Collisional Loss of One-Dimensional Fermions Near a $p$-Wave Feshbach Resonance

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(Received 4 July 2020; accepted 26 October 2020; published 30 December 2020)

We study collisional loss of a quasi-one-dimensional spin-polarized Fermi gas near a $p$-wave Feshbach resonance in ultracold $^6$Li atoms. We measure the location of the $p$-wave resonance in quasi-1D and observe a confinement-induced shift and broadening. We find that the three-body loss coefficient $L_3$ as a function of the quasi-1D confinement has little dependence on confinement strength. We also analyze the atom loss with a two-step cascade three-body loss model in which weakly bound dimers are formed prior to their loss arising from atom-dimer collisions. Our data are consistent with this model. We also find a possible suppression in the rate of dimer relaxation with strong quasi-1D confinement. We discuss the implications of these measurements for observing $p$-wave pairing in quasi-1D.

DOI: 10.1103/PhysRevLett.125.263402

The realization of ultracold atomic Fermi gases has provided experimental access to a wide array of phenomena, largely because of the presence of Feshbach resonances (FRs) that provide for externally tunable interactions [1–4]. In addition to the usual $s$-wave interactions between distinguishable fermions, higher partial-wave interactions may be tuned via FRs [5]. $p$-wave interactions are of particular interest as they are the dominant low-energy scattering process between identical fermions and are predicted to exhibit phenomena distinct from those observed in $s$-wave interacting Fermi gases [6]. In particular, pairing between identical fermions is an essential ingredient of the Kitaev chain Hamiltonian [7], which supports Majorana zero modes at the ends of the chain. These zero modes have been observed in semiconducting nanowires [8] and are a promising candidate platform for fault-tolerant quantum computing [9,10].

$p$-wave FRs have been observed in $^{40}$K [11–13] and $^6$Li [14–19]. The severe atom losses associated with these resonances, however, have limited their usefulness. Three-body losses, which are suppressed by symmetry in the case of a fermionic two-spin system with $s$-wave interactions [20], are not suppressed for $p$-wave interactions. Much work has been done in characterizing the atom loss associated with $p$-wave FRs [21–24], and there is renewed interest in studying these resonances in reduced dimensions. Recent theoretical work has suggested that three-body losses may be suppressed in quasi-1D [25]. The absence of a centrifugal barrier in 1D results in Feshbach dimers that have extended wave functions which overlap less with deeply bound molecules. If three-body loss is suppressed by this mechanism, it might open a path toward realizing $p$-wave pairing in quasi-1D and emulating the Kitaev chain Hamiltonian.

We present an experimental study of three-body losses near a $p$-wave FR of identical $^6$Li fermions in quasi-1D.

We measure the three-body loss coefficient ($L_3$) as a function of 1D confinement for a direct three-body process. We also analyze the observed atom loss within the framework of a cascade model with explicit dimer formation and relaxation steps [26,27], using in situ imaging to reduce the effect of the inhomogeneous density. Finally, we characterize the confinement-induced shifts in the resonance position that appear in quasi-1D [28–32]. These shifts allow us to extract a value for the effective range.

