Inelastic Collisions of a Fermi Gas in the BEC-BCS Crossover

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We measure inelastic three-body and two-body collisional decay rates for a two-component Fermi gas of ^{6}Li, which are highly suppressed by the Pauli exclusion principle. Our measurements are made in the BEC-BCS crossover regime, near the two-body collisional (Feshbach) resonance. At high temperature (energy) the data show a dominant three-body decay process, which is studied as a function of bias magnetic field. At low energy, the data show a coexistence of two-body and three-body decay processes near and below the Feshbach resonance. Below resonance, the observed two-body inelastic decay can arise from molecule-atom and molecule-molecule collisions. We suggest that at and above resonance, an effective two-body decay rate arises from collisions between atoms and correlated (Cooper) pairs that can exist at sufficiently low temperature.

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Quantum statistics dramatically affects the inelastic collision rates that determine the lifetime of cold atomic gases. In an inelastic three-body collision, two of the colliding atoms decay to a bound molecular state, releasing energy. Interactions between atoms can be strongly enhanced by tuning a bias magnetic field near a collisional (Feshbach) resonance [1,2]. In a Bose gas, this enhancement is accompanied by an inelastic collision rate that increases by two or 3 orders of magnitude compared to that obtained away from resonance [3], and a correspondingly short lifetime of just a few ms at typical atomic densities. In contrast, for a Fermi gas in a mixture of one or two different spin states, the probability of three atoms colliding is highly suppressed by the Pauli exclusion principle. The lifetime of the cloud is on the order of 0.1 s for fermionic ^{40}K [4,5] and 50 s for ^{6}Li [6,7]. The long lifetime of Fermi gases is essential to the study of strongly interacting Fermi gases in the BEC-BCS crossover region near a Feshbach resonance [8,9]. In this region, for bias magnetic fields below resonance, where the s-wave scattering length $a > 0$, stable diatomic molecules can form and condense into a molecular BEC at sufficiently low temperatures. Above resonance, where $a < 0$, the system exhibits Cooper pairing, becoming a superfluid at sufficiently low temperature. On resonance, the system contains tightly bound pairs that share the properties of both Cooper pairs and molecules. This unique system offers unprecedented opportunities to test nonperturbative theoretical techniques that apply to exotic systems ranging from high temperature superconductors to nuclear matter. Determination of the inelastic collision rate coefficients [10] provides new information on the microscopic structure and pair correlations of a Fermi gas in the strongly interacting regime and enables tests of few-body theories [11–19].

In this Letter we report on the precision measurement of three-body inelastic collision rate constants K_3 for an ultracold two-component ^{6}Li Fermi gas in the BEC-BCS crossover regime near a Feshbach resonance at 834 G. We also observe two-body inelastic decay below the Feshbach resonance, which arises from molecules [7,17]. From the data, we estimate the corresponding rate constants K_2. Finally, we observe two-body decay at and just above the Feshbach resonance. We suggest that this process arises from correlated pairs, which is a many-body effect. We load a Fermi gas from a single beam CO_2 laser trap into a CO_2 laser standing wave that is formed by the incoming and retroreflected beam. The standing wave produces a potential with a period of 5.3 μm that is 4 times deeper than that of the single beam trap and tightly confining in the axial direction (along the standing wave). The corresponding atomic density is up to $10^{14}/\mathrm{cm}^3$, $\sim$20 times higher than that obtained in the single beam optical trap. This dramatically increases the inelastic collision rates, making precise measurement of the rate constants feasible.

In the experiments, a sample of ^{6}Li atoms in a 50-50 mixture of the two lowest hyperfine states is loaded into a CO_2 laser trap with a bias magnetic field of 840 G, where the two states are strongly interacting. Evaporative cooling is performed to lower the temperature of the sample [8]. The magnetic field is then changed in 0.8 seconds to a final magnetic field where we perform the measurement. Subsequently, the gas is adiabatically loaded into a CO_2 laser standing wave by slowly turning on the retro-reflected CO_2 laser beam. A quasi-two-dimensional Fermi gas is then formed and absorption images are taken at various times after the formation of the 2D system to determine the inelastic decay rate.

At a final optical trap depth of $U_0 = 180$ μK (20% of the maximum attainable), the measured trap oscillation frequencies in the standing wave are $\omega_\perp = 2\pi \times 3250$ Hz in the transverse directions and $\omega_z = 2\pi \times 83.5$ kHz in the axial direction. The corresponding frequencies in the single beam trap are $\omega_\perp = 2\pi \times 1650$ Hz and $\omega_z = 2\pi \times 56$ Hz, respectively. Our mea-

surements indicate very good standing wave alignment, as the transverse frequency is nearly twice that of the single beam trap, as expected.

