Detection of Spatial Correlations in an Ultracold Gas of Fermions

M. Greiner,* C. A. Regal, C. Ticknor, J. L. Bohn, and D. S. Jin†

JILA, University of Colorado and National Institute of Standards and Technology, and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440, USA

(Received 26 August 2003; published 15 April 2004)

Spatial correlations are observed in an ultracold gas of fermionic atoms close to a Feshbach resonance. The correlations are detected by inducing spin-changing rf transitions between pairs of atoms. We observe the process in the strongly interacting regime for attractive as well as for repulsive atom-atom interactions and both in the regime of high and low quantum degeneracy. The observations are compared with a two-particle model that provides theoretical predictions for the measured rf transition rates.

DOI: 10.1103/PhysRevLett.92.150405 PACS numbers: 03.75.Ss, 34.50.–s

Close to a Feshbach resonance [1–3], ultracold fermionic atoms form a strongly interacting quantum gas. Recently, it has become possible to study this exotic quantum regime with ^{40}K and ^{6}Li atoms. Mean-field interactions [4–6] and hydrodynamic behavior [4,5,7] have been observed. However, a Feshbach resonance does more than simply alter the interactions between atoms. The resonance occurs when the collision energy of two free atoms coincides with that of a molecular state in a closed channel. Fermionic atom pairs populating this closed channel can be described by a composite-boson field. It has been proposed that this composite-boson field can lead to fermionic superfluidity at critical temperatures T_c comparable to the Fermi temperature T_F [8–10].

For a magnetic-field detuning on the side of the resonance with repulsive atom-atom interactions, coupling between the open and the closed channels gives rise to a new molecular bound state [11]. By adiabatically scanning over a magnetic-field Feshbach resonance, large numbers of these extremely weakly bound molecules have been created reversibly in a ^{40}K fermionic quantum gas [12] and recently also with other fermionic [13–15] and bosonic [16,17] atomic species. Bose-Einstein condensation of these molecules is being pursued. By inducing radiofrequency (rf) transitions, these molecules have been photodissociated into free pairs of atoms, and the corresponding dissociation spectra provided precise information about molecular wave functions and binding energies [12].

With the opposite sign of the magnetic-field detuning, this new molecular state does not exist. However, coupling to the resonance state in the closed channel still significantly changes the atom pair wave function. For example, a well-studied effect of the resonance, for either sign of the magnetic-field detuning, is to modify the scattering phase shift at large internuclear separation R, and thus change the scattering length. In this Letter, we instead probe the effect of a Feshbach resonance on the wave function for an interacting atom pair at small internuclear separation. By driving rf transitions selectively for closely spaced pairs of atoms, we can detect spatial correlations on a short length scale. Thereby we probe the population of the closed channel or composite-boson field.

Coupling to the resonance state in the closed channel enhances the amplitude of the wave function at very small internuclear separation. The spatial size of the closed channel resonance state, which is approximately $50a_0$, where a_0 is the Bohr radius, is 2 orders of magnitude smaller than the average separation between particles for a typical trapped gas. Thus, the effect of the resonance is to increase the pair correlation function at $R \sim 0$ and thereby increase spatial correlations on a short length scale. To demonstrate how large this effect can be, we calculate that near a Feshbach resonance the fraction of atom pairs at $R \leq 50a_0$ is 5 orders of magnitude larger than away from the resonance.

We probe these atom pair correlations at $R \sim 0$ by inducing a class of spin-changing rf transitions that is expected to occur only for spatially correlated and interacting pairs of atoms. For bare atoms, spin-changing transitions can be induced by applying an rf field with a frequency ν_0 corresponding to the Zeeman splitting of the spin states. The transition probability diminishes if the detuning Δ of the rf field is large compared to the Rabi frequency Ω. In contrast, an interacting pair of atoms at small R can have a significant transition probability for relatively large detunings. In Fig. 1, we illustrate this process with a two-particle model. Here an rf transition can occur, in which not only the spin but also the relative momentum of the free atom pair is changed (Fig. 1).

