Crossover from a Molecular Bose-Einstein Condensate to a Degenerate Fermi Gas

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We demonstrate a reversible conversion of a $^6$Li$_2$ molecular Bose-Einstein condensate to a degenerate Fermi gas of atoms by adiabatically crossing a Feshbach resonance. By optical in situ imaging, we observe a smooth change of the cloud size in the crossover regime. On the Feshbach resonance, the ensemble is strongly interacting and the measured cloud size is 75(7)% of the one of a noninteracting zero-temperature Fermi gas. The high condensate fraction of more than 90% and the adiabatic crossover suggest our Fermi gas to be cold enough to form a superfluid.

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To measure the condensate fraction, we adiabatically reduce the magnetic field from 764 to 676 G in a 200-ms linear ramp after completion of the evaporation ramp. This reduces the scattering length \( a_{\text{mol}} \) and thus increases the visibility of the characteristic bimodal distribution. Figure 1(a) shows a bimodal profile observed in this way with \( N_{\text{mol}} = N/2 = 4 \times 10^5 \) molecules remaining at a final evaporation ramp power of 28 mW. A Gaussian fit to the thermal wings (dashed line) yields a temperature of \( T = 430 \text{ nK} \), which is a factor of 7.5 below the calculated trap depth of 3.2 \( \mu \text{K} \). The observed condensate fraction of \( \sim 20\% \) is consistent with \( 1 - (T/T_c)^3 \), where \( T_c = 0.8k_B^{-1}\hbar \bar{\omega}(N_{\text{mol}}/1.202)^{1/3} = 500 \text{ nK} \) is the critical temperature, \( \bar{\omega} = (\omega_x^2 + \omega_z^2)^{1/2} \) is the mean vibration frequency, and the factor of 0.8 takes into account the \( \sim 20\% \) down-shift in \( T_c \) due to interactions [21].

We obtain pure molecular condensates when we continue the evaporation process down to final power levels of a few mW. Figure 1(b) shows an essentially pure condensate of \( N_{\text{mol}} = 2.0 \times 10^5 \) molecules obtained at a final power of 3.8 mW, where the trap depth is 450 nK. The density profile is well fit by a Thomas-Fermi density distribution \( \propto (1 - z^2/\zeta_{\text{TF}}^2)^2 \) with a radius \( \zeta_{\text{TF}} = 105 \mu\text{m} \). The corresponding peak molecular density is \( 1.2 \times 10^3 \text{ cm}^{-3} \). In the image a thermal component is not discernable. A careful analysis of the profile provides us with a lower bound of 90\% for the condensate fraction. For the chemical potential of the BEC, we obtain \( \mu = \frac{1}{2}m_{\text{mol}}\bar{\omega}^2\zeta_{\text{TF}}^2 = k_B \times 130 \text{ nK} \). Here \( m_{\text{mol}} = 2m \) is the mass of the \(^6\text{Li}\) dimer. Based on the prediction \( a_{\text{mol}} = 0.6a = 650a_o \), the calculated chemical potential of \( \frac{1}{2}(15\hbar^2N_{\text{mol}}\bar{\omega}^3a_{\text{mol}}\sqrt{m_{\text{mol}}})^{2/5} = k_B \times 155 \text{ nK} \) is consistent with the observed value of \( k_B \times 130 \text{ nK} \) considering the experimental uncertainty. In particular, the particle number is calibrated to within a factor of 1.5 through fluorescence imaging [10].

The pure molecular BEC at 764 G serves as our starting point for exploring the crossover to the degenerate Fermi gas. Before we change the magnetic field, we first adiabatically increase the trap power from 3.8 to 35 mW in a 200-ms exponential ramp. The higher power provides a trap depth of \( \sim k_B \times 2 \mu\text{K} \) for the atoms, which is roughly a factor of 2 above the Fermi energy, and avoids spilling of the Fermi gas produced at magnetic fields above the resonance [1]. The compression increases the peak density of the condensate by a factor of 2.5. All further experiments reported here are performed in the recompressed trap with \( \omega_z/2\pi = 640 \text{ Hz} \) and \( \omega_x/2\pi = (600B/kG + 32)^{1/2} \text{ Hz} \).