The apparatus and the experimental methods we use to prepare degenerate Fermi gases have been described previously [33–35]. A $^6$Li degenerate Fermi gas is first prepared in the two lowest hyperfine states of the $S_{1/2}$ manifold (states $|1\rangle$ and $|2\rangle$, respectively) at 595 G, and then loaded into a crossed-beam dipole trap formed by three linearly polarized mutually orthogonal laser beams of wavelength $\lambda = 1.064 \mu m$. Each beam is retroreflected, with the polarizations of the incoming and retroreflected beams initially set to be perpendicular to each other to avoid lattice formation. We eliminate state $|1\rangle$ from the trap with a resonant burst of light. At this stage, we obtain $9(1) \times 10^4$ atoms in state $|2\rangle$ in a nearly isotropic harmonic trap with a geometric-mean trapping frequency of $2\pi \times 305(2)$ Hz, and at a temperature $T/T_F \approx 0.1$ where $T_F$ is the Fermi temperature. The optical trap depths are increased and the polarizations of the retroreflected beams are rotated to achieve a 7 $E_r$ deep 3D optical lattice, where $E_r = h^2/(2m\lambda^2)$ = $k_B \times 1.41 \mu K$ is the recoil energy, and $m$ is the atomic mass. During the lattice ramp-up, a copropagating beam of 532 nm light is introduced along each trapping-beam dimension to flatten the trapping potential [33,34]. By tuning these compensation beam powers, we create a 3D band insulator with a central density of approximately 1 atom per site. In order to produce a 2D lattice, which is an array of quasi-1D tubes,
we slowly turn off the compensation beams and the vertical lattice beam, while increasing the intensity of the two remaining beams to achieve a desired 2D lattice depth $V_L$. This depth determines the confinement in the quasi-1D traps, which is parametrized by $a_\perp = \sqrt{2\hbar/m\omega_z}$ transversely and $R_F$ axially, where $\omega_z = \sqrt{4E_z V_L}/\hbar$ is the trapping frequency of a lattice site when approximated as a harmonic potential, and $R_F(N_{j,j},\omega_z) = \sqrt{2(N_{j,j} + 1)\hbar/m\omega_z}$ is the Fermi radius of tube $j$ with number of atoms $N_{j,j}$ and an axial frequency $\omega_z$. The aspect ratio of the quasi-1D tubes $\omega_z/\omega_r \approx 170$. We load a maximum of around 30 atoms per quasi-1D tube with $T \ll T_F$ to avoid exciting any radial modes.

We use a two-step servo scheme to stabilize the current in the coils producing the Feshbach magnetic field, because the $^6$Li $|1\rangle - |1\rangle$ $p$-wave FR near 159 G is very narrow. The first servo $S_1$ provides the large dynamic range required to run our experimental sequence, while the second servo $S_2$ controls the current in a bypass circuit added in parallel to the magnetic coils. This improves the stability of the magnetic field to ±10 mG and provides finer magnetic-field resolution. After reaching the hold field $B$, the atoms are transferred into $|1\rangle$ with a π pulse of duration 75 μs using rf radiation resonant with the $|1\rangle - |2\rangle$ transition. After a hold time $\tau$, we ramp the field back to 595 G, where the distribution of the remaining atoms is imaged using in situ phase-contrast imaging with a probe beam propagating perpendicular to the tube axis [35]. By using the inverse Abel transform, which exploits the approximate cylindrical symmetry of the 2D lattice, we measure the distribution with a spatial resolution of approximately three lattice constants. We sector the 2D lattice into concentric shells in which the tubes have similar chemical potentials $\mu$. This procedure is useful as scattering processes are in general energy dependent, so observables depend on rate coefficients that are averaged over the Fermi-Dirac distribution for atoms in each tube.

We characterize the $|1\rangle - |1\rangle$ $p$-wave FR in 3D and quasi-1D by measuring atom loss as functions of $B$ and $\tau$. In 3D, we find the onset of loss at 159.05(1) G, which agrees with previous measurements of the location in 3D [15,17] but differs with other measurements [19,36] by a few tens of milligauss. We are not able to resolve the expected doublet feature arising from the dipole-dipole interaction [12,19,37] because of limitations of the field stability. All the 1D data in this Letter were measured with the magnetic field aligned with the $z$ axis, and thus only involve collisions with the $m_I = 0$ projection of the angular momentum. As $V_L$ is increased, we observe a confinement-induced shift in the resonance field and broadening of the atom-loss feature, as shown in Fig. 1(a).

We review $p$-wave scattering in 3D and quasi-1D to show how the measured confinement-induced shift can be used to extract $\alpha_p$, the 3D effective range. For low-energy collisions in 3D, the cotangent of the phase shift $\delta_p$ associated with $p$-wave scattering can be expanded as a function of scattering volume $V_p$ and effective range $\alpha_p$ [38]:

$$k^3 \cot[\delta_p(k)] = \frac{1}{V_p} - \frac{\alpha_p k^2}{2} + O(k^4),$$

where $\alpha_p > 0$ and has units of inverse length. These scattering properties are modified in quasi-1D,

$$k \cot[\delta_p(k)] = \frac{1}{L_p} - \xi_p k^2 + O(k^4),$$

where $L_p$ is the 1D scattering length and $\xi_p$ is the 1D effective range, which has units of length. These quasi-1D scattering parameters are given by $L_p = 3a_\perp [a_\perp^2/2V_p + \alpha_p a_\perp + 6]\zeta(-1/2)]^{-1}$ and $\xi_p = \alpha_p a_\perp^2/6$ [30–32], where $\zeta$ is the Riemann zeta function $\zeta(-1/2) \approx -0.208$. The second and third terms in $1/L_p$ lead to a confinement-induced shift in the resonance location. In this formalism, only dynamics along the axial dimension are relevant, and scattering...
quantities, such as the elastic scattering cross section, are expressed in units appropriate for 1D.