In the following, we show that we experimentally observe rf transitions between correlated pairs of atoms when a detuned rf field is applied to an ultracold gas of fermions. This process is only detected close to a Feshbach resonance and thereby directly demonstrates strong spatial correlations in this exotic quantum regime. Although many-body physics is likely to play a significant role in this regime, we compare the observations

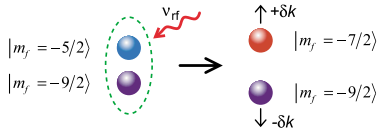

FIG. 1 (color online). Two-particle model of spin-changing rf transitions between interacting pairs of atoms in the $m_f = -5/2$ and $m_f = -9/2$ spin state. After the transition the spin state of the first atom is changed to $m_f = -7/2$. In addition, the relative momentum of the atoms at large internuclear separation can be changed by $2\delta k$ in this process if the applied radio frequency ν_{rf} is detuned with respect to the $m_f = -5/2 \rightarrow m_f = -9/2$ transition of bare atoms. The total kinetic energy of the free atoms is changed by an amount equal to the excess energy of the rf photon.

with a two-particle model as a first step toward understanding the correlations.

The experimental setup and procedure are similar to that in our previous experimental work [4,12,18]. In brief, we evaporatively cool a spin mixture of ^{40}K atoms in the lowest hyperfine ground state. The first cooling step is carried out in a magnetic trap. Then, the atoms are loaded into an optical dipole trap, where further evaporative cooling is performed by lowering the depth of the trapping potential. Finally, we prepare about 10^6 atoms at an adjustable temperature, which for these experiments is between $T = 0.33T_F$ and $1.0T_F$. The final radial trapping frequency ranges between $\nu_r = 200$ Hz and $\nu_r = 450$ Hz, and the axial trapping frequency is given by the fixed ratio $\nu_r/\nu_z = 70$. In the experiments, the Fermi momentum at temperatures $T = 0.33T_F$ is on the order of $k_F = (2000a_0)^{-1}$.

We can widely vary the interaction between atoms using an s-wave Feshbach resonance, which is located at a magnetic field of $B = 224.21 \pm 0.05$ G and has a width of 9.7 ± 0.6 G [4]. Feshbach resonances have been exploited for quantum degenerate Bose and Fermi gases [4–7,11–22]. The s-wave resonance used in this experiment affects collisions between atoms in the $|f = 9/2, m_f = -5/2\rangle$ and $|f = 9/2, m_f = -9/2\rangle$ spin states. Here f denotes the total angular momentum and m_f the magnetic quantum number. The effective scattering length of the atoms can then be varied by tuning the strength of a homogenous magnetic field around the Feshbach resonance value.

Initially, the atoms are prepared in the $f = 9/2$ hyperfine state in an incoherent spin mixture of the $m_f = -7/2$ and the $m_f = -9/2$ states. In these states, the atoms are not affected by the Feshbach resonance. Then, after ramping to the final magnetic-field value B, the atoms in the $m_f = -7/2$ state are transferred into the $m_f = -5/2$ state by applying an rf π pulse between the Zeeman sublevels. In these states, the atoms are strongly interacting if the magnetic field is chosen close to resonance. This sequence, which may result in a nonequilibrium sample, was chosen to suppress the population of the molecular bound state close to threshold that exists on the repulsive side of the resonance. This is in contrast to our previous work, where large numbers of molecules were reversibly created by ramping the magnetic field across the Feshbach resonance.

The basic idea of the experiment is to use the rf spectroscopy method described above to look for an enhancement in the $R \sim 0$ pair correlation function near a Feshbach resonance. We apply an rf field pulse to induce transitions from the $m_f = -5/2$ to the $m_f = -7/2$ state. The frequency of the rf field ν_{rf} is far detuned with respect to the bare atom transition frequency ν_0, with a detuning $\Delta = 2\pi(\nu_{\mathrm{rf}} - \nu_0)$ whose magnitude is larger than the resonant Rabi frequency Ω. Therefore, only a small fraction of bare atoms undergo an off-resonant rf transition. The detuning is also large compared to mean-field shifts [4]. Nevertheless we find a significant, magnetic-field dependent transition rate that peaks in the strongly interacting regime close to the Feshbach resonance.

In Fig. 2, the fraction of atoms transferred into the $m_f = -7/2$ state is plotted as a function of magnetic field B. We observe pair transitions on both the repulsive (low B) and attractive (high B) sides of the resonance. Figure 3 demonstrates that for longer pulses the fraction of transferred atoms saturates at a finite value.

