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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 $a_t = -2140a_0$, 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.

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 radiofrequency (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

polarized and primarily differ by their nuclear spin projection. The pairwise s-wave scattering lengths between these states (a_{12}, a_{23}, and a_{13}) exhibit three broad overlapping Feshbach resonances as shown in Fig. 1 [15]. For very large magnetic fields, each of the pairwise scattering lengths asymptote to the triplet scattering length for ^{6}Li, $a_t = -2140a_0$. Therefore, in the limit of large magnetic fields, the interactions are SU(3) symmetric [5].

Two-body spin-flip processes are expected to be especially small for this ultracold ^{6}Li mixture. Spin-exchange collisions are energetically forbidden in a magnetic field. Dipolar relaxation by electron spin flip is suppressed at high field as the gas becomes increasingly electron spin polarized in the lowest energy electron-spin state.

We can produce a degenerate Fermi gas (DFG) with an equal mixture of atoms in states $|1\rangle$ and $|2\rangle$ once every 5 s by evaporatively cooling this mixture in a red-detuned optical dipole trap [16]. During the first second, $\sim 10^8$ ^{6}Li atoms from a Zeeman-slowed atomic beam are collected in a magneto-optical trap (MOT). A crossed optical dipole trap which overlaps the MOT is then turned on and optimally loaded by tuning the MOT laser beams $\simeq 6$ MHz below resonance and reducing their intensity for 7 ms. The atoms are then optically pumped into states $|1\rangle$ and $|2\rangle$ prior to extinguishing the MOT laser beams and field gradient. The two beams which form the optical trap derive from a linearly polarized multi-longitudinal-mode 110 W fiber laser operating at 1064 nm. The beams nearly co-propagate in the vertical direction ($\hat{y}$), have orthogonal polarizations, and cross at an angle $\simeq 11°$. The beams are elliptical with calculated e^{-2} waist radii ~ 30 μm and ~ 100 μm at the point of intersection. The maximum trap depth per beam is $\simeq 1$ mK allowing $\sim 5 \times 10^6$ atoms to be initially loaded. We apply a bias field and a noisy rf pulse to create a 50-50 mixture of atoms in states $|1\rangle$ and $|2\rangle$ [16].

Forced evaporation of the atoms occurs at a field of 330 G where the two-state scattering length $a_{12} \simeq -280a_0$. We lower the depth of the optical trap U_0 by a factor of 107 over 3.6 s to obtain our final temperature. For the work presented here we study a gas at a temperature $T \gtrsim 0.5T_F$ (T_F is the Fermi temperature) so that it is appropriate to treat the cloud as a thermal gas in the

analysis. To suppress further loss by evaporation for the remainder of the experiment, U_0 is increased by a factor of 4 increasing the ratio of $U_0/k_B T$ by a factor $\simeq 2$. The final oscillation frequencies of the trap are $\nu_x = 3.84$ kHz, $\nu_y = 106$ Hz, and $\nu_z = 965$ Hz [17] with a final trap depth per beam $\simeq 40$ μK. The total number of atoms $\simeq 3.6 \times 10^5$ in a balanced two-state mixture at $T \simeq 1.9$ μK for which $T_F \simeq 3.7$ μK. The background limited $1/e$ lifetime $\simeq 30$ s.

To create an incoherent three-state mixture we first increase the strength of the magnetic field in 10 ms to 568 G where the mixture is stable. We then apply a noisy rf magnetic field with two frequencies centered on the $|1\rangle$-$|2\rangle$ and $|2\rangle$-$|3\rangle$ transitions (each with a power corresponding to an on-resonance Rabi frequency $\Omega \sim 2\pi \times 18$ kHz and both broadened to a width of 1 MHz). A magnetic field gradient of $\simeq 1$ G/cm in the direction of the bias field ($\hat{z}$) is simultaneously applied to destroy any internal state coherence in the sample. The noisy rf field remains on for 50 ms to create an equal mixture of $N \simeq 1.2 \times 10^5$ atoms in each state. At this point, $T = 1.9$ μK with $T_F = 3.2$ μK and the peak density in a single spin state is 5.5×10^{12} atoms/cm^3. We measure the population and temperature of atoms in each state separately by spectroscopically resolved absorption imaging (Fig. 2).

