

Condensation of Pairs of Fermionic Atoms near a Feshbach Resonance

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We have observed Bose-Einstein condensation of pairs of fermionic atoms in an ultracold ${}^6\text{Li}$ gas at magnetic fields above a Feshbach resonance, where no stable ${}^6\text{Li}_2$ molecules would exist in vacuum. We accurately determined the position of the resonance to be 822 ± 3 G. Molecular Bose-Einstein condensates were detected after a fast magnetic field ramp, which transferred pairs of atoms at close distances into bound molecules. Condensate fractions as high as 80% were obtained. The large condensate fractions are interpreted in terms of preexisting molecules which are quasistable even above the two-body Feshbach resonance due to the presence of the degenerate Fermi gas.

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Ultracold atomic gases have become a medium to realize novel phenomena in condensed matter physics and test many-body theories in new regimes. The particle densities are 10^8 times lower than in solids, but at temperatures in the nanokelvin range, which are now routinely achieved, interactions and correlations become important. Of particular interest are pairing phenomena in fermionic gases, which have direct analogies to superconductivity [1].

The interactions which drive the pairing in these gases can be controlled using a Feshbach resonance [2], in which a molecular level is Zeeman tuned through zero binding energy using an external magnetic field. This provides an opportunity to experimentally probe what is known as the BCS-BEC crossover; as the strength of the effective attractive interaction between particles is increased a continuous transition from condensation of delocalized Cooper pairs to condensation of tightly bound bosonic molecules is predicted [3–6]. Whereas in the BCS limit the pairing is a strictly many-body effect [7], in the BEC limit a pair of fermions is bound even as an isolated molecule. A novel form of high-temperature superfluidity has been predicted to emerge in the crossover region [3–6]. Until recently, the observation of condensation phenomena in fermionic atomic gases was restricted to the extreme BEC limit, where several groups have observed Bose-Einstein condensation of diatomic molecules [8–11].

An important step was recently reported, in which condensation of atomic ${}^{40}\text{K}$ fermion pairs was observed on the BCS side of a Feshbach resonance [12]. It was argued that those pairs were not bound into molecules, but merely moved together in a correlated fashion, similar to Cooper pairs of electrons in a superconductor [13]. However, the exact nature of these pairs remained unclear. In this Letter, we apply similar techniques to ${}^6\text{Li}$ atoms, which have very different collisional properties [14], and observe the pair condensation phenomenon above a Feshbach resonance. In contrast to the previous work,

where at most 15% of the atom pairs were condensed [12], condensate fractions of up to 80% were observed. We argue that such a high condensate fraction is unlikely for pairs which are long range, but rather it indicates a condensate of short-range atom pairs which are essentially molecular in character even on the BCS side of the resonance.

A simple argument supports this possibility. In the basic picture of a Feshbach resonance, a molecular state above the dissociation threshold has a finite lifetime, which becomes shorter as the energy of the state increases, as recently observed [15]. In the presence of the Fermi sea, its lifetime will be increased due to Pauli blocking. The molecular level will be populated until its energy becomes larger than twice the Fermi energy corresponding to the total number of atoms. The BCS-BEC crossover is expected to occur at this point, and not at the location of the two-body Feshbach resonance [5,6].

