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Thomas Bourdel, Christophe Salomon. Experimental Study of the BEC-BCS Crossover Region in Lithium 6. 2004. hal-00001237v1

HAL Id: hal-00001237

<https://hal.science/hal-00001237v1>

Preprint submitted on 2 Mar 2004 (v1), last revised 2 Apr 2004 (v3)

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Experimental Study of the BEC-BCS Crossover Region in Lithium 6

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(Dated: March 2, 2004)

We report Bose-Einstein condensation of weakly bound ${}^6\text{Li}_2$ molecules in a crossed optical trap near a Feshbach resonance. We measure a molecule-molecule scattering length of 170_{-60}^{+100} nm at 770 G, in good agreement with theory. We study the expansion of the cloud in the BEC-BCS crossover region.

PACS numbers: 03.75.Ss, 05.30.Fk, 32.80.Pj, 34.50.-s

By applying a magnetic field to a gas of ultra-cold atoms, it is possible to tune the strength and the sign of the effective interaction between particles. This phenomenon, known as Feshbach resonance, offers in the case of fermions the unique possibility to study the crossover between situations governed by Bose-Einstein and Fermi-Dirac statistics. Indeed, when the scattering length a characterizing the 2-body interaction at low temperature is positive, the atoms are known to pair in a bound molecular state. When the temperature is low enough, these bosonic dimers can form a Bose-Einstein condensate (BEC) as observed very recently in ${}^{40}\text{K}$ [1] and ${}^6\text{Li}$ [2, 3]. On the side of the resonance where a is negative, one expects the well known Bardeen-Cooper-Schrieffer (BCS) model for superconductivity to be valid. However, this simple picture of a BEC phase on one side of the resonance and a BCS phase on the other is valid only for small atom density n . When $n|a|^3 \gtrsim 1$ the system enters a strongly interacting regime that represents a challenge for many-body theories [4, 5, 6, 7, 8, 9, 10, 11] and that now begins to be accessible to experiments [12, 13].

In this letter, we report on Bose-Einstein condensation of ${}^6\text{Li}$ dimers in a crossed optical dipole trap and a study of the BEC-BCS crossover region. Unlike all previous observations of molecular BEC made in single beam dipole traps with very elongated geometries, our condensates are formed in nearly isotropic strongly confining traps. Analyzing nearly pure condensate expansions with up to 4×10^4 molecules, we measure the molecule-molecule scattering length $a_m = 170_{-60}^{+100}$ nm at a magnetic field of 770 gauss. This measurement is in good agreement with the value deduced from the resonance position and the relation $a_m = 0.6 a$ of ref. [14], but differs strongly from the value of 8 nm given in ref. [3]. Combined with tight confinement, these large scattering lengths lead to a regime of strong interactions where the chemical potential μ is on the order of $k_B T_C$ where $T_C \simeq 1.5 \mu\text{K}$ is the condensation temperature. As a consequence, we find an important modification of the thermal cloud time of flight expansion induced by the large condensate mean field. Moreover, the gas parameter $n_m a_m^3$ is no longer small but on the order of 0.3. In this regime, the validity of mean field theory becomes questionable [17, 18, 19]. We

show, in particular, that the gas energy released during expansion varies smoothly and monotonically across the Feshbach resonance.

Our experimental setup has been described previously [21, 22]. A gas of ${}^6\text{Li}$ atoms is prepared in the absolute ground state $|1/2, 1/2\rangle$ in a Nd-YAG crossed beam optical dipole trap. The horizontal beam (resp. vertical) propagates along x (y), has a maximum power of $P_o^h = 2$ W ($P_o^v = 3.3$ W) and a waist of $\sim 25 \mu\text{m}$ ($\sim 40 \mu\text{m}$). At full power, the ${}^6\text{Li}$ trap oscillation frequencies are $\omega_x/2\pi = 2.4(2)$ kHz, $\omega_y/2\pi = 5.0(3)$ kHz, and $\omega_z/2\pi = 5.5(4)$ kHz, as measured by parametric excitation, and the trap depth is $\sim 80 \mu\text{K}$. After sweeping the magnetic field B from 5 G to 1060 G, we drive the Zeeman transition between $|1/2, 1/2\rangle$ and $|1/2, -1/2\rangle$ with a 76 MHz RF field to prepare a balanced mixture of the two states. As measured very recently [23], the Feshbach resonance between these two states is peaked at 822(3) G, and for $B=1060$ G, $a = -167$ nm. After 100 ms the coherence between the two states is lost and plain evaporation provides $N_\uparrow = N_\downarrow = N_{\text{tot}}/2 = 1.5 \times 10^5$ atoms at $10 \mu\text{K} = 0.8 T_F$, where $k_B T_F = \hbar^2 k_F^2 / 2m = \hbar(3N_{\text{tot}}\omega_x\omega_y\omega_z)^{1/3} = \hbar\bar{\omega}(3N_{\text{tot}})^{1/3}$ is the Fermi energy. Lowering the intensity of the trapping laser to $0.1 P_0$, the Fermi gas is evaporatively cooled to temperatures T at or below $0.2 T_F$ and $N_{\text{tot}} \approx 7 \times 10^4$.