To investigate the magnetic field dependence of decay in this three-state mixture, we compared the number of atoms remaining in each spin state after spending two different times, 1 and 201 ms, at a particular field of interest B [see Fig. 3(a)]. For each experimental cycle the magnetic field was ramped in 10 ms from 568 G (where the mixture was first created) to the field of interest where it was held constant for either 1 or 201 ms. The field was then ramped in 10 ms to 953 G and held for 20 ms before absorption imaging at 953 G to measure the atom number ($N_{1\text{ ms}}$ or
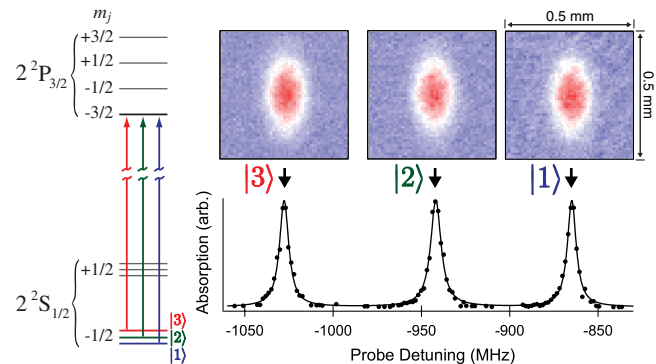
FIG. 2 (color online).   The population in states $|1\rangle$, $|2\rangle$ and $|3\rangle$ measured by absorption imaging in the Paschen-Back regime at a bias field of 568 G [23]. A σ^- polarized probe beam drives $m_j = -\frac{1}{2} \rightarrow m_{j'} = -\frac{3}{2}$ transitions which, due to the hyperfine interaction in the ground state, are spectroscopically resolvable. (Top right) The on-resonance absorption images show the density profile for the three states following a 900 μs time-of-flight expansion. (Bottom right) The total absorption vs probe detuning (relative to the $|f = \frac{1}{2}, m_f = -\frac{1}{2}\rangle \rightarrow |f' = \frac{3}{2}, m_{f'} = -\frac{3}{2}\rangle$ transition frequency in zero field).
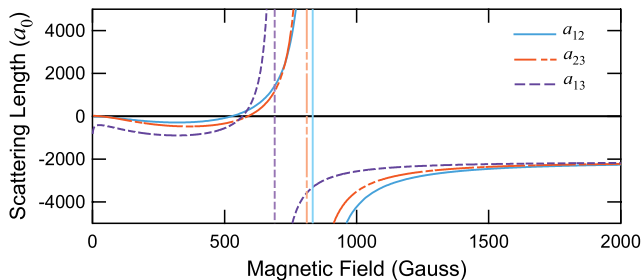

FIG. 1 (color online).   The s-wave scattering lengths as a function of magnetic field for interactions between the three lowest energy hyperfine ground states of ^{6}Li ($|1\rangle$, $|2\rangle$, and $|3\rangle$) [15]. Feshbach resonances occur at 690, 811, and 834 G.
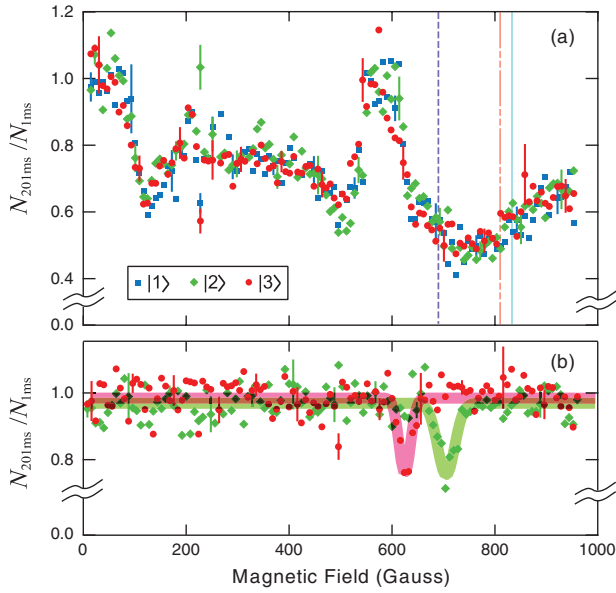
FIG. 3 (color). (a) Number remaining in each of the three spin states after spending 201 ms at the field of interest B (normalized to the number remaining after spending 1 ms at B). (b) Magnetic field dependence of decay in individual two-state mixtures. ◆ (●) indicates the normalized number remaining in state $|2\rangle$ ($|3\rangle$) of a $|2\rangle$-$|3\rangle$ ($|1\rangle$-$|3\rangle$) mixture after 201 ms. The thick lines guide the eye. The representative error bars indicate the standard deviation in the mean. Absorption images are taken at 953 G to ensure that any weakly bound molecules which remain trapped are dissociated and measured.