The basic setup of our experiment was described in [10]. By sympathetic cooling of ${}^6\text{Li}$ atoms with ${}^{23}\text{Na}$ in a magnetic trap, a degenerate gas of about 3×10^7 ${}^6\text{Li}$ fermions at $\sim 0.3T/T_F$ was created. After transfer into an optical dipole trap (maximum power 9 W focused to an e^{-2} radius of 25 μm), an equal mixture of atoms in the lowest two hyperfine states $|1\rangle$ and $|2\rangle$ was prepared. The sample was evaporatively cooled at a magnetic field of 770 G using an exponential ramp-down (time scale ~ 400 ms) of the optical trap to a final laser power of 15 mW. This created essentially pure Bose-Einstein condensates of up to 3×10^6 ${}^6\text{Li}_2$ molecules. The observed trap vibrational frequencies could be described by the following expression: $\nu_{\text{rad}} \approx 115 \text{ Hz } \sqrt{P}$, $\nu_{\text{ax}} \approx 1.1 \text{ Hz } \sqrt{P + 120B}$, where P is the optical power in mW, and B is the magnetic field in kG. The latter dependence arises from the residual axial curvature of the magnetic field. Considerable improvements over our previous setup [10] led to an improved e^{-1} condensate lifetime of 10 s at 770 G. Moreover, within the experimental uncertainty in the total number of molecules ($\sim 50\%$), mean-field

measurements were consistent with a molecule-molecule scattering length of $0.6a$, where a is the atomic scattering length [16,17].

Previously, the location of the ${}^6\text{Li}$ Feshbach resonance was determined either by observing a peak in the inelastic loss [18] or the interaction energy of a $|1\rangle - |2\rangle$ mixture [19]. A more accurate determination can be made by mapping out the onset of dissociation of the molecular state [12,15]. After releasing an almost pure molecular sample from the trap at 770 G, the magnetic field was linearly ramped up in 10 ms to a variable value. During that time, the particle density dropped by a factor of 1000. If the field crossed the resonance, molecules dissociated into atoms. These atoms were then imaged at zero field, where the remaining molecules were not detected [10]. The Feshbach resonance appeared as a sharp onset in the number of detected atoms (Fig. 1). The speed of the downward ramp to zero field had to be chosen carefully. Fast ramps could dissociate very weakly bound molecules [20], such that the Feshbach resonance appeared systematically shifted to lower fields. For too slow a ramp-down, on the other hand, we found that even for clouds as dilute as $\sim 3 \times 10^{10} \text{ cm}^{-3}$ molecules were recreated, lowering the measured atomic fraction. However, when we varied the ramp rate over more than 3 orders of magnitude, we found a range of rates which gave identical thresholds at $822 \pm 3 \text{ G}$ (Fig. 1).

To produce samples in the crossover region, we started with an essentially pure Bose-Einstein condensate of molecules formed at 770 G. The laser power of the optical trap was increased in 500 ms from 15 to 25 mW in order to accommodate larger Fermi clouds above the resonance. In some experiments, we used a deeper trap with up to 150 mW of power; the additional compression was carried

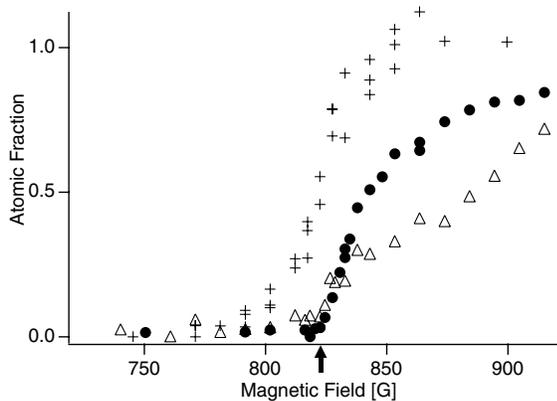


FIG. 1. Determination of the Feshbach resonance position. Shown is the onset of molecule dissociation when the magnetic field was slowly raised and then ramped down to zero field with a variable rate: Using a switch-off of the power supply at an initial rate of $30 \text{ G}/\mu\text{s}$ (crosses), a linear ramp to zero field of $100 \text{ G}/\text{ms}$ (circles), a linear ramp for 16 ms at $12.5 \text{ G}/\text{ms}$, followed by switch off (triangles). The identical threshold for the two lowest ramp rates determines the resonance position to be $822 \pm 3 \text{ G}$, marked by an arrow.