Then, sweeping the magnetic field to 770 G in 200 ms, the Feshbach resonance is slowly crossed. In this process atoms are adiabatically and reversibly transformed into cold molecules [21, 24] near the BEC critical temperature as presented in figure 1a. The onset of condensation is revealed by bimodal and anisotropic momentum distributions in time of flight expansions of the molecular gas. These images are recorded as follows. At a fixed magnetic field, the optical trap is first switched off. The cloud expands typically for 1 ms and then the magnetic field is increased by 100 G in 50 μs . This converts the molecules back into free atoms above resonance without releasing their binding energy [3]. Switching the field abruptly off in 10 μs , we detect free ${}^6\text{Li}$ atoms by light absorption near the D2 line. Using this method, expansion images are not altered by the adiabatic following of the molecular state to a deeper bound state during switch-off as

observed in our previous work [21]. Furthermore, we have checked that, in the trap before expansion, there are no unpaired atoms. In figure 1b, a Bose-Einstein condensate of ${}^7\text{Li}$ atoms produced in the same optical trap is presented. The comparison between the condensate sizes after expansion dramatically reveals that the mean field interaction and scattering length are much larger for ${}^6\text{Li}_2$ dimers (Fig. 1a) than for ${}^7\text{Li}$ atoms (Fig. 1b).

As evaporation proceeds, the condensate size becomes comparable to the width of the thermal pedestal making it increasingly difficult to discriminate between them. To measure the molecule-molecule scattering length, we produce pure molecular condensates by taking advantage of our crossed dipole trap. We recompress the horizontal beam to full power while keeping the vertical beam at the low power of $0.035 P_0^v$ corresponding to a trap depth for molecules $U = 5.6 \mu\text{K}$. Temperature is then limited to $T \leq 0.9 \mu\text{K}$ assuming a conservative $\eta = U/k_B T = 6$, whereas the critical temperature increases with the mean oscillation frequency. Consequently, with an axial (resp. radial) trap frequency of 440 Hz (resp. 5 kHz), we obtain $T/T_C^0 \leq 0.3$, where $T_C^0 = \hbar\bar{\omega}(0.82N_{\text{tot}}/2)^{1/3} = 2.7 \mu\text{K}$ is the non interacting BEC critical temperature. Thus, the condensate should be pure as confirmed by our images. After 1.4 ms of expansion, the measured condensate anisotropy is 2.0(1) in agreement with the value 2.06 expected from superfluid hydrodynamic scaling laws [25, 26]. From the 2D Thomas-Fermi profiles, we deduce the molecule-molecule scattering length $a_m = 170_{-60}^{+100}$ nm at 770 G, where most of the uncertainty comes from the

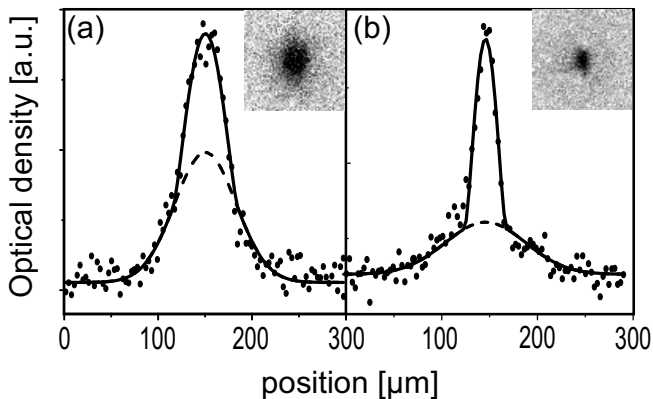


FIG. 1: Onset of Bose-Einstein condensation in a cloud of 2×10^4 ${}^6\text{Li}$ dimers at 770 G (a) and of 2×10^4 ${}^7\text{Li}$ atoms at 610 G (b) in the same optical trap. (a): 1.2 ms expansion profiles along the weak direction x of confinement. (b): 1.4 ms expansion. The different sizes of the condensates reflect the large difference in scattering length $a_m = 170$ nm for ${}^6\text{Li}$ dimers and $a_7 = 0.55$ nm for ${}^7\text{Li}$. Solid line: Gaussian+Thomas-Fermi fit. Dashed line: gaussian component. Condensate fractions are both 28%. $\omega_x/2\pi = 0.59(4)$ kHz, $\omega_y/2\pi = 1.6(1)$ kHz, and $\omega_z/2\pi = 1.7(1)$ kHz in (a). $\omega_x/2\pi = 0.55(4)$ kHz, $\omega_y/2\pi = 1.5(1)$ kHz, and $\omega_z/2\pi = 1.6(1)$ kHz in (b).

calibration of our atom number. At this field, we calculate an atomic scattering length of $a = 306$ nm. Combined with the prediction $a_m = 0.6 a$ of [14], we obtain $a_m = 183$ nm in good agreement with our measurement. For ${}^7\text{Li}$, we obtain with the same analysis a much smaller scattering length of $a_7 = 0.65(10)$ nm at 610 G also in agreement with theory [15].

