

Formation Dynamics of a Fermion Pair Condensate

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The dynamics of pair condensate formation in a strongly interacting Fermi gas close to a Feshbach resonance was studied. We employed a phase-shift method in which the delayed response of the many-body system to a modulation of the interaction strength was recorded. The observable was the fraction of condensed molecules in the cloud after a rapid magnetic field ramp across the Feshbach resonance. The measured response time was slow compared to the rapid ramp, which provides final proof that the molecular condensates reflect the presence of fermion pair condensates before the ramp.

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Atomic Fermi gases close to a Feshbach resonance [1] offer the unique possibility of studying many-body phenomena in a strongly interacting system with tunable interactions. Recently a major focus has been on condensates of pairs of fermionic atoms [2–8]. By changing the magnetic field, the interaction strength between atoms in two spin states can be varied. That way, condensates of either tightly bound molecules or of extended pairs of fermions can be created, whose size can become comparable or even larger than the interparticle spacing. The description of this so-called BEC-BCS crossover [9] is an active frontier in many-body physics with still controversial interpretations [10–13].

The control of interactions via magnetic fields does not only give access to very different physical regimes, it also allows one to apply a time-varying interaction strength [14,15] and to study the dynamics of a many-body system in novel ways. This was used in recent experiments in which molecular condensates were observed after a rapid field ramp from the BCS to the Bose-Einstein condensate (BEC) side of the Feshbach resonance [6,7]. It was argued that if the ramp time was faster than the formation time of a molecular condensate, its presence after the sweep necessarily reflected a preexisting condensate of fermion pairs. However, without access to that formation time, secondary evidence was gathered, namely, the invariance of the condensate fraction under variations of the sweep rate [6] or of the density immediately before the ramp [7]. This excluded simple models of the molecular condensate formation during the ramp, but left room for more sophisticated many-body effects. In particular, the time to cross the Feshbach resonance in these experiments was not faster than the unitarity limited collision time $\propto \hbar E_F^{-1}$, and therefore dynamics during the sweep could not be ruled out.

Here we present an experimental study of the formation dynamics of a fermion pair condensate on the BCS side of the Feshbach resonance [16]. We employ a novel phase-shift method, which records the delayed response of the many-body system to a modulation of the magnetic field that changes periodically its interaction strength. The ob-

servable is again the molecular condensate fraction after a rapid sweep to the BEC side of the Feshbach resonance. Its sensitivity to changes in the scattering length on the BCS side [6,7] arises through the dependence of the critical temperature for pair condensation on the interaction strength. By showing that the delayed response time of the molecular condensate fraction is long compared to the sweep times used in the present and previous experiments, we infer that the observed condensates could not have been created during the rapid transfer and thus must originate from preexisting fermion pair condensates. However, we do find evidence that condensed pairs are more likely to be transferred into molecules than thermal pairs. Therefore, in contrast to assumptions made in previous work [6,7], the molecular condensate fraction after the ramp may not equal the fraction of condensed atom pairs above resonance.

The experimental setup was the same as in our previous work [7]. A degenerate cloud of ${}^6\text{Li}$, sympathetically cooled with ${}^{23}\text{Na}$, was loaded into an optical dipole trap to access a broad Feshbach resonance at 834 G [17,18] between the two lowest hyperfine states of ${}^6\text{Li}$, labeled $|1\rangle$ and $|2\rangle$. An equal mixture of these states was evaporatively cooled at 770 G using an exponential ramp-down of the optical trap to 15 mW. This resulted in an essentially pure Bose-Einstein condensate of 3×10^6 molecules. An upper limit for the temperature of the gas is $\frac{T}{T_F} < 0.2$, with the Fermi temperature T_F given by the zero-temperature, ideal gas relation $T_F = \hbar\omega(3N)^{1/3}$, $\omega/2\pi$ is the geometric mean of the trapping frequencies, and N is the total atom number. Next, the trap was recompressed to 25 mW (trap frequencies: $\nu_x = \nu_y = 580$ Hz, $\nu_z = 12.1 \text{ Hz}\sqrt{0.2 + B}$ with the magnetic field B in kG) and the magnetic field was adiabatically increased in 500 ms to 1000 G, the starting point for the following experiments. Here, in the wings of the Feshbach resonance, the scattering length a was still sufficiently large and negative for the gas to be in the strongly interacting regime, with $k_F|a| = 1.6$ at a Fermi energy of $E_F = 2.0 \mu\text{K}$ and a Fermi wave number $k_F = 1/2700a_0$. The temperature at this point could therefore not be reli-

ably determined, but is expected to be significantly lower than the one on the BEC side due to adiabatic cooling [19]. Subsequently, the magnetic field and thus the interaction strength in the gas were modulated at frequencies in the range of 100–500 Hz, and an amplitude of about 50 G [20]. At a variable time t after the start of the modulation, the fraction of condensed fermion pairs was recorded by time-of-flight analysis.