The total energy of the gas obeys the virial theorem [20] when the bias magnetic field is tuned to a broad Feshbach resonance, where the Fermi gas is unitary. Since the trap depth is large compared to the energy of the cloud, the confining potential U is approximately harmonic. Then the total energy is $E = 2\langle U\rangle = E_z + E_\perp$, where E_z is the axial energy and $E_\perp$ is the transverse energy, referred to the trap minimum. We determine only the transverse energy $E_\perp = 2m\omega_\perp^2\langle x^2\rangle$, by measuring the mean square transverse cloud size $\langle x^2\rangle$. For reference, the transverse energy for the ground state of an ideal two dimensional Fermi gas is $E_{I\perp} = \frac{2}{3}E_{F\perp}$, where $E_{F\perp}$ is the transverse Fermi energy, $E_{F\perp} = \hbar\omega_\perp N_s^{1/2}$. Here m is atomic mass of ^{6}Li and N_s is the total atom number in one site. For our experiments in the unitary gas, we measure $E_\perp/E_{F\perp} \sim 1.8$ with $N_s = 2600$ and $E_\perp/E_{F\perp} \sim 0.7$ with $N_s = 1600$. If the 2D unitary gas has the same effective mass as the 3D case, the 2D ground state transverse energy would be $2E_{F\perp}\sqrt{1+\beta}/3 \simeq 0.42E_{F\perp}$, using $\beta = -0.60$ [21].

In general, for magnetic fields away from resonance where the scattering length is finite, the total energy is dependent on the scattering length [22]. In this case, we measure the number-independent mean square transverse cloud size $\langle x^2\rangle/x_{F\perp}^2$, where $x_{F\perp}^2$ is defined by $2m\omega_\perp^2 x_{F\perp}^2 \equiv E_{F\perp}$. For an ideal gas in the ground state, we note that $\langle x_0^2\rangle = \frac{2}{3}x_{F\perp}^2$.

We measure inelastic collision rates by measuring the time dependence of the atom number and the radial cloud size. We observe that a 50-50 mixture of both spin states is maintained within 5%. In this case, the atom number N as a function of time can be written as [3]

$$\frac{dN}{dt} = -\Gamma N - \int K_2 n^2 d^3x - \int K_3 n^3 d^3x, \qquad (1)$$

where n is the total atomic density. On the right side, the first term arises from background collisions with a density-independent rate Γ ($1/\Gamma = 64$ s for our trap). The second term arises from loss due to two-body inelastic collisions with a rate coefficient K_2, while the third term arises from loss due to three-body collisions with a rate coefficient K_3.

For the conditions of our experiments, where $E_{F\perp}/\hbar\omega_z \simeq 1.5$, the ground axial state contains 90% of the atoms for an ideal Fermi gas at zero temperature. For simplicity, we assume that the 2D Fermi gas is primarily in the ground axial state of a single site for our experiments at the lowest energies. Then, the atomic density is

$$n(\rho, z) = \frac{2}{\pi^{3/2}}\frac{N(z)}{\sigma_\perp^2\sigma_z}\left(1 - \frac{\rho^2}{\sigma_\perp^2}\right)\exp\left(-\frac{z^2}{\sigma_z^2}\right), \qquad (2)$$

for $0 \le \rho \le \sigma_\perp$. Here, $N(z)$ is the atom number in the site at position z. $\sigma_\perp$ is the transverse width for a fit of a Thomas-Fermi distribution to the atomic density profile in the transverse directions, $\sigma_z = (\frac{\hbar}{m\omega_z})^{1/2}$ is axial width for the ground state (along the standing wave), and ω_z is the corresponding axial trap frequency. The transverse width is determined by releasing the cloud and imaging, using the measured trap frequencies and assuming hydrodynamic expansion to determine the scale factor [8].

In our experiments, $N(z)$ varies as a Gaussian distribution function of z with width L_z over the whole cloud in the axial direction. Strictly speaking, $\sigma_\perp$, σ_z and ω_z also vary with z since the depth $U(z)$ of the potential for a site at z is a Lorentzian function of z. However, we measure a restricted part of the cloud from $z = -0.83L_z$ to $z = 0.83L_z$ over which $U(z)$ varies less than 10%. Since the central sites with higher density lose atoms faster than the edge sites at lower density, the densities and hence the loss rates for different sites tend to approach similar values. For this reason, we assume for simplicity that $\sigma_\perp$, σ_z, and ω_z are spatially constant.