We measure the lifetime of the BEC in the compressed trap at 764 G to be \( 40 \text{ s} \). The peak molecular density is estimated to be \( n_{\text{mol}} = (15/8\pi)(\omega_x/\bar{\omega})^2N_{\text{mol}}/\zeta_{\text{TF}}^3 = 1.0(5) \times 10^{13} \text{ cm}^{-3} \). This provides an upper bound for the binary loss coefficient of \( 1 \times 10^{-14} \text{ cm}^3/\text{s} \), and is consistent with previous measurements in thermal molecular gases [8,10] together with the predicted scattering length scaling [20] and the factor-of-2 suppression of binary collision loss in a condensate.

For exploring the crossover to a Fermi gas we apply slow magnetic-field ramps. To ensure their adiabiaticity, we performed several test experiments. In one series of measurements we ramped up the field from 764 to 882 G and back to 764 G with variable ramp speed. This converts the molecular BEC into a strongly interacting Fermi gas and vice versa. Therefore substantial changes are expected in the cloud size. After the up-and-down ramp, we observe an axial oscillation of the ensemble at the quadrupolar excitation frequency [1,22]. This collective oscillation is the lowest excitation mode of the system and is thus sensitive to nonadiabaticity effects. We observe axial oscillations with relative amplitudes of \( > 5\% \) for ramp speeds above \( 1.2 \text{ G/ms} \). For ramp speeds of 0.6 G/ms and lower, the axial oscillation was no longer visible.

We also checked the reversibility of the crossover process by linearly ramping up the magnetic field from 764 to 1176 G and down again to 764 G within 2 s (ramp speed of \( \pm 0.41 \text{ G/ms} \)). In Fig. 2, we compare the axial profile taken after this ramp (○) with the corresponding profile obtained after 2 s at fixed magnetic field (○). The comparison does not show any significant deviation. This highlights that the conversion into a Fermi gas and its back-conversion into a molecular BEC are lossless and proceed without noticeable increase of the entropy.

To investigate the spatial profile of the trapped gas in different regimes, we start with the molecular BEC at 764 G and change the magnetic field in 1-s linear ramps to final values between 740 and 1440 G. Images are then taken at the final ramp field. To characterize the size of

FIG. 1. Axial density profiles of a partially condensed (a) and fully condensed (b) molecular cloud. The profiles are derived from averaging seven \textit{in situ} images taken at a magnetic field of \( B = 676 \text{ G} \) after evaporation at the production field of 764 G. (a) When the evaporation ramp is stopped with \( 4 \times 10^5 \) molecules at a final laser power of 28 mW, a characteristic bimodal distribution is observed with a condensate fraction of \( \sim 20\% \). The dashed curve shows Gaussian fit to the thermal fraction. (b) At a final laser power of 3.8 mW, an essentially pure condensate of \( 2 \times 10^5 \) molecules is obtained.
the trapped gas, we determine the root-mean-squared axial size \( z_{\text{rms}} \). This rms size is related to the axial radius \( z_{\text{TF}} \) by \( z_{\text{rms}} = z_{\text{TF}} / \sqrt{7} \) in the case of a pure BEC in the Thomas-Fermi limit and by \( z_{\text{rms}} = z_{\text{TF}} / \sqrt{8} \) in the cases of zero-temperature noninteracting or strongly interacting Fermi gases [23].

Figure 3(b) shows how the measured axial size \( z_{\text{rms}} \) changes with the magnetic field. For comparison, Fig. 3(a) displays the magnetic-field dependence of the atomic scattering length \( a \). Up to 950 G, an increase in \( z_{\text{rms}} \) is due to the crossover from the molecular BEC to the degenerate Fermi gas. For higher magnetic fields, the axial cloud size of the Fermi gas shrinks with \( B \) as the axial magnetic confinement increases (\( \omega_z \propto \sqrt{B} \)).

For the following discussions, we normalize the observed size to the one expected for a noninteracting Fermi gas. In particular, this removes the explicit trap dependence. In Fig. 3(c), we show the normalized axial size \( \xi = z_{\text{rms}} / z_0 \), where \( z_0 = (E_F/4ma_0^2)^{1/2} \) is the rms axial size of a noninteracting zero-temperature Fermi gas with \( N = 4 \times 10^5 \) atoms. The Fermi energy \( E_F = \hbar^2 k_F^2 / 2m = \hbar \omega (3N)^{1/3} \) amounts to \( k_B T \approx 1.1 \mu \text{K} \) at 850 G, and the Fermi wave number \( k_F \) corresponds to a length scale of \( k_F^{-1} = 3600a_0 \).

