Connecting Few-Body Inelastic Decay to Quantum Correlations in a Many-Body System: A Weakly Coupled Impurity in a Resonant Fermi Gas

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We study three-body recombination in an ultracold Bose-Fermi mixture. We first show theoretically that, for weak interspecies coupling, the loss rate is proportional to Tan's contact. Second, using a ^{7}Li/^{6}Li mixture we probe the recombination rate in both the thermal and dual superfluid regimes. We find excellent agreement with our model in the BEC-BCS crossover. At unitarity where the fermion-fermion scattering length diverges, we show that the loss rate is proportional to $n_f^{4/3}$, where n_f is the fermionic density. This unusual exponent signals nontrivial two-body correlations in the system. Our results demonstrate that few-body losses can be used as a quantitative probe of quantum correlations in many-body ensembles.

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Understanding strongly correlated quantum many-body systems is one of the most daunting challenges in modern physics. Thanks to a high degree of control and tunability, quantum gases have emerged as a versatile platform for the exploration of a broad variety of many-body phenomena [1], such as the crossover from Bose-Einstein condensation (BEC) to Bardeen-Cooper-Schrieffer (BCS) superfluidity [2], quantum magnetism [3], or many-body localization [4]. At ultralow temperatures, atomic vapors are metastable systems and are plagued by three-body recombination which represents a severe limitation for the study of some dense interacting systems. A prominent example is the strongly correlated Bose gas [5,6] that bears the prospect of bridging the gap between dilute quantum gases and liquid helium. However, inelastic losses can also be turned into an advantage. For instance, they can be used to control the state of a system through the Zeno effect [7–9], or serve as a probe of nontrivial few-body states, as demonstrated by the observation of Efimov trimers, originally predicted in nuclear physics, but observed for the first time in Bose gases as resonances in three-body loss spectra [10].

In this Letter, we study inelastic losses in a mixture of spinless bosons and spin 1/2 fermions with tunable interaction. We show that when the Bose-Fermi coupling is weak, the loss rate can be related to the fermionic contact parameter, a universal quantity overarching between microscopic and macroscopic properties of a many-body system with zero-range interactions [11–19]. We first check our prediction on the strongly attractive side of the fermionic Feshbach resonance, where we recover known results on atom-dimer inelastic scattering. We then turn to the unitary limit where the fermion-fermion scattering length is infinite. We demonstrate both theoretically and experimentally—with a ^{6}Li/^{7}Li Fermi-Bose mixture—that the bosons decay at a rate proportional to $n_f^{4/3}$, where n_f is the fermion density. The unusual fractional exponent results from nontrivial quantum correlations in the resonant gas. Our method offers a new way to measure the two-body contact of the homogeneous Fermi gas. More generally, our work shows that the decay of an impurity immersed in a strongly correlated many-body system is a quantitative probe of its quantum correlations.

Inelastic decay of an impurity inside a two-component Fermi gas has been studied previously both in the weakly