Integrating the atomic density over each well and then over the restricted region of the cloud, we obtain from Eq. (1)

$$\frac{dN_c}{dt} = -\Gamma N_c - \alpha_2 K_2 \frac{N_c^2}{\sigma_\perp^2(t)\sigma_z} - \alpha_3 K_3 \frac{N_c^3}{\sigma_\perp^4(t)\sigma_z^2}, \qquad (3)$$

where N_c is total number of atoms in the restricted region. If we assume that all of the atoms are in the ground axial vibrational state, we obtain $\alpha_2 = \frac{2\sqrt{2}}{3}\pi^{-3/2}$ and $\alpha_3 = \frac{2}{\sqrt{3}}\pi^{-3}$. Note that $\sigma_\perp(t)$ is a function of time since heating leads to an increase in temperature and hence the width of the cloud during the atom loss process. Typically $\sigma_\perp^2(t)$ can be fit well to exponential curves, $\propto \exp(\gamma t)$, Fig. 1 inset.

Note that at the highest energies used in our experiments, a significant fraction of atoms can occupy excited axial states. For the higher energy experiments, where $E_\perp/E_{F\perp} \simeq 2$, if we assume a Maxwell-Boltzmann distribution for an ideal gas, we find that 50% of the atoms are in

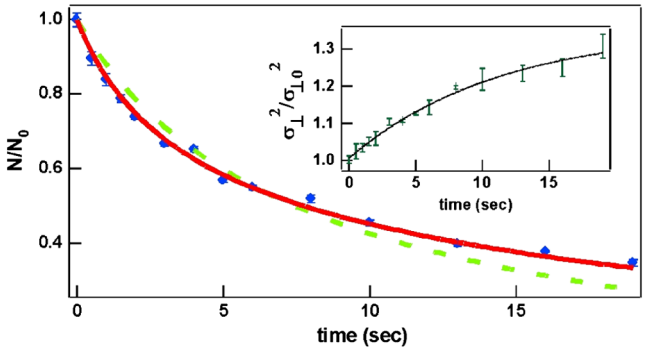

FIG. 1 (color online). Atom number versus time. Data were taken at 823 G and $E_\perp/E_{F\perp} = 1.8$. N is total atom number and N_0 is initial atom number in the observed region of the cloud. Blue dots: Experimental data; red solid curve: Three-body decay fit; green dashed line: Two-body decay fit. Inset shows the increase in the mean square transverse width versus time, due to heating.

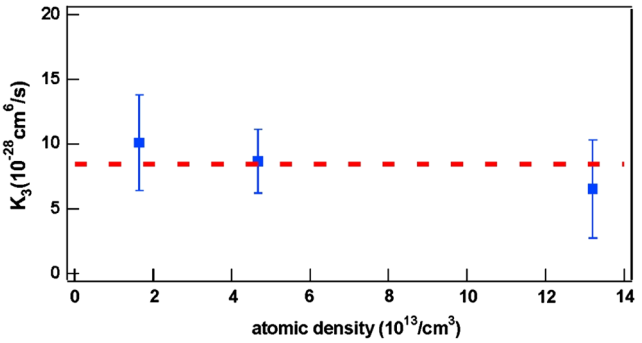

FIG. 2 (color online). Three-body inelastic collision rate coefficient K_3 versus atomic density for $E_\perp/E_{F\perp} = 1.8$. Blue dots: Experimental data. Error bars indicate statistical errors; Red dashed line: Fit to the data with $K_3 = (8.4 \pm 1.0) \times 10^{-28}$ cm^6/s. Bars denote statistical error.

the ground state, and the increased axial width reduces α_3 by a factor of 0.7 and α_2 by a factor of 0.8. As the gas heats, $E_\perp/E_{F\perp} \simeq 2$ increases up to 2.5 (see Fig. 1 inset), these correction factors change to 0.6 and 0.7, respectively. As the estimated changes in these systematic corrections introduce an error that is comparable to or smaller than the statistical uncertainty in our data, we neglect them in our initial analysis and assume that the axial width is time independent and equal to the ground state value. The rate constants determined from the fits can then be increased by the appropriate factor.