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out after ramping in 500 ms to 900 G to avoid enhanced losses on the BEC side of the resonance. Once the final trap depth was reached, the magnetic field was ramped in 500 ms to values between 650 and 1025 G. The adiabaticity of this ramp was checked by ramping back to 770 G and observing an identical density profile and condensate fraction, similar to studies in Ref. [8]. At 1025 G, the total peak density of the spin mixture in the deepest trap was $3 \times 10^{13} \text{ cm}^{-3}$, corresponding to a Fermi energy of $3.6 \mu\text{K}$ and inverse Fermi wave vector $k_F^{-1} \approx 2000a_0$, where a_0 denotes the Bohr radius.

To probe the gas, we released it from the trap, and after a variable delay τ_d of usually $40 \mu\text{s}$, applied a rapid transfer technique [12]: the magnetic field was switched off exponentially to zero with an initial slew rate of $30 \text{ G}/\mu\text{s}$, which adiabatically converted pairs of atoms into deeply bound molecules at zero field [21]. As long as no collisions or other dynamics occur during this ramp, the velocity distribution of the resulting molecules then constitutes a probe of the atom pairs' center-of-mass motion before the measurement. After 3–6 ms time of flight at zero field, we dissociated the molecules with a 3 ms field pulse to 900 G and imaged the resulting atoms after 2 ms at zero field [10,22]. We could also selectively detect any remaining atoms by omitting the dissociation pulse, and we observed that for $\tau_d \leq 500 \mu\text{s}$, less than 10% of the sample consisted of atoms, independent of the initial magnetic field. At longer delay times, the atom-molecule conversion became less efficient due to the decreased density.

Typical absorption pictures of molecular clouds after the rapid transfer ramp are shown in Fig. 2 for different temperatures, clearly exhibiting a bimodal distribution. This is evidence for condensation of pairs of ${}^6\text{Li}$ atoms on the BCS side of the Feshbach resonance. The condensate fractions were extracted from images like these, using a Gaussian fit function for the “thermal” part and a

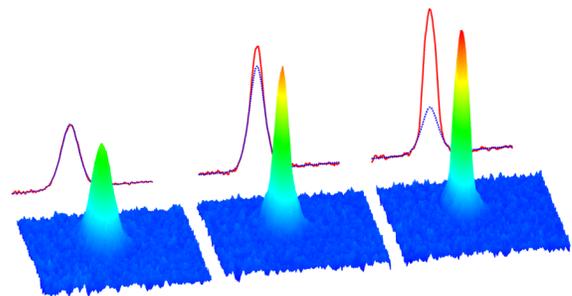


FIG. 2 (color online). Emergence of a Bose-Einstein condensate of atom pairs as the temperature was lowered. Shown are column densities (after 6 ms of time of flight) of the fermion mixture after a rapid transfer ramp from 900 G for three different initial temperatures $T/T_F \approx 0.2, 0.1$ and 0.05 , together with their axially integrated radial density profiles. The dashed line is a Gaussian fit to the thermal component. Condensate fractions are 0.0, 0.1, and 0.6. Each cloud consists of about 2×10^6 molecules. The field of view is $3 \times 3 \text{ mm}$.

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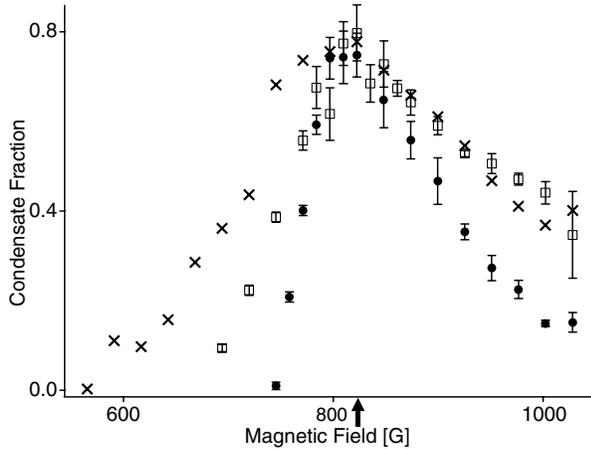