Below the Feshbach resonance, the observed dependence of the cloud size agrees well with the mean-field behavior of a BEC in the Thomas-Fermi limit. In this regime, the normalized size is given by \( \xi = 0.688(a_{\text{mol}}/a)^{1/4}(E_F/E_b)^{1/10} \), where \( E_b = \hbar^2 / ma^2 \) is the molecular binding energy. Figure 3(c) shows the corresponding curve (solid line) calculated with \( a_{\text{mol}}/a = 0.6 \) [20]. This BEC limit provides a reasonable approximation up to \( \sim 800 \) G; here the molecular gas interaction parameter is \( n_{\text{mol}} G_{\text{mol}}^3 = 0.08 \). Alternatively, the interaction strength can be expressed as \( k_Fa = 1.9 \).

The crossover to the Fermi gas is observed in the vicinity of the Feshbach resonance between 800 and 950 G; here \( \xi \) smoothly increases with the magnetic field until it levels off at 950 G, where the interaction strength is characterized by \( k_Fa = -1.9 \). Our results suggest that the crossover occurs within the range of \( -0.5 \leq (k_Fa)^{-1} \leq 0.5 \), which corresponds to the strongly interacting regime. The smoothness of the crossover is further illustrated in Fig. 4. Here the spatial profiles near the resonance show the gradually increasing cloud size without any noticeable new features.

On resonance a universal regime is realized [12–14], where scattering is fully governed by unitarity and the scattering length drops out of the description. Here the normalized cloud size can be written as \( \zeta = (1 + \beta)^{1/4} \), where \( \beta \) parametrizes the mean-field contribution to the chemical potential in terms of the local Fermi energy [14]. At 850 G our measured value of \( \zeta = 0.75 \pm 0.07 \) provides \( \beta = -0.68_{-0.10}^{+0.13} \). Here the total error range includes all statistic and systematic uncertainties with the particle number giving the dominant contribution. Note that the uncertainty in the Feshbach resonance position is not included in the errors [18]. Our experimental results reveal a stronger interaction effect than previous measurements that yielded \( \beta = -0.26(7) \) at \( T = 0.15T_F \) [14].
and $\beta = -0.3$ at $T = 0.6 T_F$ [15]. Our value of $\beta$ lies within the range of the theoretical predictions for a zero-temperature Fermi gas: $-0.67$ [12, 24], $-0.43$ [24], and, in particular, $-0.56(1)$ from a recent quantum Monte Carlo calculation [25].

Beyond the Feshbach resonance, in the Fermi gas regime above 950 G, we observe an essentially constant normalized cloud size of $\xi = 0.83 \pm 0.07$. In this regime, the interaction parameter $k_F a$ is calculated to vary between $-2$ (at 950 G) and $-0.8$ (at 1440 G), which allows us to estimate $\xi$ to vary between 0.90 and 0.95 based on the interaction energy calculations in Ref. [12]. Our observed values are somewhat below this expectation, which requires further investigation.

In summary, we have demonstrated the smooth crossover from a molecular condensate of $^6$Li dimers to an atomic Fermi gas. Since the conversion is adiabatic and reversible, the temperature of the Fermi gas can be estimated from the conservation of entropy [11]. Our high condensate fraction of $> 90\%$ suggests a very small entropy which in the Fermi gas limit corresponds to an extremely low temperature of $k_B T < 0.04 E_F$. In this scenario, superfluidity can be expected to extend from the molecular BEC regime into the strongly interacting Fermi gas regime above the Feshbach resonance where $k_F a \leq -0.8$. Our experiment thus opens up intriguing possibilities to study atomic Cooper pairing and superfluidity in resonant quantum gases.

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[18] The resonance position is uncertain within a few 10 G.
[23] We fit the density profiles with the function $\rho(z) = \rho_0 (1 - z^2/z_{rms}^2)^\alpha$, where $\rho_0$, $z_r$, and $2 \leq \alpha \leq 2.5$ are free parameters. This function interpolates between the density profile of a pure BEC in the Thomas-Fermi limit with $\alpha = 2$ and a zero-temperature noninteracting or strongly interacting Fermi gas with $\alpha = 2.5$. The rms cloud size $z_{rms}$ is obtained from $z_r$ and $\alpha$ by $z_{rms} = z_r/\sqrt{3 + 2 \alpha}$.