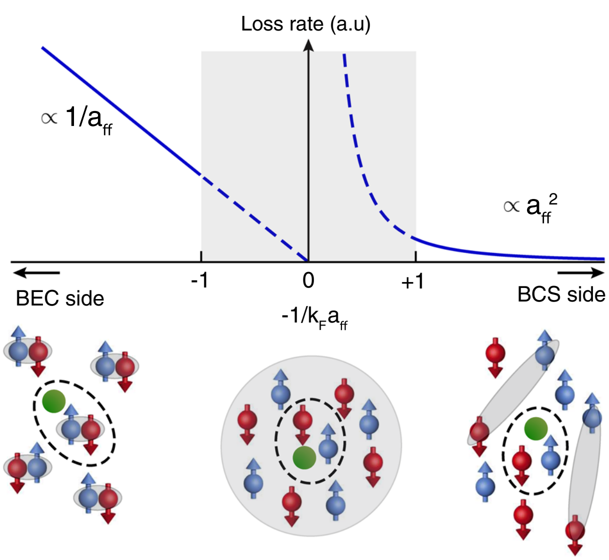

FIG. 1. Sketch of inelastic decay of an impurity immersed in a tunable Fermi gas. On the BEC side, ↑ and ↓ fermions are paired in tightly bound molecules and the decay mechanism is a two-body process involving the impurity (green disk) and a molecule. The loss rate scales as $1/a_{ff}$ [20,24]. On the BCS side, the loss occurs through a three-body process and it scales as a_{ff}^2 in the mean-field limit [20]. The extrapolation of these two asymptotic behaviors towards the strongly correlated regime yields contradictory results (grey area).

TABLE I. Scaling of the boson-fermion mixture loss rate and of Tan's contact [11], C_2, in the BEC-BCS crossover. Both scalings are identical in the weakly and strongly attractive limits. As $k_F = (3\pi^2 n_f)^{1/3}$, at unitarity C_2 scales as $n_f^{4/3}$. ζ is a dimensionless constant, $\zeta = 0.87(3)$ [17,25].

	BEC	Unitary	BCS
$(\dot{n}_b/n_b)$	$\propto (n_m/a_{ff})$ [20]	$\propto n_f^{4/3}$	$\propto a_{ff}^2 n_f^2$ [20]
C_2	$8\pi(n_m/a_{ff})$	$(2\zeta/5\pi)k_F^4$	$4\pi^2 a_{ff}^2 n_f^2$

and strongly attractive limits of the BEC-BCS crossover [20–23], see Fig. 1 and Table I. When the fermion-fermion interaction is weak, the fermions behave almost as isolated particles and the recombination can be described as a three-body process involving one spin-up (↑), one spin-down (↓) fermion and the impurity (a boson in our experiments). In this case, the impurity or boson density n_b follows a rate equation $\dot{n}_b = -L_3 n_f^2 n_b$, with $L_3 \propto a_{ff}^2$, where a_{ff} is the fermion-fermion scattering length [20,22,24]. In contrast, on the strongly attractive side of the Feshbach resonance, the fermions form halo dimers of size $\simeq a_{ff}$ and the relaxation occurs through two-body processes between one such molecule and one boson. In this case the rate equation for bosons reads $\dot{n}_b = -L_2 n_m n_b$, where $n_m = n_f/2$ is the molecule density. Far from the Feshbach resonance, the two-body loss rate scales as $1/a_{ff}$ as a consequence of the enhanced overlap of the halo dimer wave function with the deeply bound product molecules [20,24]. However, these two scalings give rise to a paradox in the central region of the BEC-BCS crossover. Indeed, as depicted in Fig. 1, the extrapolation towards unitarity leads to contradictory results depending on whether we approach the resonance from the BEC or the BCS side. In the former case, one would predict an increasingly long lifetime at unitarity while it tends to a vanishingly small value in the latter case. This paradox has a fundamental origin: these two scalings are obtained in the dilute limit where the recombination can be described by a well-defined few-body process, whereas this hypothesis fails in the strongly correlated regime where $n_f|a_{ff}|^3 \gg 1$. There, it is not possible to single out two fermions from the whole many-body system. Instead, the inelastic loss involving a boson and two fermions is tied to the correlations of the whole ensemble. A first hint towards reconciling these two behaviors near unitarity is to assume that they saturate for $a_{ff} \simeq n_f^{-1/3}$, yielding the same scaling $\dot{n}_b \propto n_f^{4/3} n_b$.