Such large values of the scattering length bring our molecular condensates into a novel regime where the gas parameter $n_m a_m^3$ is no longer very small. Indeed, with $a_m = 170$ nm, $n_m = 6 \times 10^{13} \text{cm}^{-3}$ and $n_m a_m^3 = 0.3$. As a first consequence, corrections due to beyond mean field effects [16, 17] or to the underlying fermionic nature of atoms may play a role, since the average spacing between molecules is then of the order of the molecule size $\sim a/2$. Second, even in a mean field approach, thermodynamics is expected to be modified. For instance, in the conditions of Fig. 1a, we expect a large shift of the BEC critical temperature [17, 18, 19]. The shift calculated to first order in $n^{1/3} a \Delta T_C/T_C^0 = -1.4$ in [18] is clearly inapplicable and a more refined approach is required [20]. Third, we observe that partially condensed cloud expansions are modified by interactions. Indeed, double structure fits lead to temperatures inconsistent with the presence of a condensate. In Fig. 1, we find $T = 1.6 \mu\text{K}$, to be compared with $T_C^0 = 1.4 \mu\text{K}$, whereas for the ${}^7\text{Li}$ condensate $T = 0.7 \mu\text{K} = 0.6 T_C^0$.

This inconsistency results from the large mean field interaction which modifies the thermal cloud expansion. To get a better estimate of the temperature, we rely on a release energy calculation. In the trap, the condensate produces a repulsive potential which expels thermal atoms from the trap center. We calculate the thermal Bose distribution in a mexican hat potential that is the sum of the external potential and the mean field potential created by the condensate. For simplicity we neglect the mean field resulting from the thermal component. The release energy is the sum of the thermal kinetic energy, condensate interaction energy, and Hartree-Fock interaction energy between the condensate and thermal cloud. The temperature and chemical potential are then adjusted to fit the measured atom number and release energy. For figure 1a, we obtain a condensate fraction of 28% and $\mu = \hbar\bar{\omega}/2(15N_{\text{tot}}a_m/2a_{\text{ho}})^{2/5} = 0.45 \mu\text{K}$, where $a_{\text{ho}} = \sqrt{\hbar/2m\bar{\omega}}$ is the molecule harmonic oscillator length. The temperature $T = 1.1 \mu\text{K}$ is then found below $T_C^0 = 1.4 \mu\text{K}$. Introducing in the model the mean field energy between thermal molecules would lower the temperature further.

The condensate lifetime is typically ~ 300 ms at 715 G ($a_m = 66$ nm) and ~ 3 s at 770 G ($a_m = 170$ nm), whereas for $a = -167$ nm at 1060 G, the lifetime exceeds 30 s. On the BEC side, the molecule-molecule loss rate constant is $G = 0.26_{-0.06}^{+0.08} \times 10^{13} \text{cm}^3/\text{s}$ at 770 G and $G = 1.75_{-0.4}^{+0.5} \times 10^{13} \text{cm}^3/\text{s}$ at 715 G with the fit procedure for condensates described in [27]. As a function of the scat-

tering length, we find $G \propto a^{-1.9 \pm 0.8}$. Our data are in agreement with the theoretical prediction $G \propto a^{-2.55}$ of ref. [14] and with our previous measurement of G in a thermal gas at 690 G [21].

We now present an investigation of the crossover from a Bose-Einstein condensate to an interacting Fermi gas (Fig. 2 and 3). We prepare a nearly pure condensate with 3.5×10^4 molecules at 770 G and recompress the trap to frequencies of 2.5 kHz, 2.4 kHz, and 830 Hz. The magnetic field is then slowly swept at a rate of 2 G/ms to various values across the Feshbach resonance. The 2D momentum distribution after a time of flight expansion of 1.4 ms is then detected as previously.