$N_{201\,\mathrm{ms}}$). The 10 ms field ramp to 953 G (where a_{12}, a_{23}, $a_{13} < 0$) ensured that any atoms which had formed weakly bound molecules in the vibrational state associated with the Feshbach resonances (but remained trapped) would be dissociated and measured. For each field value, $N_{201\,\mathrm{ms}}$ is normalized by $N_{1\,\mathrm{ms}}$ to correct for the fraction of atoms lost during the field sweeps, both to and from the field of interest B, which exhibited a slowly varying dependence on B. See Ref. [18] for the data before normalization.

To confirm that two-body loss does not contribute significantly to the measurements described above, we measured the ratio of atoms remaining after evolution times of 201 and 1 ms at fixed magnetic field values for each of the three possible two-state mixtures. Figure 3(b) shows the ratio $N_{201\,\mathrm{ms}}/N_{1\,\mathrm{ms}}$ for atoms in state $|3\rangle$ (state $|2\rangle$) of a $|1\rangle$-$|3\rangle$ ($|2\rangle$-$|3\rangle$) mixture. Data for the $|1\rangle$-$|2\rangle$ mixture (not shown) is very similar to that of the $|2\rangle$-$|3\rangle$ mixture (e.g., Ref. [19]). With the exception of loss features between 600 and 750 G, each two-state mixture was stable. The loss features are due to three-body recombination to bound molecular states associated with the Feshbach resonance. Since the two-state mixtures are stable for fields ≤ 600 and ≥ 750 G, loss features observed in three-state mixtures at these fields are due to three-body events involving one atom from each spin state.

In Fig. 3(a), the broad dominant loss feature centered at 720 G occurs in the vicinity of three overlapping interspe-

cies Feshbach resonances. Significant loss due to three-body recombination is expected near these resonances since recombination events involving one atom in each spin state are *not* suppressed by the exclusion principle and one expects a significant increase in the event rate when two or more scattering lengths are resonantly enhanced [20]. Similarly, high stability at zero field and near the zero crossings of the Feshbach resonances is not surprising since at least two of the scattering lengths are small at these fields. At high field, the stability increases relative to that at 720 G.

Unexpected resonant loss features are observed at 127 and 504 G, where the two-body scattering lengths are not predicted to exhibit any resonances. We have observed these features at higher temperatures and in a different trap configuration [18]. A possible explanation for the feature at 127 G is that the binding energy of a three-body bound state crosses through zero near this field value. At 504 G, we observe differing degrees of enhanced loss for the three states leading to population imbalance. This resonance was not observed in Ref. [13].

The feature at 228 G in Fig. 3 is consistent with our estimated location of a $|1\rangle$-$|3\rangle$ p-wave Feshbach resonance which would yield the observed preferential loss of atoms from states $|1\rangle$ and $|3\rangle$ [21]. We also observed a very narrow but inconsistent loss feature at 259 G (not shown). The modest increase in stability observed near 200 G did not appear in our other experimental data [18].

A second set of experiments measured three-body loss coefficients at fixed magnetic fields where the decaying populations remained balanced. In these experiments, the magnetic field is swept to the field of interest B in 10 ms after creation of the three-state mixture and the number $N(t)$ and temperature $T(t)$ of atoms in state $|3\rangle$ are then measured at the field B for various delay times t. To extract the three-body loss coefficients, we fit this data assuming one- and three-body loss and heating due to three-body recombination.