The three asymptotic regimes—BEC, BCS, and unitary—were obtained using different theoretical approaches and we now show that, using Tan's contact, they can be unified within the same framework. The recombination rate is proportional to the probability of having the three particles within a distance b from each other, where b is the typical size of the deeply bound molecule formed during the collision [26–28]. Take $\rho_3(\boldsymbol{r}_\uparrow, \boldsymbol{r}_\downarrow, \boldsymbol{r}_b)$ the three-body probability distribution of the system. When the bosons are weakly coupled to the fermions, we can factor it as $\rho_3(\boldsymbol{r}_\uparrow, \boldsymbol{r}_\downarrow, \boldsymbol{r}_b) = \rho_f(\boldsymbol{r}_\uparrow, \boldsymbol{r}_\downarrow)\rho_b(\boldsymbol{r}_b)$. Integrating over the positions of the three atoms we readily see that the three-body loss rate is proportional to Tan's contact parameter C_2 of the fermions that gives the probability of having two fermions close to each other [11]. C_2 is calculated using the equation of state of the system thanks to the adiabatic-sweep theorem

$$C_2 = -\frac{4\pi m_f}{\hbar^2}\frac{\partial F}{\partial(1/a_{ff})}, \tag{1}$$

where m_f is the fermion mass and F is the free-energy of the fermionic gas per unit-volume [12,13]. The asymptotic expressions of C_2 in the BEC, BCS and unitary regimes are listed in Table I. In the deep BEC limit, the free energy is dominated by the binding energy of the molecules $\hbar^2/m_f a_{ff}^2$; in the BCS regime C_2 is derived using the mean-field approximation [11]. At unitary, the expression of the contact stems from the absence of any length scale other than the interparticle distance. The dimensionless parameter $\zeta = 0.87(3)$ was determined both theoretically [29] and experimentally [14–19]. Expressions listed in Table I confirm that the contact parameter and the bosonic loss rate follow the same scalings with density and scattering length.

We support this relationship between inelastic losses and Tan's contact by considering a microscopic model where the recombination is described by a three-body Hamiltonian

$$\begin{aligned}\hat{H}_3 = &\int d^3\boldsymbol{r}_b d^3\boldsymbol{r}_\uparrow d^3\boldsymbol{r}_\downarrow g(\boldsymbol{r}_b, \boldsymbol{r}_\uparrow, \boldsymbol{r}_\downarrow)\\ &\times \hat{\Psi}_m^\dagger\left(\frac{\boldsymbol{r}_\uparrow + \boldsymbol{r}_\downarrow}{2}\right)\hat{\Psi}_b^\dagger(\boldsymbol{r}_b)\hat{\Psi}_b(\boldsymbol{r}_b)\hat{\Psi}_\uparrow(\boldsymbol{r}_\uparrow)\hat{\Psi}_\downarrow(\boldsymbol{r}_\downarrow)\\ &+ \mathrm{H.c.},\end{aligned} \tag{2}$$

where $\hat{\Psi}_\alpha$ is the field operator for the species α and the coupling g takes significant values only when the three particles are within a distance b [30]. Assuming that b is the smallest distance scale in the problem and that this Hamiltonian can be treated within Born's approximation we find that (see Ref. [31])

$$\dot{n}_b = -\gamma C_2 n_b. \tag{3}$$

The constant γ depends on the coupling g and describes the coupling to deeply bound nonresonant states; hence, γ has essentially no variation with the magnetic field across the fermionic Feshbach resonance.

Equation (3) is the main prediction of this Letter and we explore the consequences of this equation by measuring the lifetime of an ultracold Fermi-Bose mixture of ^{6}Li and ^{7}Li atoms. Our experimental setup is described in Ref. [37].

The ^{6}Li atoms are prepared in a spin mixture $\uparrow,\downarrow$ of $|F = 1/2, m_F = \pm 1/2\rangle$ for which there is a broad Feshbach resonance at 832 G [33]. The ^{7}Li atoms are transferred into the $|F = 1, m_F = 0\rangle$ featuring two Feshbach resonances, a narrow one at 845.5 G and a broad one at 893.7 G [31]. The scattering length between bosons and fermions is $a_{\rm bf} = 40.8 a_0$ and is equal for the $\uparrow,\downarrow$ states. It can be considered constant in the magnetic field range that we explored, 680–832 G. The atoms are confined in a hybrid magnetic-optical trap and are evaporated at the ^{6}Li Feshbach resonance until we reach dual superfluidity or any target temperature. We ramp the magnetic field to an adjustable value in 200 ms and wait for a variable time t. We then measure the atom numbers of the two species by *in situ* imaging or after time of flight.