For comparison to this measurement, we have constructed a complete two-body multichannel scattering theory that includes the rf interaction [23,24]. Here nearby atoms perturb each other's internal structure so that a pair can absorb an rf photon that is not resonant

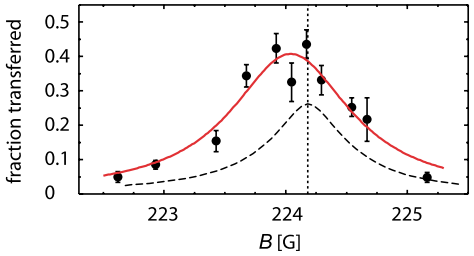

FIG. 2 (color online). Atom pair signal for different magnetic-field values B near the Feshbach resonance. The fraction of atoms transferred from the $m_f = -5/2$ into the $m_f = -7/2$ spin state is measured by spin-selective time-of-flight absorption imaging after an rf pulse with a Rabi frequency of $\Omega = 2\pi \times 32$ kHz is applied for 100 μs. For each B, ν_{rf} is chosen so that the rf field is kept at a constant large detuning $\Delta = -2\pi \times 100$ kHz with respect to the bare atom transition. A calculated 6.3% of off-resonantly transferred bare atoms has been subtracted. The solid line is a Lorentzian fit with an amplitude of 0.41 ± 0.03 and a width of 1.2 ± 0.2 G. It is shifted to the repulsive side of the resonance (dotted line) by 0.13 ± 0.04 G. The temperature of the atoms in this measurement was $T = 0.33 \pm 0.06T_F$ and the peak density was $n_p = (1.2 \pm 0.6) \times 10^{13}$ cm^{-3} per spin state. The dashed line shows a theoretical plot for a two-body multichannel scattering theory including the rf field. The calculated maximum fraction of atoms is 0.25 and the width is 0.79 G.

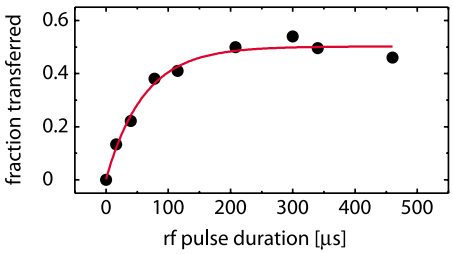

FIG. 3 (color online). Fraction of atoms transferred from the $m_f = -5/2$ into the $m_f = -7/2$ spin state versus the duration of the applied rf pulse. This measurement is performed on the attractive side of the resonance at a magnetic field of $B = 224.30$ G, with an rf detuning of $\Delta = -2\pi \times 100$ kHz. The solid line is a fit to an exponentially saturating growth curve. The curve saturates at a fraction of 0.49 ± 0.03 with a time constant of 61 ± 8 μs.

with either atom separately. Furthermore, the rf photon contributes a quantum of angular momentum, introducing a coupling between atom pairs with $m_{\text{tot}} = -7$ and $m_{\text{tot}} = -8$, where m_{tot} is the sum of the spin projections of the two atoms. This two-body theory provides transition rates for a given density, momentum distribution, magnetic field B, and rf detuning Δ.

The dashed line in Fig. 2 shows the results of such a calculation, which includes inhomogeneous broadening due to the spread in relative momentum of the particles. The momentum distribution has been modeled by a $T = 0.34$ μK Boltzmann distribution that approximates the measured momentum distribution of the atoms. All other parameters are identical to the measurement shown in Fig. 2. The calculated profile is nearly symmetric with respect to the resonance position. A comparison with the measurement shows reasonable agreement with the two-particle theory within experimental uncertainties, which include a $\pm 50\,\%$ systematic uncertainty in atom number. However, we observe a shift of the experimental curve to the repulsive side of the resonance. We attribute this to the presence of a small number of residual bound molecules that exist only on the repulsive side. These molecules get photodissociated by the rf field and therefore contribute to the signal on this side of the resonance. In addition, we note that there may be significant many-body effects in this experiment.

An intriguing result of the calculation is that the rf pair process occurs deep within the interatomic potential where the spacing of the atom pair is about $22a_0$. At this distance, an rf-mediated spin exchange avoided crossing appears in the coupled channel Hamiltonian. The process therefore measures spatial correlations between atoms on a very short length scale. Close to a Feshbach resonance these correlations are strongly enhanced by the population of the closed channel state. Therefore the rf process predominantly probes the composite-boson field of the closed channel.

The rf transitions reported here are reminiscent of the recently observed rf photodissociation of bound molecules created at a Feshbach resonance [12]. The measurements, however, differ from each other in several ways. In this experiment, we did not deliberately populate the molecule state. In addition, in order to maximize the signal here we used an rf pulse duration that is an order of magnitude longer than in the molecule dissociation experiment. Also, within the precision of these experiments we do not observe a frequency shift corresponding to a binding energy. Finally, the rf transitions between interacting atom pairs are observed on both the attractive and the repulsive sides of the Feshbach resonance. Bound molecules, on the other hand, exist only on the repulsive side of the resonance.