By performing a coupled-channel calculation, which requires detailed knowledge of the interatomic potentials [39], we obtain an expansion $1/V_L(B)$ up to second order in $B$. The effective range $\alpha_p$ can be approximated as a constant independent of $B$ for the relevant range of magnetic field. The FR in 3D occurs at the magnetic field $B_{3D}$ at which $V_p$ diverges. Similarly, in quasi-1D, the resonance occurs when $l_p$ diverges at a magnetic field $B_{1D}$, which is a function of $V_L$ and $\alpha_p$. The confinement-induced shift, $\delta_B(V_L, \alpha_p) = B_{1D} - B_{3D}$, can be approximated to leading order in confinement strength $V_L$ by [40]

$$
\delta_B = \frac{-2m}{\hbar^2} \left. \frac{\partial (1/V_L)}{\partial B} \right|_{B=B_{3D}} \alpha_p \sqrt{V_L E_r} \tag{3}
$$

We cannot accurately measure $B_{3D}$ for $m_i = 0$ alone due to the unresolved $|m_i| = 1$ collisions in 3D, so we fit the measured $\delta_B$ as a function of $V_L$ to Eq. (3) by taking $\alpha_p$ and $B_{3D}$ as fitting parameters. The result of the fit to the quasi-1D data is shown by the solid curve in Fig. 1(b). We obtain $\alpha_p = 0.14(1) a_0^{-1}$, which is consistent with our coupled-channel result of $0.1412 a_0^{-1}$, where $a_0$ is the Bohr radius, and $B_{3D} = 159.07(1)$ which is consistent with our loss-onset measurement and a dipolar splitting of 10 mG in 3D [19]. We also find a consistent value by analyzing previous measurements performed on a 2D gas of $^6$Li in state $1s$ [21,40].

The observed atom loss is presumably due to the formation of deeply bound molecules. To characterize the loss, we measured $N$, the number of atoms remaining in the trap after a hold time $\tau$, for various $B$ and $V_L$. Background-gas collisions lead to a $1/e$ atom lifetime of 38 s in this apparatus, and are negligible for this analysis. Atom loss due to three-body collisions is described by

$$
\frac{\dot{N}}{N} = -L_3 n^2, \tag{4}
$$

where $n^2 = (N_{i,c}/2R_{F,c})^2$ is the squared atomic line density for a central tube, determined using a length scale of twice the local Fermi radius $R_{F,c}$. We measure the time evolution with $V_L$ between 15 and 75 $E_r$ and extract $L_3$ by fitting loss versus $\tau$ to Eq. (4). Figure 2(a) shows such a fit to typical loss data. Since $L_3$ also depends on $\Delta B$, the field detuning from resonance, we extract $L_3$ from the time evolution at several $\Delta B$ to find the peak value for each $V_L$. The peak $L_3$ for all $V_L$ are found to be approximately $(7(2) \times 10^{-6})$ cm$^2$/s. We observe no dependence on 1D confinement in this range [40]. Because of the inhomogeneity of the initial distribution of atoms across the 2D lattice, however, we find a rather poor agreement of the data to Eq. (4).

The results of a more comprehensive analysis of the same data that provides an improved fit to Eq. (4) is shown in Fig. 2(b). Here, we group the tubes into separate cylindrical shells (labeled by $i$) [40] and a corresponding Fermi temperature $T_{F,i}$. Since the tunneling rate is small compared to the hold time, we assume that the atoms remain in the same tube, and thus the same shell during the collision process. Figure 3(a) shows $L_3$ for each shell extracted from data with $V_L = 75 E_r$ versus $\Delta B$. The peak $L_3$ for each shell is in the range of $5 \times 10^{-6}$ to $1 \times 10^{-5}$ cm$^2$/s, and is similar to the peak $L_3$ extracted from the whole atomic cloud.