We first show that the dominant boson loss mechanism on the BEC side of the resonance involves one boson, one fermion $\uparrow$, and one fermion $\downarrow$. This is easily done by comparing the boson losses for spin-balanced and spin-polarized fermionic samples. Figure 2 displays the remaining fraction of bosons and fermions after a waiting time of 1 s for balanced fermions and 1.5 s for spin-polarized fermions with 90% polarization. We observe that the losses for high spin polarization are strongly suppressed indicating that fermions of both spin components are required to eliminate one boson.

Second we show that the losses in the weakly interacting regime $na_{ff}^3 \ll 1$ (deep BEC side of the resonance, 720 G) are proportional to the fraction of molecules in the sample, $\eta = 2N_m/(N_f + 2N_m)$. This fraction is varied by changing the temperature from 1 μK to 4 μK and ^{6}Li densities from 2×10^{12} cm^{-3} to 1.0×10^{13} cm^{-3}. In these temperature and density ranges, both gases are well described by Maxwell-Boltzmann position and velocity distributions. The molecular fraction is calculated using the law of mass action [31,36] and is assumed to be time independent owing to the high formation rate of halo dimers ($\simeq \hbar a_{ff}^4/m_f$)[38]. We extract the interspecies decay rate by fitting the time evolution of the bosonic population

$$\dot{N}_b = -L_{\rm bf}\langle n_f\rangle N_b - \Gamma_v N_b, \tag{4}$$

where $\langle\cdots\rangle$ represents the trap average, and Γ_v is the one-body residual gas loss rate (0.015 s^{-1}).

The data in Fig. 3(a) show that the boson loss rate is proportional to the molecule fraction of the fermionic cloud. Introducing the boson-fermion dimer molecule loss rate $L_{\rm bm}$ defined by $L_{\rm bm}\langle n_m\rangle = L_{\rm bf}\langle n_f\rangle$, we check the proportionality of $L_{\rm bm}$ with $1/a_{ff}$ predicted in Table I by

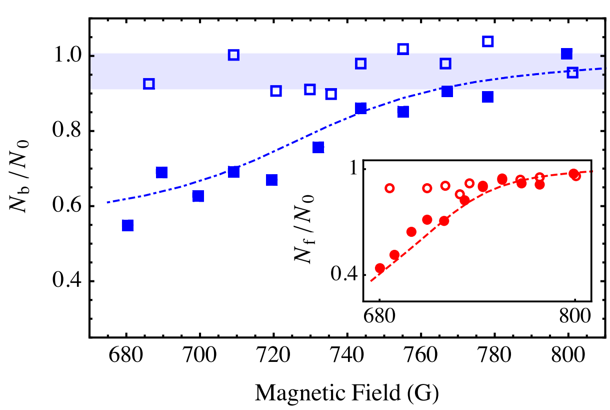

FIG. 2. Remaining fraction of bosons (blue symbols) and fermions (red symbols, inset) after a 1 s and 1.5 s waiting time for spin-balanced (filled symbols), resp. 90% polarized (open symbols) fermions. The blue dash-dotted (red dashed, inset) curve is a coupled loss model describing the competition between boson fermion-dimer decay ($\propto 1/a_{ff}$) and dimer-dimer decay ($\propto 1/a_{ff}^{2.55}$) [27,31]. The blue-shaded area represents the 1σ fluctuations for the remaining fraction of bosons with spin-polarized fermions. The initial atom numbers are 3×10^5 for ^{6}Li and 1.5×10^5 for ^{7}Li at a temperature $T \simeq 1.6$ μK with trap frequencies $\nu_z = 26$ Hz and $\nu_r = 2.0$ kHz.