To identify fermionic condensates across the resonance region, we proceeded as in [6,7]. Immediately after the release of the cloud from the optical potential, the magnetic field was switched to zero field (initial ramp rate 30 G/ μ s), where further expansion of the cloud took place. This rapid ramp out of the resonance region transformed large fermion pairs into deeply bound molecules with high efficiency [21]. Figure 1 details the imaging procedure used to determine molecular condensate fractions and the number of unpaired atoms in each state after the ramp. In our previous work, we showed that the condensate fractions had a peak around the Feshbach resonance and fell off on either side [7]. Here, this dependence was exploited to observe the delayed response of the system to the magnetic field modulation on the BCS side.

Figure 2 shows the main result of this Letter: The condensate fraction in the molecular clouds after the rapid

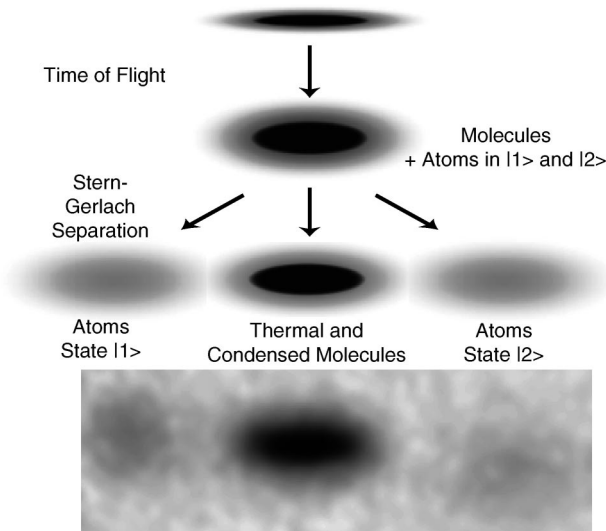


FIG. 1. Imaging of molecular condensates. The rapid ramp to zero field after release from the trap created a cloud containing both molecules and unpaired atoms. A Stern-Gerlach field gradient separated atoms (magnetic moment $\pm \frac{1}{3} \mu_B$ for states $|1\rangle$ and $|2\rangle$, respectively) from molecules, which are purely singlet at zero field. At the end of 5 ms of ballistic expansion, the molecules were dissociated in a fast ramp (in 3 ms to ~ 1200 G) across the Feshbach resonance. After another 2 ms expansion again at zero field, an absorption image of the separated clouds was taken. Condensate fractions were determined from the molecular cloud, and the numbers in each component were recorded. An absorption image is shown on the bottom, the field of view is 3 mm \times 1 mm.

ramp did not follow the magnetic field modulation instantaneously, but lagged behind. At a Fermi energy of $E_F = 2 \mu\text{K}$, the peak condensate fraction was delayed by $\tau_R = (500 \pm 100) \mu\text{s}$ with respect to the magnetic field's closest approach to resonance [22]. This time scale was independent of the modulation frequency [compare Figs. 2 and 4(a), below]. This also rules out that our results are affected by the excitation of collective modes. τ_R equals 130 times the unitarity limited collision time, $\hbar E_F^{-1} = 3.8 \mu\text{s}$. The rapid magnetic field ramp utilized here and in [7] traversed the Feshbach resonance in less than 10 μs , which is much smaller than τ_R .

This delay time can be interpreted as the relaxation time of the fermionic condensate. In a normal Fermi gas of N particles at temperatures much smaller than the Fermi temperature T_F , relaxation occurs through collisions between the thermally excited particles close to the Fermi surface, whose number scales as $N_{\text{th}} \approx N \frac{k_B T}{E_F}$. The number of available scattering states again being proportional to $\frac{k_B T}{E_F}$, the relaxation time will be $\tau_R \approx \hbar \frac{E_F}{(k_B T)^2}$. In general, if the Fermi surface is smeared out over an energy width ΔE , the relaxation time is $\approx \hbar \frac{E_F}{(\Delta E)^2}$. This formula with $\Delta E = \Delta$ should apply also to the superfluid state [23] when the gap parameter Δ is rapidly changed to a much smaller value. Generally, one would expect ΔE to be the larger of Δ and $k_B T$. Using $\tau_R = 500 \mu\text{s}$, we obtain the estimate $\Delta E = 0.1 E_F$ which may set an upper bound for both temperature and pairing gaps.

A decay is superimposed to the periodic modulation of the condensate fraction. It could be caused by heating due to the nonadiabaticity of the process. Another source of heating could be the excitation of the cloud via the small accompanying variation of the magnetic field curvature.