FIG. 3. Condensate fraction after the rapid transfer vs initial magnetic field, for different hold times at that field in the shallow trap ($P = 25$ mW). Crosses: 2 ms hold time, after 500 ms ramp to 1000 G and 4 ms ramp to the desired field; squares and circles: 100 ms and 10 s hold time, after 500 ms ramp from 770 G. The reduction of the condensate fraction for long hold times far on the left side of the resonance is probably due to the rapidly increasing inelastic losses for the more tightly bound molecules [20,23]. The lower condensate fraction at high field for long hold times is probably an effect of lower density since the number of atoms had decayed by a factor of 4 without change in temperature.

Thomas-Fermi profile for the “condensate.” Figures 3–5 show the observed condensate fraction as a function of both magnetic field and temperature. The striking features of these data are the high condensate fraction of 80% near resonance, and the persistence of large condensate fractions on the BCS side of the resonance all the way to our maximum field of 1025 G. After 10 s hold time, this value was still as high as 20%. These observations were independent of whether the final magnetic field was approached starting with a Fermi sea or a molecular condensate. Note that for our peak densities, the strongly interacting region of $k_F|a| > 1$ extends from 710 G onward.

There is experimental evidence that the observed pair condensates existed before the sweep and were not produced during the sweep by collisions. First, the observed condensate fraction depended on the initial magnetic field. Second, the condensate fraction did not change when we varied the delay time τ_d (between release of the atoms from the trap and the magnetic field ramp) from 0 to 200 μ s, although the density of the cloud changed by a factor of ~ 4 [25]. However, we cannot rule out with certainty that the momentum distribution of the pairs is modified by collisions during the ramp [26]. At our highest densities, it takes about 4 μ s to take the molecules created during the ramp out of the strongly interacting region ($k_F|a| \geq 1$). A classical gas at the Fermi temperature would have a unitarity limited collision time comparable to the inverse of the Fermi energy divided by \hbar , which is about 2 μ s. However, this may be affected by

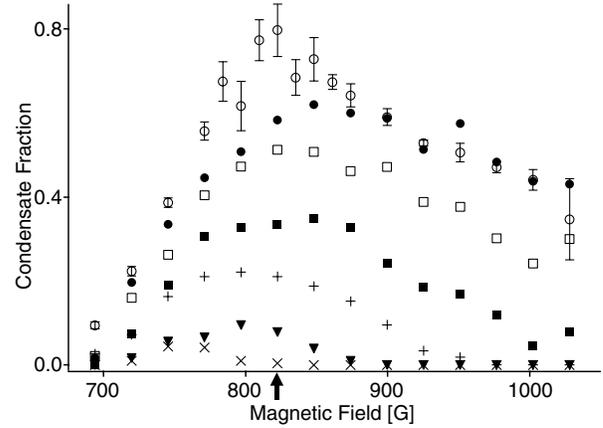


FIG. 4. Condensate fraction for different temperatures as a function of magnetic field. The temperature of the molecular cloud was varied by stopping the evaporative cooling earlier and applying parametric heating before ramping to the final magnetic field. Temperatures are parametrized by the molecular condensate fraction N_0/N at 820 G (open circles: 0.8; filled circles: 0.58; open squares: 0.51; filled squares: 0.34; “+”: 0.21; triangles: 0.08; “x”: <0.01). The lowest temperature was realized in the shallow trap ($P = 25$ mW); the higher temperatures required a deeper trap ($P = 150$ mW).

Pauli blocking for the atoms and bosonic stimulation for the molecules.

