta k_{\mathrm{F}}$ is greater than that of an ideal Fermi gas k_{F} because of the interspecies attraction.

We estimate the enhancement factor $\eta = (1 - g_{\mathrm{BF}} n_{\mathrm{B}}/E_{\mathrm{F}})^{1/2} \approx 2.2$ from the mean-field model, consistent with our independent measurement which gives $\eta = 2.0$–2.1 [41]. Here n_{B} is the boson density, $g_{\mathrm{BF}} = 2\pi\hbar^2 a_{\mathrm{BF}}/m_r$, and $m_r = Mm/(M+m)$ is the reduced mass of the impurities and fermion. An alternative theory that incorporates both the RKKY and the Efimov potentials in the strong coupling regime [38] gives $a_{\mathrm{th}} = -1600a_0$ [41]. Both predictions are in fair agreement with our measurement.

The Li Fermi gas behaves differently from the Cs BEC. Near the mediated resonance, Li trap loss is much slower than the BEC damping and decay rates. This supports the picture that Li atoms only "catalyze" the collision resonance between Cs atoms. Pushing to even stronger interspecies attraction, a distinct loss peak appears in the Fermi gas at $a_2 = -1800(100)a_0$. The resonance is persistent for different fermion numbers, and is clearly different from the Efimov resonance at $a_{\mathrm{BF}} = -3300(240)a_0$ and the Feshbach resonance at $a_{\mathrm{BF}} = \pm\infty$, measured previously in thermal mixtures of Cs and Li atoms [30].

What is the nature of the two resonances at $a_{\mathrm{BF}} = a_1$ and a_2 in the transition regime? To understand the underlying processes, we monitor the resonant features as the mixture is prepared in the classical and quantum regime. Starting with a mixture at the lowest temperature $T \approx 30$ nK, we quickly step up the optical trap intensity to excite the mixture and wait for the mixture to reach a new equilibrium. This process provides precise heating of the sample without discernible trap loss. We then perform trap loss measurement across the resonances; see Fig. 4.

We observe drastic changes in the resonance positions when crossing from the thermal regime into the quantum degeneracy regime. For thermal mixtures above the Cs BEC critical temperature $T > T_c$, both species show resonant features consistent with the Efimov resonance at $a_{\mathrm{BF}} = -3300a_0$ and Feshbach resonance $a_{\mathrm{BF}} = \pm\infty$, in agreement with previous works [30]. Below the BEC critical temperature $T < T_c$, the resonances appear at weaker interspecies attraction and a gap between the