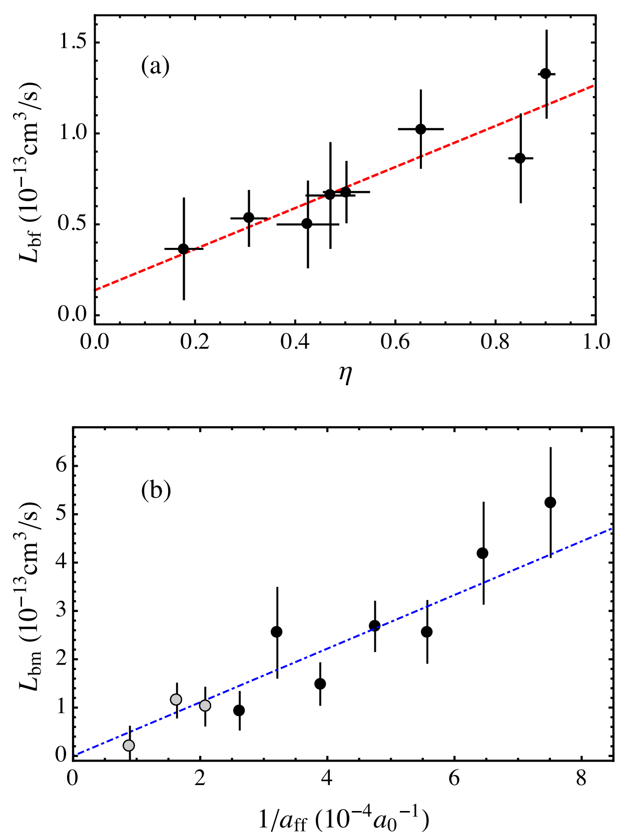

FIG. 3. (a) Boson-fermion loss rate vs molecule fraction. Circles: Experimental data. The vertical error bars represent the statistical errors for $L_{\rm bf}$ from fitting the loss curves. The horizontal error bars represent the statistical errors on the molecule fraction due to ^{6}Li number fluctuations. The red dashed line is a linear fit to the data. (b) Boson-dimer loss rate vs inverse scattering length. The blue dot-dashed line is a linear fit to the data with $n_f a_{ff}^3 \leq 0.025$ (black circles), providing $\gamma = 1.17(11)\times 10^{-27}$ m$^4\cdot$s^{-1}, see Eq. (3).

repeating the loss measurements for different magnetic fields in the interval 690–800 G, see Fig. 3(b). From a linear fit to the data where interaction effects are negligible ($n_f a_{ff}^3 \leq 0.025$), we extract the slope $\gamma = 1.17(11) \times 10^{-27}$ $\mathrm{m}^4 \cdot \mathrm{s}^{-1}$ entering in Eq. (3).

Since γ doesn't depend on the magnetic field, we can now predict the loss rate anywhere in the BEC-BCS crossover using Eq. (3). The strongly interacting unitary regime ($1/a_{ff} = 0$) is particularly interesting and we measure the boson decay rate at 832 G in the low temperature dual superfluid regime [37]. The mixture is initially composed of about 40×10^3 fully condensed ^{7}Li bosons and 150×10^3 ^{6}Li spin-balanced fermions at a temperature $\mathrm{T} \simeq 100$ nK which corresponds to $T/T_\mathrm{F} \simeq 0.1$ where T_F is the Fermi temperature. At this magnetic field value, the atoms are now closer to the boson Feshbach resonance located at 845.5 G and bosonic three-body losses are no longer negligible. The time dependence of the boson number is then given by

$$\dot{N}_b = -L_b \langle n_b^2 \rangle N_b - \Gamma_{\mathrm{bf}} N_b - \Gamma_v N_b. \tag{5}$$