When three-body recombination involves one atom from each spin state, the number of trapped atoms in each of the equally populated spin states $N(t)$ evolves according to $\dot{N} = -L_1 N - L_3 \langle n^2 \rangle N$. Here, $\langle n^2 \rangle$ is the average value of the squared density per spin state and L_3 (L_1) is the three-body (one-body) atom-loss rate coefficient. The density distribution in the trap is well described by a thermal distribution so that

$$\frac{dN}{dt} = -L_1 N - \gamma \frac{N^3}{T^3}, \qquad (1)$$

where $\gamma = L_3 (m\bar{\omega}^2 / 2\pi k_B)^3 / \sqrt{27}$ and $\bar{\omega} = (\omega_x \omega_y \omega_z)^{1/3}$. Following Ref. [22], we model the temperature increase in the gas as arising from "antievaporation" and recombination heating. The temperature evolves as

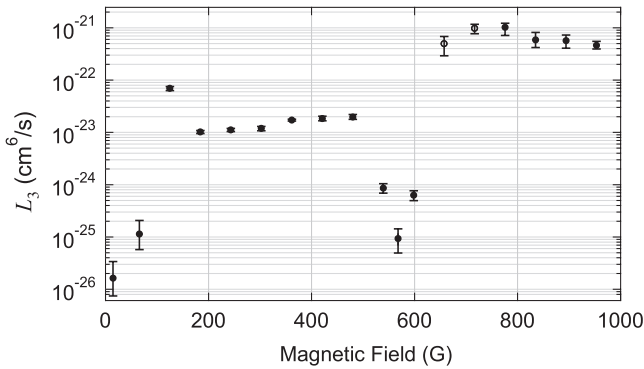$$\frac{dT}{dt} = \gamma \frac{N^2}{T^3} \frac{(T + T_h)}{3}, \qquad (2)$$

FIG. 4.   Three-body loss rate coefficient, L_3, at various fields.

where $k_B T_h$ is the average energy deposited in the gas per recombination event.

For a given parameter set $[N(0), T(0), L_1, L_3$ and $T_h]$, Eqs. (1) and (2) can be numerically integrated to give $N(t)$ and $T(t)$. The best-fit parameters for a data set at a given field are determined by minimizing χ^2. The best-fit L_3 values at various fields are displayed in Fig. 4. For these fits, T_h varied from 1.5–4 μK and L_1 varied from 0.1–0.33 s^{-1}. The error bars in Fig. 4 indicate the 68% confidence interval due to statistical uncertainty in all fit parameters. The error bars do not include a systematic uncertainty of $\pm 70\%$ arising from our uncertainty in atom number ($\pm 30\%$) and trap frequencies ($\pm 5\%$).

As shown in Fig. 4, L_3 varies by over 4 orders of magnitude. In the range 600 G $< B <$ 750 G, the L_3 values may be overestimated since the measured decay includes loss events we observe in two-state mixtures at these field values. Near 0 and 568 G, three-body recombination rates are relatively small and stable three-state Fermi gases can be created. For $L_3 = 10^{-25}$ cm^6/s, a gas with a density $n = 10^{12}$ cm^{-3} per spin state has a $1/e$ lifetime $\sim$10 s. Consistent with the data shown in Fig. 3(a), a resonant peak in L_3 is observed at $B \simeq 127$ G. We do not report a value for L_3 at the location of the 504 G resonant feature [Fig. 3(a)] since a population imbalance develops there. The highest L_3 value we report (10^{-21} cm^6/s) occurs at 775 G and is likely unitarity limited (for fields >600 G, $T \simeq 6$ μK due to heating). We observe that L_3 decreases by a factor of $\simeq 2.5$ as the field is increased from 775 to 953 G, the highest field we currently access. This trend suggests that L_3 may decrease further in the high field limit where $a_{12}, a_{23}, a_{13} \rightarrow -2140 a_0$.

In conclusion, we can create long-lived three-state DFGs of ^{6}Li atoms for fields near 568 G. The minimal two-body loss we observe makes this system promising for future studies of Efimov trimers. Indeed, the loss resonances at 127 and 504 G may be occurring at field values where trimer states cross the dissociation threshold. The recombination rates at high fields need not preclude experiments designed to study color superfluidity and trion formation [5]. For instance, using low density gases ($n \sim 5 \times 10^{10}$ cm^{-3}) and large period ($d \simeq 2$ μm) optical latti-

ces, long lifetimes ($\gtrsim 0.1$ s), and strong interactions can simultaneously be achieved.

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