In the first set of experiments, we have measured atom number as a function of time in the unitary regime at 823 G, as shown in Fig. 1. The trap depth is set at 20% of the maximum attainable by reducing the laser intensity. The measured transverse energy of the cloud is $E_\perp/E_{F\perp} = 1.8$. We observe a significant ($> 60\%$) loss of the atoms in $\sim$20 sec. The data are fit with Eq. (3). We find that a three-body decay curve fits the data very well while a two-body decay curve increases χ^2 by a factor of 10. This indicates that three-body inelastic collisions play a dominant role in the atom loss.

Figure 2 shows the inelastic decay rate coefficient K_3 as a function of atomic density, at 823 G, for $E_\perp/E_{F\perp} = 1.8$. The atomic density is varied by varying the final trap depth. Data are fit to three-body decay curves, from which we determine K_3. A constant value of K_3 over a factor of 10 in atomic density indicates the atom loss is indeed a three-body decay process. By fitting all of the data with the same K_3, we obtain $K_3 = (8.4 \pm 1.0) \times 10^{-28}$ cm^6/s.

Table I shows K_3 as a function of magnetic field for $\langle x^2\rangle/x_{F\perp}^2 \sim 1.8$, which corresponds to the transverse energy $E_\perp/E_{F\perp} = 1.8$ at unitarity. In the table, $k_{F\perp} = (2mE_{F\perp})^{1/2}/\hbar$ is the two-dimensional Fermi wave vector for an ideal gas at the trap center and a is the s-wave scattering length. We fit our data on the BCS side of the Feshbach resonance, $a < 0$, with the function $K_3 = C|a|^s$ and find $s = 0.79 \pm 0.14$. As our experiments were not done in the threshold regime $(k_F a)^2 \ll 1$, it is not surprising that the exponent s differs from the theoretical prediction $s = 2.455$ of Ref. [14]. On the BEC side, K_3 increases as the magnetic field is tuned away from the Feshbach resonance, instead of peaking on the resonance. This is consistent with the experiments by other groups [5–7].

TABLE I. Three-body decay coefficient K_3. Here, K_3 is determined from Eq. (3) without the systematic correction for finite temperature (see text). $B(G)$ is the bias magnetic field in gauss. Scattering length a is calculated using the formula in [23]. $T_{F_\perp}$ is the transverse Fermi temperature for an ideal gas. Error bars are statistical.

B(G)	$a(10^3 a_0)$	$T_{F\perp}(\mu K)$	$1/k_{F\perp}a$	$\langle x^2\rangle/x_{F\perp}^2$	$K_3(10^{-28}$ cm^6/s)
780	6.4	8.7	0.20	2.1	17.3(3.2)
800	11	8.7	0.12	2.0	10.8(4.0)
823	36	9.9	0.03	1.8	8.4(1.0)
848	−32	9.0	−0.04	1.9	4.1(0.5)
877	−11	9.4	−0.11	1.9	3.5(0.9)
905	−7.4	8.7	−0.17	1.8	2.3(0.9)
934	−5.6	8.7	−0.23	1.8	1.9(0.7)
1174	−2.7	9.3	−0.46	1.8	0.45(0.23)

We have repeated the measurement of atom number versus time at 823 G, but at a lower energy $E_\perp/E_{F\perp} = 0.7$, Fig. 3. Neither two-body decay alone nor three-body decay alone fits the data. Instead, the combination of two-body and three-body decay fits the data well, which indicates two-body and three-body decays both contribute to the atom loss. We find $K_3 = (3.3 \pm 1.8) \times 10^{-28}$ cm^6/s and $K_2 = (0.42 \pm 0.16) \times 10^{-14}$ cm^3/s.

Surprisingly, the observed scaling of K_3 with transverse energy at 823 G is consistent with the threshold prediction of Ref. [14] for the scaling with *total* energy, where $K_3 \propto E$ for the lowest order process. We note that the suppression of K_3 with decreasing energy cannot arise from Pauli blocking, as the energetic final states are unoccupied. We observe $K_3(E_\perp/E_{F\perp} = 1.8)/K_3(E_\perp/E_{F\perp} = 0.7) = 2.5 \pm 1.4$, while the predicted ratio is $1.8/0.7 = 2.6$. Above