In Ref. [25], Zhou and Cui suggest that the rate of three-body loss near a $p$-wave FR can be suppressed by reducing the overlap between the wave functions of a deeply bound molecule and a Feshbach dimer with increasing confinement. To investigate this hypothesis, we analyze our
observed loss data using a cascade model of two consecutive two-body processes instead of a direct three-body event: two atoms resonantly form a dimer, followed by a collision between the dimer and an atom, resulting in a deeply bound molecule and an atom [26]. This approach has previously been applied to the particular p-wave FR we study, but in 3D and quasi-2D [27]. It is the natural formalism in which to evaluate the predicted suppression, as it models the formation and relaxation of dimers. The equations governing this loss process are

\[
\frac{dN_a}{dt} = 2\frac{\Gamma}{\hbar} N_a - 2K_{aa} \frac{N_a(N_a - 1)}{4R_F} - K_{ad} N_a N_d, \quad (5a)
\]

\[
\frac{dN_d}{dt} = -\frac{\Gamma}{\hbar} N_d + K_{aa} \frac{N_a(N_a - 1)}{4R_F} - K_{ad} N_a N_d, \quad (5b)
\]

where \(N_a\) is the number of atoms, \(N_d\) is the number of dimers, \(K_{aa}\) is the two-body event rate for atom-atom collisions converting atoms into dimers, and \(K_{ad}\) is the two-body atom-dimer inelastic collision event rate. \(\Gamma\), the one-body decay rate of dimers, is the width of the FR. The rate of dimer formation is proportional to the number of possible pairs of atoms, given by \(N_a(N_a - 1)/2\).

\(K_{ad}\) is of particular interest, as it depends on the overlap between dimers and deeply bound molecules. Both \(\Gamma\) and \(K_{aa}\) are related to the elastic scattering cross section \(\sigma_{1D}(E)\), which can be calculated, thus constraining the fit to the cascade process to a single parameter, \(K_{ad}\). \(\sigma_{1D}(E)\) may be approximated by a Lorentzian in collision energy, \(E = \hbar^2 k^2/m\), centered at the above-threshold binding energy of the Feshbach dimer \(E_{\text{res}} = -\hbar^2/4\xi_p^2 \mu > 0\) and with width \(\Gamma = (\hbar/\xi_p)^2\sqrt{4E_{\text{res}}/m} [6,40]\).

\[K_{aa} = \langle \sigma_{1D}(k_r) v_r \rangle = \hbar \int_{-\infty}^{\infty} dk_r \sigma_{1D}(k_r) v_r P(k_r), \quad (6)\]

where \(P(k_r)\) is the probability density function of \(k_r\) obtained from the density distribution of a trapped Fermi gas [40]. We assume a global temperature \(T\) across the entire sample. However, \(\mu\) varies significantly from tube to tube due to the density inhomogeneity across the 2D lattice. This effect is mitigated by sectoring the cloud into shells of similar \(\mu\), as discussed earlier, thus giving a distinct value of \(K_{ad}\) for each shell. For each quasi-1D tube, \(\mu\) is determined by \(N_{ij}\) and \(T\).

Although we cannot directly measure \(T\), we exploit the fact that at a sufficiently large \(\Delta B\), the rate equations can be approximated as a direct three-body loss process with a loss coefficient \(\tilde{L}_3 = (3/2)\hbar K_{ad}\Gamma/\Gamma\) under the assumptions of a steady-state dimer population \((dN_d/dt = 0)\) and \(\Gamma/\hbar \gg K_{ad} N_a/2R_F [27]\). Assuming that these assumptions hold for large \(\Delta B\), we fit the measured values of \(L_3\) for each shell with \(T\) and \(K_{ad}\) as fitting parameters to \(\tilde{L}_3\). We find that \(T = 0.1T_{F,1}\), and that \(K_{ad} = 0.67\ \text{cm/s}\) is independent of field for \(\Delta B > 100\ \text{mG}\). The assumptions given above are confirmed in this section. The solid lines in Fig. 3(a) show \(L_3\) for each shell.