In order to study the observed rf process in more detail, we have measured the kinetic energy of the transferred atoms. If the observed rf transitions for large rf detunings can be attributed to pairs of atoms as illustrated in Fig. 1, the kinetic energy of each transferred atom should increase by half the excess energy of the rf photon as [12]

$$\delta E_{\text{kin}} = -0.5(h\nu_{\text{rf}} - h\nu_0). \quad (1)$$

Here ν_0 is the rf transition frequency for bare atoms including mean-field shifts. The prefactor is negative since we observe an rf transition to a lower lying Zeeman state, where an rf photon is emitted in a stimulated process. Therefore, we expect that the atoms gain kinetic energy when the rf is detuned to lower frequencies.

Experimentally, the energy of the transferred atoms is determined by fitting time-of-flight expansion images of atoms in the $m_f = -7/2$ spin state to a Gaussian model [25]. Figure 4 shows a plot of the measured increase in kinetic energy of the atoms transferred versus the rf frequency, at $B = 224.40$ G on the attractive side of the Feshbach resonance. For rf frequencies lower than the

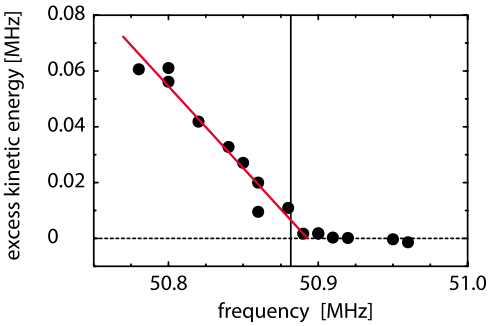

FIG. 4 (color online). Increase of the kinetic energy δE_{kin} of the transferred atoms versus the frequency ν_{rf} of the applied 100 μs rf pulse, on the attractive side of the resonance. The solid line is a linear fit to the data yielding a slope of -0.59 ± 0.05. This result is close to the expected value for an atom pair process. The vertical line indicates the expected resonant rf transition frequency for bare atoms at $\nu_0 = 50.882 \pm 0.005$ MHz, neglecting mean-field shifts that are on the order of -1 kHz. The measured zero crossing at $\nu_{\text{rf}} = 50.893 \pm 0.008$ MHz agrees fairly well with this value.

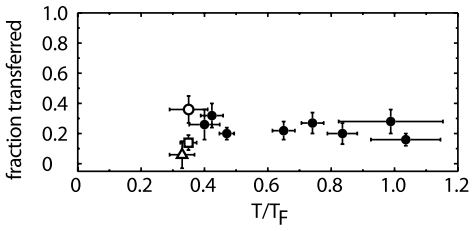

FIG. 5. Fraction of atoms transferred by an 100 μs rf pulse with a detuning of $\Delta = -2\pi \times 100$ kHz for various temperatures T on the attractive side of the resonance ($B = 224.37$ G). No explicit temperature or degeneracy dependence is observed. The data points at low temperature show a density dependence, where $n_p = 2.8 \times 10^{12}$ cm^{-3} (triangle), 5.0×10^{12} cm^{-3} (square), and 1.2×10^{13} cm^{-3} (open circle). The solid points have an average density of $n_p = 5 \times 10^{12}$ cm^{-3}.

resonant frequency ν_0, the kinetic energy indeed increases linearly with a slope $\delta E_{\rm kin}/(h\nu_{\rm rf} - h\nu_0) = -0.59 \pm 0.05$. The same measurement on the repulsive side of the Feshbach resonance at $B = 223.84$ G yields a slope of -0.51 ± 0.06. This result is in reasonable agreement with the expected value in Eq. (1) and demonstrates that the excess energy of the applied rf photon corresponds to the increase in kinetic energy of the atoms. Because of energy and momentum conservation, this is possible only in a process involving an interacting pair of atoms.

We find that the observed process does not strongly depend upon quantum degeneracy. In Fig. 5, the fraction of transferred atoms on the attractive side of the resonance is plotted for temperatures between $0.33T_F$ and $1.0T_F$. We observe similar rates for all of these temperatures and an increase of the rate for higher densities.

In conclusion, we have observed rf transitions between strongly interacting pairs of atoms close to a Feshbach resonance. The rf transitions probe spatial correlations between atoms on a short length scale. These results demonstrate that a Feshbach resonance not only increases the strength of atom-atom interactions, but also introduces strong pair correlations between atoms for both positive and negative magnetic-field detunings from the resonance. It will be interesting to study how the pairs evolve as resonance superfluidity occurs.