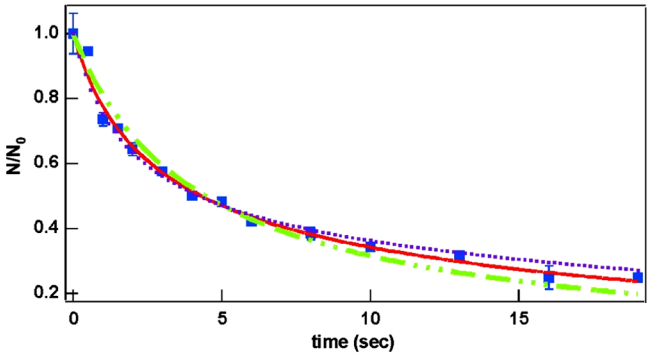

FIG. 3 (color online). Atom number versus time. Data were taken at $E_\perp/E_{F\perp} = 0.7$ in the unitary regime at 823 G. Blue dots: Experimental data; red solid curve: Combination fit including two-body and three-body decay; violet dotted line: Three-body decay fit; green dashed line: Two-body decay fit. Bars denote statistical error.

resonance at $B = 877$ G, we find $K_3 = 3.5 \pm 0.9 \times 10^{-28}$ cm^6/s at $\langle x^2\rangle/x_{F\perp}^2 = 1.9$ and $K_3 = 1.9 \pm 0.3 \times 10^{-28}$ cm^6/s at $\langle x^2\rangle/x_{F\perp}^2 = 0.8$. In this case, $K_3(\langle x^2\rangle/x_{F\perp}^2 = 1.9)/K_3(\langle x^2\rangle/x_{F\perp}^2 = 0.8) = 1.8 \pm 0.6$, while the ratio of the mean square widths is $1.9/0.8 = 2.4$. For data taken below resonance at a magnetic field of 780 G at $\langle x^2\rangle/x_{F\perp}^2 = 2.1$, we find $K_3 = (17.3 \pm 3.2) \times 10^{-28}$ cm^6/s. At $\langle x^2\rangle/x_{F\perp}^2 = 0.9$, we obtain $K_3 = (9.4 \pm 3.1) \times 10^{-28}$ cm^6/s. Then $K_3(\langle x^2\rangle/x_{F\perp}^2 = 1.8)/K_3(\langle x^2\rangle/x_{F\perp}^2 = 0.9) = 1.8 \pm 0.7$, while the ratio of the mean square widths is $2.1/0.9 = 2.3$, again consistent with linear scaling with energy [14].

We observe two-body loss rates at low energy $\langle x^2\rangle/x_{F\perp}^2 \leq 1$, in addition to the three-body rate. In contrast, at high energy, $\langle x^2\rangle/x_{F\perp}^2 \simeq 2$, we find $K_2 = 0$. At 780 G we obtain $K_2 = (0.57 \pm 0.22) \times 10^{-14}$ cm^3/s at $\langle x^2\rangle/x_{F\perp}^2 = 0.9$. On the BEC side of the Feshbach resonance, we expect that two-body inelastic collisions arise from molecule-atom or molecule-molecule [17]. We also observe a two-body rate in the unitary regime at $B = 823$ G for $E_\perp/E_{F\perp} = 0.7$ as noted above, $K_2 = (0.42 \pm 0.16) \times 10^{-14}$ cm^3/s. This is reasonable, since at low energy, pair-atom or pair-pair inelastic collisions are possible. Therefore, both two-body decay and three-body decay processes can play a role in the atom loss. Above the Feshbach resonance, we do not observe a two-body decay process for $1/(k_{F\perp}a) \leq -0.04$, i.e., $B > 848$ G. This suggests that no pairs are formed for $B > 848$ G at the lowest energy $E_\perp/E_{F\perp} = 0.7$ we achieve.

In conclusion, we have measured two- and three-body inelastic collision rates for a Fermi gas near a Feshbach resonance. The study of the two-body rate is quite interesting. Below resonance, it is known that inelastic atom-molecule or molecule-molecule collisions arise from decay to lower molecular vibrational states. Since the crossover regime involves tightly bound pairs, it is not farfetched to suggest that inelastic processes near and just above resonance arise from collisions involving correlated pairs. It is now accepted that the unitary Fermi gas system has preformed pairs [24], which exist at temperatures above the superfluid transition. These pairs share properties of Cooper pairs (they do not exist in free space) but they are small enough to behave much like molecules. Hence, a decay of a pair to a bound molecular state appears reasonable conjecture. That fact that the two-body rate just below resonance (molecular regime) is similar to the rate at resonance (no bound molecules) supports this conjecture, as does the vanishing of the two-body rate at high temperature. In this case, a many-body theory of inelastic collisions will be needed to replace the few-body theory that is valid far from resonance. The investigation of the energy (or temperature [21]) dependence of K_3 and K_2, will be an important topic for future work.

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