To extract Γ_{bf} we measure independently L_b with a BEC without fermions in the same trap and inject it in Eq. (5), see Ref. [31]. We typically have $L_b \langle n_b^2 \rangle = 0.1$–$0.4\ \mathrm{s}^{-1}$, and $L_b = 0.11(1) \times 10^{26}$ $\mathrm{cm}^6 \cdot \mathrm{s}^{-1}$ consistent with the model of Ref. [35]. Repeating such measurements for different fermion numbers and trap confinement, we now test the expected $n_f^{4/3}$ dependence of the Bose-Fermi loss rate at unitarity (central column in Table I). In this dual superfluid regime, the size of the BEC is much smaller than that of the fermionic superfluid and the BEC will mainly probe the central density region $n_f(r = 0)$. However, it is not truly a pointlike probe, and introducing the ratio ρ of the Thomas-Fermi radii for bosons and fermions, we obtain the finite size correction for Eq. (3) [31]:

$$\Gamma_{\mathrm{bf}} = \gamma C_2(0) \left(1 - \frac{6}{7}\rho^2\right), \tag{6}$$

where $C_2(0) = (2\zeta/5\pi)(3\pi^2 n_f(0))^{4/3}$, and the last factor in parenthesis amounts to 0.9. The prediction of Eq. (6) is plotted as a red line in Fig. 4 and is in excellent agreement with our measurements without any adjustable parameter. Alternatively, a power-law fit An^p to the data yields an exponent $p = 1.36(15)$ which confirms the $n_f^{4/3}$ predicted scaling at unitarity. Finally, fixing p to $4/3$ provides the coefficient A and a value of the homogeneous contact $\zeta = 0.82(9)$ in excellent agreement with previous measurements, $\zeta = 0.87(3)$ [17,25]. This demonstrates that impurity losses act as a microscopic probe of quantum correlations in a many-body system.

The bosonic or fermionic nature of the probe is of no importance. Provided the coupling between the impurity and the resonant gas is weak, our method can also be applied to other mixtures. It gives a framework to interpret the experimental data on ^{6}Li/^{40}K [22] and, in particular, to test our prediction on the BCS side of the Feshbach resonance. It can also be applied to the recently observed ^{6}Li/^{174}Yb [39], ^{6}Li/^{41}K [40], and ^{6}Li/^{7}Li [41] dual-superfluid Bose-Fermi mixtures and even to the case where one of the collision partners is a photon as in photo-association experiments [42,43]. Our observation of a loss rate scaling $\propto n_f^{4/3}$ at unitarity is in stark contrast with the generic case n^p, where the integer p is the number of particles involved in the recombination process. A fractional exponent is also predicted to occur for the resonant Bose gas [5,6] and Fermi gas [27,44].

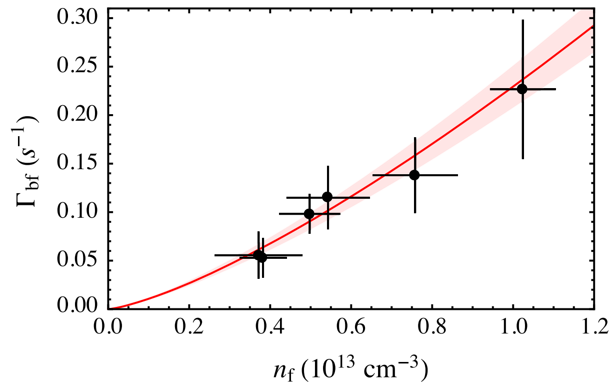

FIG. 4. Boson loss rate versus fermion central density at unitarity, $n_f = n_f(0)$. Circles: Experimental data. The red line is the $n_f^{4/3}$ prediction of Eq. (6) without any adjustable parameter. The red shaded area represents the 1σ uncertainty resulting from the error on γ.

A first extension of this work is to investigate regimes where $a_{\mathrm{bf}} \simeq a_{ff} \gg n^{-1/3}$ and the Born approximation breaks down. In this case Efimovian features are expected to occur [45,46]. Second, our method provides a unique microscopic way to measure the contact quasilocally in a harmonic trap. An important perspective is to determine the homogeneous contact of the unitary Fermi gas at finite temperature, whose behavior is largely debated near the normal-superfluid transition [18].

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