Assuming that collisions during the ramp can be neglected, it is still crucial to ask what exactly happens during the rapid transfer ramp, and what kind of pairs would likely be detected. A reasonable assumption is that atoms form molecules preferentially with their nearest neighbor, independent of the center-of-mass velocity of the pair. If, as our data show, a large fraction of the

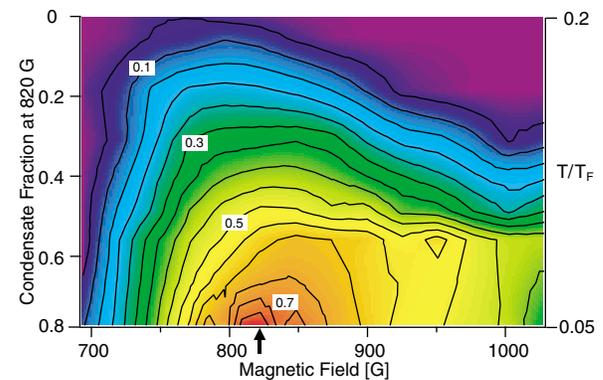


FIG. 5 (color online). Temperature and magnetic field ranges over which pair condensation was observed (using the same data as in Fig. 4). The right axis shows the range in T/T_F (measured at 1025 G) which was covered. For high degeneracies, fitting T/T_F was less reliable and we regard the condensate fraction as a superior “thermometer.” Note that for an isentropic crossover from a BEC to a Fermi sea, T/T_F is approximately linearly related to the condensate fraction on the BEC side [24]. For our maximum densities the region where $k_F|a| \geq 1$ extends from about 710 G onward.

detected molecules are in a zero-momentum state after the fast transfer, this means that nearest neighbors had opposite momenta. If the distance between the fermions with opposite momenta making up each pair were comparable to or larger than the interatomic distance (as in long-range Cooper pairs) one would not expect to find high condensate fractions; on the contrary, the transfer into a tightly bound molecular state would randomly pick one of the nearest neighbors, resulting in a thermal molecule. We regard our observed high condensate fractions as evidence for the existence of condensed atomic pairs above the Feshbach resonance, which are smaller in size than the interatomic distance and, therefore, molecular in character. Their stability may be affected by Pauli blocking and mean-field effects, but their binding should be a two-body effect and not a many-body effect as in the case of Cooper pairs.

In conclusion, we have observed ${}^6\text{Li}_2$ molecular Bose-Einstein condensates after a fast downward magnetic field ramp starting with equilibrium samples at fields on either side of the broad ${}^6\text{Li}$ Feshbach resonance. Since there are no truly bound molecular states above the resonance, we tentatively interpret our results as a Bose-Einstein condensate of pairs of atoms which are molecular in character and stabilized by the existence of the Fermi sea. This condensate would drain particles from the Fermi sea and lead to a reduced atomic Fermi energy roughly equal to half the energy of the molecular level [5,6]. Indeed, both in Ref. [8] and in the present work, a reduction in the size of the cloud was observed as the Feshbach resonance was approached from above, which may be due to this effect. In agreement with theoretical predictions [6] we have observed pair condensation in the regime where $T/T_F < 0.2$ and $k_F|a| > 1$ (Fig. 5). The exact nature of the atom pairs remains to be elucidated; they could be related to virtual states or scattering resonances in the continuum; they may turn out to be the tight-binding limit of Cooper pairs. It is also possible that the pair condensate is a superposition state of molecules and Cooper pairs [4–6]. We regard the characterizing feature of the BCS-BEC crossover a qualitative change of the pairing phenomenon which has not yet been observed.

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- [1] H.T.C. Stoof and M. Houbiers, in *Bose-Einstein Condensation in Atomic Gases, Proceedings of the International School of Physics Enrico Fermi, Course CXL*, edited by M. Inguscio, S. Stringari, and C. Wieman (IOS Press, Amsterdam, 1999), pp. 537–553.