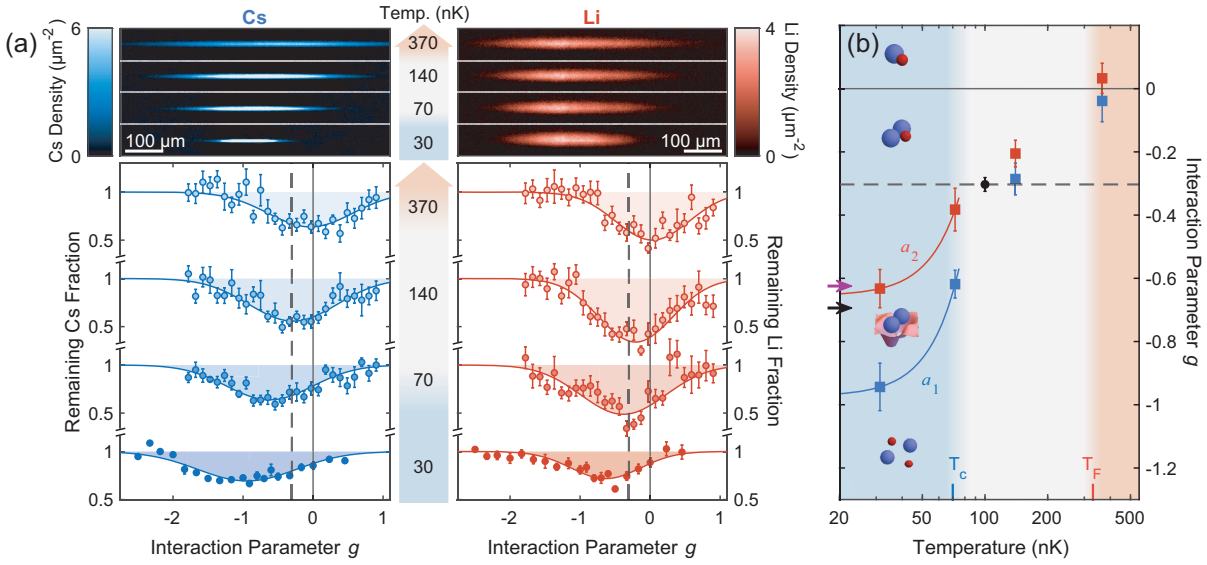


FIG. 4. Fermion mediated resonances in the thermal and quantum regimes. (a) Sample images of 30,000 Cs atoms and 10,000 Li atoms, prepared at different temperatures. Lower panels show the Cs and Li surviving fraction after hold time $t_h = 2.8$, 3, 6, and 10 ms for the 30, 70, 140, and 370 nK samples, respectively. We determine the positions of the loss peaks from Gaussian fits (solid lines). (b) Summary of fitted loss peaks in the classical and quantum regime. Here $T_c = 75$ nK is the BEC critical temperature, and $T_F = 360$ nK is the Fermi temperature. Cs (Li) loss peaks are shown in blue (red) squares. At low temperature they correspond to the resonances at a_1 (a_2). The black circle is the Efimov resonance position from Ref. [30]. Red and blue solid lines are guides to the eye. Cartoons show the hypothesized many-body ground state: free Li (red balls) and Cs atoms (blue balls) for weak attractions $g < -0.9$, fermion-mediated Cs_2 pairs for $-0.9 < g < -0.6$ and Cs_2Li trimer for $-0.6 < g < 0$. Finally, CsLi dimers form above the Feshbach resonance $g > 0$. The black and magenta arrows indicate the values of the theory predictions of Eq. (1) and Ref. [38], respectively. In all plots, error bars are 1-σ standard deviations of the mean. The solid and dashed black lines indicate the Feshbach and Efimov resonances, respectively.

resonances in the Cs BEC and the Li Fermi gas widens. The result is summarized in Fig. 4(b).

We propose a physical picture to elucidate the impact of quantum degeneracy to the Cs-Li mixtures in the RKKY-Efimov transition regime. As we increase the interspecies attraction from zero, the Fermi gas first mediates bosonic interactions through the RKKY mechanism. When the attraction strengthens and the scattering length reaches the critical value $a_{BF} = a_1 = -1100(100)a_0$ or $g = -0.9(1)$, a resonant scattering of bosons occurs, which we denote as a degenerate Fermi gas (DFG) mediated reaction process: $Cs + Cs \xrightarrow{\text{Li DFG}} Cs_2$. Enhancing the attraction further brings the system to the second threshold $a_2 = -1800(100)a_0$ or $g = -0.55(4)$ in our system, where Li atoms are also bound to the boson pairs, denoted as another DFG mediated process: $Li + Cs_2 \xrightarrow{\text{Li DFG}} Cs_2Li$. Both reaction processes are many-body in nature, discussed in Refs. [38,39]. When the system enters the normal gas regime, the many-body processes merge into a single three-body process $Cs + Cs + Li \rightarrow Cs_2Li$, which is precisely the picture of an Efimov resonance [54].

Our picture offers a consistent understanding of this and previous works [3,7] on interacting Cs-Li mixtures in all regimes. It also highlights the rich physics of fermion-mediated binding as a unique feature in the RKKY-Efimov transition regime. The observed smaller bosonic binding length $|a_1|$ and the larger fermionic binding length $|a_2|$ can be understood since heavy particles tend to bind more easily than light particles [41]. This is a trend that persists in the many-body regime, e.g., the mass scaling of Eq. (1) favors pairing of heavier impurities.

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Data availability—The data that support the findings of this article are openly available [55].

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