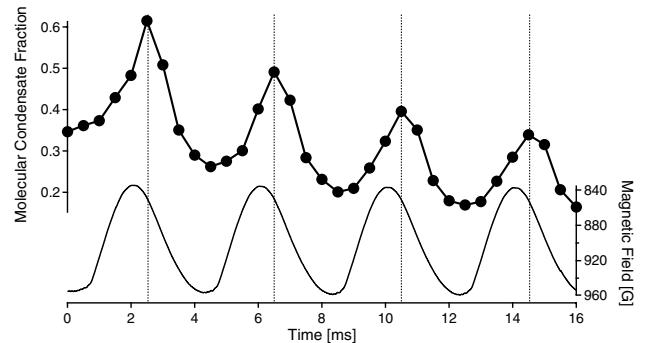


FIG. 2. Measurement of the relaxation time of fermionic pair condensates. Shown is the delayed response of the observed condensate fraction (data points and thick line to guide the eye) to a 250 Hz magnetic field modulation (thin line) on the BCS side of the Feshbach resonance at 834 G. The condensates were detected as described in Fig. 1. Three measurements per point were taken in random order, the size of the data points reflecting the standard deviation. The vertical lines indicate the points of maximum condensate fraction, which are delayed with respect to the times at which the magnetic field is closest to resonance.

Despite the decay of the condensate fraction, the relaxation time was constant for subsequent cycles of modulation, within the (limited) accuracy of our measurement.

In a compressed trap of $p = 150$ mW, at a 1.8 times higher Fermi energy of $3.6 \mu\text{K}$, the measured delay time was $\tau_R \approx (230 \pm 100) \mu\text{s}$. BCS theory predicts that the relaxation time should scale with density like $\tau_R \propto E_F^{-1} e^{\pi/(k_F|a|)}$, giving $\tau_R \approx 200 \mu\text{s}$ for this experiment performed around 900 G. However, we regard this agreement with observation as fortuitous since BCS theory cannot be rigorously applied, and finite temperature effects may contribute to the relaxation.

We now discuss further observations regarding the efficiency of converting atoms into molecules. Since the relaxation time introduces some hysteresis, we observe the same condensate fraction at two different magnetic field values. Therefore, in contrast to equilibrium experiments [6,7], we can distinguish the dependence of the conversion efficiency on condensate fraction and magnetic field.

Figure 3 shows that the total number of detected atoms (in both the atom and the molecule channels) was modulated by the magnetic field. We assume that this instantaneous response reflects the two-body physics during the magnetic field sweep. In a simple two-state Landau-Zener model, the initial magnetic field and the sweep rate determine what fraction of the atoms appears as bound molecules. However, the total number of bound or unbound atoms should be constant in contrast to our observations. This is evidence for the presence of other molecular states (e.g., lower lying vibrational states) which are populated during the magnetic field sweep, and the population is larger for initial magnetic fields closer to the Feshbach resonance. Note that the determination of the condensate fraction is immune against those “disappeared” molecules, since the two-body physics does not depend on the center-of-mass motion of the atom pair.

We now look at the molecular fraction which we define as $1 - N_{\text{atom}}/N_{\text{total}}$, where N_{atom} is the number of atoms

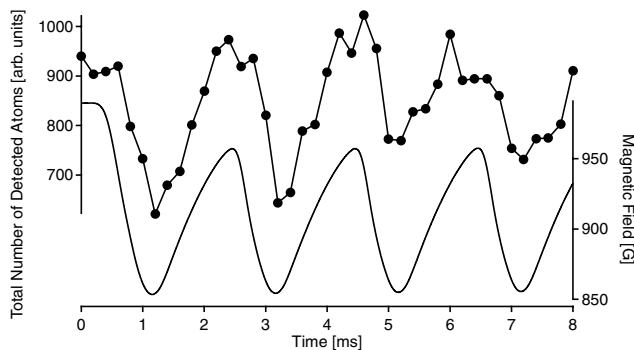


FIG. 3. Total number of detected atoms (unbound atoms and molecules) after the rapid ramp (same data set as in Fig. 4). It is modulated in phase with the magnetic field. For initial fields close to resonance, more atoms are “missing” after the rapid ramp.

observed after the sweep and N_{total} the total number of atoms before the sweep (this definition includes the disappeared molecules) [24]. If the molecule fraction would follow the instantaneous magnetic field, it would again reflect the two-body physics during the sweep. Instead, we observe a delayed response in perfect correlation with the condensate fraction (Fig. 4). Since the delay time reflects the many-body physics of condensate formation, this is clear evidence that the molecule conversion efficiency depends on the initial many-body state.