- [2] E. Tiesinga, B. J. Verhaar, and H. T. C. Stoof, *Phys. Rev. A* **47**, 4114 (1993); W. C. Stwalley, *Phys. Rev. Lett.* **37**, 1628 (1976); S. Inouye *et al.*, *Nature (London)* **392**, 151 (1998); P. Courteille *et al.*, *Phys. Rev. Lett.* **81**, 69 (1998).
- [3] D. M. Eagles, *Phys. Rev.* **186**, 456 (1969); A. J. Leggett, in *Modern Trends in the Theory of Condensed Matter. Proceedings of the XVIth Karpacz Winter School of Theoretical Physics, Karpacz, Poland, 1980* (Springer-Verlag, Berlin, Karpacz, Poland, 1980), pp. 13–27; P. Nozières and S. Schmitt-Rink, *J. Low Temp. Phys.* **59**, 195 (1985).
- [4] E. Timmermans *et al.*, *Phys. Lett. A* **285**, 228 (2001); M. Holland *et al.*, *Phys. Rev. Lett.* **87**, 120406 (2001); J. Stajic *et al.*, e-print cond-mat/0309329; A. Perali *et al.*, e-print cond-mat/0311309; R. Combescot, e-print cond-mat/0310583; J. Kinnunen, M. Rodriguez, and P. Törmä, e-print cond-mat/0401543.
- [5] Y. Ohashi and A. Griffin, *Phys. Rev. Lett.* **89**, 130402 (2002).
- [6] G. M. Falco and H. T. C. Stoof, e-print cond-mat/0402579.
- [7] M. Houbiers *et al.*, *Phys. Rev. A* **56**, 4864 (1997).
- [8] S. Jochim *et al.*, *Science* **302**, 2101 (2003); M. Barthelemy *et al.*, *Phys. Rev. Lett.* **92**, 120401 (2004).
- [9] M. Greiner, C. A. Regal, and D. S. Jin, *Nature (London)* **426**, 537 (2003).
- [10] M. W. Zwierlein *et al.*, *Phys. Rev. Lett.* **91**, 250401 (2003).
- [11] T. Bourdel *et al.*, e-print cond-mat/0403091.
- [12] C. A. Regal, M. Greiner, and D. S. Jin, *Phys. Rev. Lett.* **92**, 040403 (2004).
- [13] NIST and University of Colorado at Boulder press release, January 28, 2004; http://www.nist.gov/public_affairs/releases/fermi_condensate.htm.
- [14] M. Houbiers *et al.*, *Phys. Rev. A* **57**, R1497 (1998).
- [15] T. Mukaiyama *et al.*, e-print cond-mat/0311558 [*Phys. Rev. Lett.* (to be published)].
- [16] D. S. Petrov, C. Salomon, and G. V. Shlyapnikov, e-print cond-mat/0309010.
- [17] The smaller value reported in our previous work [10] was based on an incorrect extrapolation of trap frequencies to 100 times lower power. The radial trap frequency was strongly influenced by multiple intensity maxima in the optical focus.
- [18] K. Dieckmann *et al.*, *Phys. Rev. Lett.* **89**, 203201 (2002).
- [19] T. Bourdel *et al.*, *Phys. Rev. Lett.* **91**, 020402 (2003).
- [20] J. Cubizolles *et al.*, *Phys. Rev. Lett.* **91**, 240401 (2003).
- [21] According to Fig. 1, this fast ramp can dissociate weakly bound molecules at low density, but at high density we observed an atom-molecule conversion $\geq 90\%$.
- [22] At this point the cloud was sufficiently dilute that the final switch off of the field did not reconvert atoms into molecules.
- [23] S. Jochim *et al.*, *Phys. Rev. Lett.* **91**, 240402 (2003).
- [24] L. D. Carr, G. V. Shlyapnikov, and Y. Castin, e-print cond-mat/0308306 [*Phys. Rev. Lett.* (to be published)].
- [25] The condensate peak broadened for longer τ_d and could not be reliably discerned after 200 μs .
- [26] In the ${}^{40}\text{K}$ experiment, the ratio of the effective sweep rate through resonance and Fermi energy was similar [12].