It is a pleasure to thank E. A. Cornell, C. E. Wieman, M. Holland, S. Inouye, and W. Zwerger for stimulating discussions and J. Smith for experimental assistance. This work was supported by the NSF and NIST. C. A. R. acknowledges support from the Hertz Foundation.

*Electronic address: markus.greiner@colorado.edu
URL: http://jilawww.colorado.edu/~jin/
†Permanent address: Quantum Physics Division, National Institute of Standards and Technology.

[1] H. Feshbach, Ann. Phys. (Leipzig) **19**, 287 (1962).
[2] W. C. Stwalley and L. H. Nosanow, Phys. Rev. Lett. **36**, 910 (1976).
[3] E. Tiesinga, B. J. Verhaar, and H. T. C. Stoof, Phys. Rev. A **47**, 4114 (1993).
[4] C. A. Regal and D. S. Jin, Phys. Rev. Lett. **90**, 230404 (2003).
[5] T. Bourdel, J. Cubizolles, L. Khaykovich, K. M. F. Magalhães, S. J. J. M. F. Kokkelmans, G. V. Shlyapnikov, and C. Salomon, Phys. Rev. Lett. **91**, 020402 (2003).
[6] S. Gupta, Z. Hadzibabic, M. W. Zwierlein, C. A. Stan, K. Dieckmann, C. H. Schunck, E. G. M. van Kempen, B J. Verhaar, and W. Ketterle, Science **300**, 1723 (2003).
[7] K. M. O'Hara, S. L. Hemmer, M. E. Gehm, S. R. Granade, and J. E. Thomas, Science **298**, 2179 (2002).
[8] M. Holland, S. J. J. M. F. Kokkelmans, M. L. Chiofalo, and R. Walser, Phys. Rev. Lett. **87**, 120406 (2001).
[9] M. Holland, J. Park, and R. Walser, Phys. Rev. Lett. **86**, 1915 (2001).
[10] E. Timmermans, K. Furuya, P. W. Milonni, and A. K. Kerman, Phys. Lett. A **285**, 228 (2001).
[11] E. A. Donley, N. R. Claussen, S. T. Thompson, and C. E. Wieman, Nature (London) **417**, 529 (2002).
[12] C. A. Regal, C. Ticknor, J. L. Bohn, and D. S. Jin, Nature (London) **424**, 47 (2003).
[13] J. Cubizolles, T. Bourdel, S. J. J. M. F. Kokkelmans, G. V. Shlyapnikov, and C. Salomon, cond-mat/0308018.
[14] S. Jochim, M. Bartenstein, A. Altmeyer, G. Hendl, C. Chin, J. H. Denschlag, and R. Grimm, cond-mat/0308095.
[15] K. E. Strecker, G. B. Partridge, and R. G. Hulet, cond-mat/0308318.
[16] J. Herbig, T. Kraemer, M. Mark, T. Weber, C. Chin, H.-C. Nägerl, and R. Grimm, Science **301**, 1510 (2003).
[17] S. Dürr, T. Volz, A. Marte, and G. Rempe, cond-mat/0307440.
[18] T. Loftus, C. A. Regal, C. Ticknor, J. L. Bohn, and D. S. Jin, Phys. Rev. Lett. **88**, 173201 (2002).
[19] S. Inouye, M. R. Andrews, J. Stenger, H.-J. Miesner, D. M. Stamper-Kurn, and W. Ketterle, Nature (London) **392**, 151 (1998).
[20] S. L. Cornish, N. R. Claussen, J. L. Roberts, E. A. Cornell, and C. E. Wieman, Phys. Rev. Lett. **85**, 1795 (2000).
[21] K. Dieckmann, C. A. Stan, S. Gupta, Z. Hadzibabic, C. H. Schunck, and W. Ketterle, Phys. Rev. Lett. **89**, 203201 (2002).
[22] C. A. Regal, C. Ticknor, J. L. Bohn, and D. S. Jin, Phys. Rev. Lett. **90**, 053201 (2003).
[23] A. J. Moerdijk, B. J. Verhaar, and T. M. Nagtegaal, Phys. Rev. A **53**, 4343 (1996).
[24] J. L. Bohn and P. S. Julienne, Phys. Rev. A **60**, 414 (1999).
[25] In order to account for a background of bare atoms that undergo an atomic transition due to the finite detuning and finite spectral width of the rf pulse, the surface fit model is a bimodal sum of two Gaussians. The width of the first Gaussian is fixed and measures the bare atom transition background, while the width of the second Gaussian measures the kinetic energy plotted in Fig. 4.