One consistent explanation of these findings is that fermion pairs in the condensate are more completely transferred into tightly bound molecules than thermal pairs. With this assumption, we extrapolated the fitted line in Fig. 4(b) to a zero condensate fraction to obtain the transfer efficiency from thermal atom pairs into molecules (including the missing fraction) as $p_{\text{th}} = 75\%$ [21]. Extrapolating towards the other limit, we do not expect any unpaired atoms after the ramp already for a condensate fraction of 80% [25], suggesting a transfer efficiency for condensed fermion pairs into molecules of $p_0 = 100\%$. This effect would lead to an overestimate of the fermionic condensate fraction before the sweep. Small condensate fractions could be overestimated by as much as $\frac{p_0 - p_{\text{th}}}{p_{\text{th}}} = 33\%$. The largest absolute error occurs for an initial pair condensate

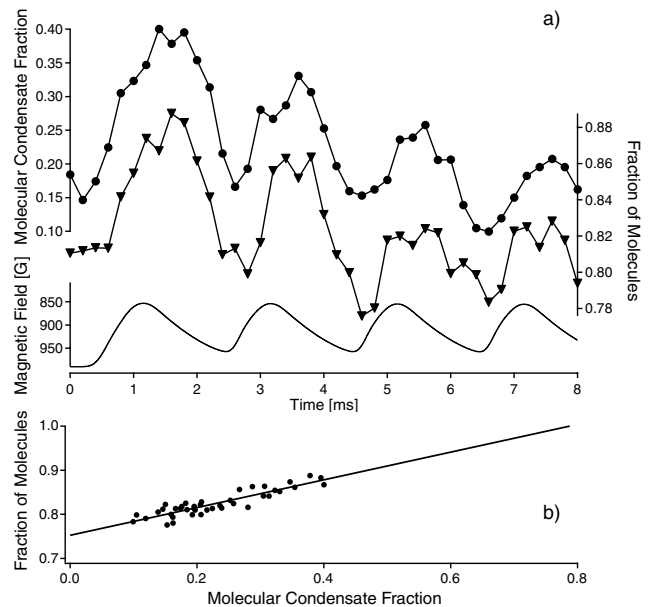


FIG. 4. Correlation between the observed condensate fraction and the molecular fraction. Shown are (a) the condensate fraction vs time during a 500 Hz field modulation (circles), the fraction of molecules (triangles) and the magnetic field. Unlike the total detected signal (Fig. 3), the molecular fraction is modulated not in phase with the magnetic field, but in complete correlation with the condensate fraction. (b) The molecular fraction vs the condensate fraction, together with a fitted line through the data.

fraction of $\frac{\sqrt{p_{th}}}{\sqrt{p_0} + \sqrt{p_{th}}} = 46\%$ and would be about 7% in our case.

This effect can have several possible origins: One is that the atomic separation in a condensed atom pair is smaller than that of two uncondensed atoms. Also, the presence of a large pair condensate increases the density of the cloud [26]. Finally, if there are incoherent processes involved during the rapid ramp, bosonic stimulation into the molecular condensate could play a role.

In conclusion, we have determined the intrinsic time scale for the growth of a fermion pair condensate by observing the delayed response of the system to a change in its interaction strength. For our trap parameters, the response was delayed by $\approx 500 \mu\text{s}$. This time is far longer than the time spent within the resonance region during the conversion of fermion pairs into molecules. This provides final proof that the observed molecular condensates originated from condensates of pairs of fermions above the resonance. Regarding the two-body physics of the rapid transfer, we found that there is a missing fraction of particles after the ramp, presumably transferred into unobserved molecular states. We found evidence that condensed fermion pairs are more efficiently transformed into molecules than thermal pairs during the rapid ramp. Thus, the observed molecular condensate fractions tend to overestimate the initial fermion pair condensate fraction.

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- [20] The instantaneous magnetic field was determined by probing the atoms using a Zeeman-sensitive optical transition. For the 500 Hz modulation, the deduced field followed the modulation current with a time delay of $(85 \pm 5) \mu\text{s}$ and a reduced amplitude of 95% compared to the dc situation. This was due to induced eddy currents in the apparatus.
- [21] The transfer probability depends on the ramp speed and on the density of the cloud. In a tighter trap with 150 mW of power we cannot discern any unpaired atoms after the ramp.
- [22] This was far shorter than evaporation time scales, which were on the order of 100 ms.
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- [24] N_{total} was determined in a different cycle of the experiment, for which the rapid ramp was omitted.
- [25] Indeed, on resonance we observe almost pure condensates, and only a negligible amount of unpaired atoms after the ramp. Note that fitting routines, saturated absorption, and imaging noise all tend to underestimate condensate fractions.
- [26] This is not true in the BCS regime, where the atomic density is independent of the presence of a condensate. Still, an additional overestimation of the condensate fraction comes from the fact that the condensed pairs are concentrated in the high density region of the cloud, where the conversion efficiency is higher. However, this does not affect the total molecular signal.