The extracted \(K_{ad}\) values from fitting loss data for \(V_L = 75\ E_r\) are shown in Fig. 3(b) for the full range of \(\Delta B\) [40]. We find that under these conditions, Eqs. (5) model the time behavior of the observed loss as well as Eq. (4), as there is little difference between the fit to the cascade model [40] and the direct three-body loss model. The values of \(K_{ad}\) extracted for \(\Delta B > 50\ \text{mG}\) are field independent. The observed field independence strongly supports the cascade model as the atom-dimer collision process is inherently nonresonant. In the dimer formation step, the atoms must collide with a momentum dictated by the binding energy of the dimer, which is field dependent. The dimer relaxation step, however, may proceed for any collision momentum, as the atom receives the binding energy of the deeply bound molecule.
The behavior of $K_{\text{ad}}$ for $\Delta B < 50$ mG is consistent with a suppression of the rate of dimer relaxation. The spatial overlap of the dimer and deeply bound wave functions increases with $\kappa a_{\perp}$, where $\kappa = \sqrt{mE_{\text{res}}}/\hbar$, so the predicted suppression is strongest for small $\Delta B$, where $E_{\text{res}}$ is smallest. The suppression is expected to be significant for $\kappa a_{\perp} < 1/2$ [25], which for $V_L = 75 E_r$ corresponds to $\Delta B < 27$ mG. Another interpretation of the small-detuning behavior of $K_{\text{ad}}$ is that the cascade model breaks down due to, for example, the existence of a shallow three-body bound state [41].

This work is the first detailed experimental study of $p$-wave collisions in quasi-1D. We confirm the confinement-induced shift and broadening as a function of $V_L$. The confinement-induced shift agrees well with quasi-1D theory [32] and the extracted value of $\alpha_p$ agrees with previous work [21]. We measure $L_3$ as a function of $V_L$ and find no dependence up to $75 E_r$. The magnetic field independence of $K_{\text{ad}}$ for $\Delta B > 50$ mG strongly supports the validity of the cascade model [26,27] for three-body loss in quasi-1D in the regime of large $\Delta B$ (> 100 mG), as well as for intermediate $\Delta B$ (50–100 mG) where the cascade model is not well approximated by the three-body loss rate equation.

The suppression in $K_{\text{ad}}$ at $\Delta B < 50$ mG is possibly explained by $p$-wave dimer stretching [25]. Achieving greater suppression in $^4$Li by increasing $V_L$ is challenging since at a fixed $\Delta B$, $\kappa a_{\perp} \propto 1/V_L^{3/4}$ [40], but future work at even higher $V_L$ or with improved magnetic field resolution and stability would enable further study of this narrow feature. The implications for loss suppression due to the closed-channel character of the $p$-wave resonance used here remains to be fully understood theoretically. Our result also provides insight into a potential path toward observing pairing between identical fermions in cold atom systems. Suppressing loss in heavier fermions with FRs, such as $^{40}$K [11–13], $^{164}$Dy [42], and $^{167}$Er [43], is promising, as small values of $\kappa a_{\perp}$ may be more readily achieved in these atoms.

We would like to thank T. L. Yang for his contributions to the apparatus and W. I. McAlexander for his coupled-channel code. This work was supported in part by the Army Research Office Multidisciplinary University Research Initiative (Grants No. W911NF-14-1-0003 and No. W911NF-17-1-0323), the NSF (Grant No. PHY-1707992), and the Welch Foundation (Grant No. C-1133). D.C.-C. acknowledges financial support from CONACyT (Mexico, Scholarship No. 472271).

Note added.—Recently, another group reported on a similar experiment [44]. Although both groups observe similar overall atom loss, they report a suppression of $L_3 \propto V_L^{-1}$, while we find $L_3$ independent of $V_L$ over a wide range (Fig. S2 of Supplemental Material [40]). The difference lies in the choice between defining $L_3$ using the 3D or the 1D densities. In their analysis, $L_3$ is defined in terms of the 3D density of a tube, which increases with $V_L^{1/2}$, while we use the 1D line density. While the two results are consistent, we argue that 1D densities are most appropriate based on physical and practical considerations. Physically, the dimensionless quantity $\kappa a_{\perp}$ parametrizes the effective dimensionality of the system near a FR, and the peak values of $L_3$ we report were measured in regions where $\kappa a_{\perp} < 1$. Practically, 1D units make it clear that the peak loss rate is independent of $V_L$.

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[40] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.125.263402 for information regarding the derivation of Eq. (3), the confinement-induced shift in quasi-2D, the dependence of $L_3$ versus $V_L$, in situ imaging data, the fitting of time evolution data to the cascade model, the quasi-1D $p$-wave scattering cross section, the probability density function of $k_\perp$, and the dependence of $k_\perp$ on $V_L$.

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