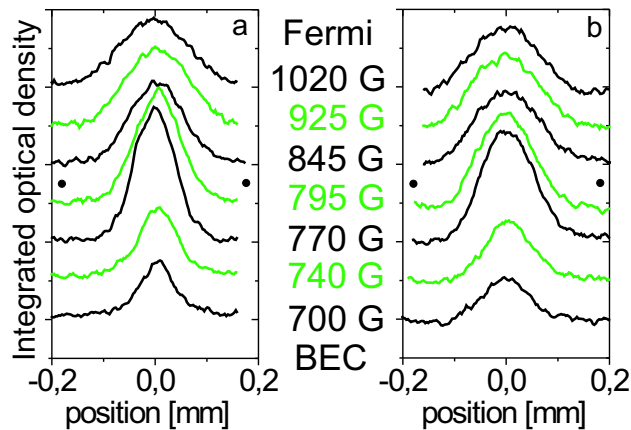


FIG. 2: Integrated density profiles across the BEC-BCS crossover region. 1.4 ms time of flight expansion in the axial (a) and radial (b) direction. The magnetic field is varied over the whole region of the Feshbach resonance from $a > 0$ ($B < 810$ G) to $a < 0$ ($B > 810$ G). •: Feshbach resonance peak.

Fig. 2 presents the observed profiles (integrated over the orthogonal direction) for different values of the magnetic field. At the lowest field values $B \leq 750$ G, $n_m a_m^3 \ll 1$, condensate number are relatively low because of the limited molecule lifetime. As B increases, the condensate width gradually increases towards the width of a non interacting Fermi gas. Near resonance, the profiles are found gaussian. At higher field ($B \geq 925$ G), where $k_F |a| \leq 3$, distributions are best fitted with zero temperature Fermi profiles. In the crossover region the expansion profiles change smoothly from a condensate of molecules to an interacting Fermi gas of atoms, and nothing dramatic happens on resonance.

More quantitatively, the anisotropy of the expanded clouds, Fig. 3b, monotonically decreases from ~ 1.5 on the BEC side of the resonance to 1.1, at 1060 G, on the BCS side. A fully hydrodynamic expansion would lead to an anisotropy of 1.7. We attribute the difference with the measured condensate anisotropy near 750 G to a residual

thermal component. On the $a < 0$ side, the decreasing anisotropy might result from the decrease of a and Pauli blocking. Both effects prevent the gas from being deeply in the collisional hydrodynamic regime [22, 28] despite a large ratio $4\pi a^2 n v_F / \omega_y \sim 80$. A quantitative theoretical analysis of this effect beyond the $T = 0$ calculation of [29] is required and should provide an accurate measurement of the temperature.

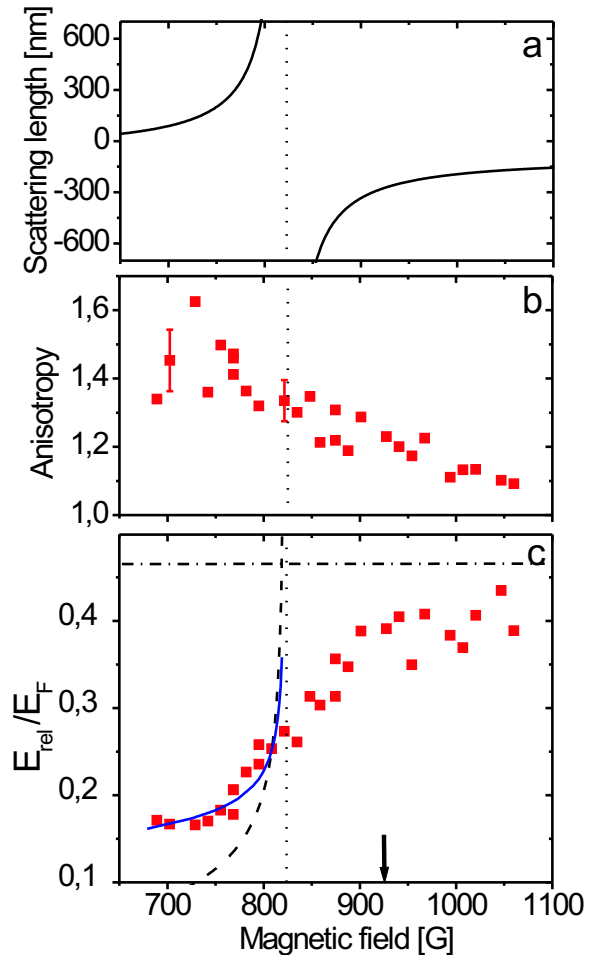


FIG. 3: (a): scattering length between the $|1/2, 1/2\rangle$ and $|1/2, -1/2\rangle$ ${}^6\text{Li}$ states. The Feshbach resonance peak is located at 820 G (dotted line). (b): anisotropy of the cloud, (c): release energy across the BEC-BCS crossover region. In (c), the dot-dashed line corresponds to a $T = 0$ ideal Fermi gas. The dashed curve is the release energy from a pure condensate in the Thomas-Fermi limit. The solid curve corresponds to a finite temperature mean field model described in the text with $T = 0.5 T_C^0$. Arrow: $k_F |a| = 3$.

In the BEC-BCS crossover regime, the gas energy released after expansion E_{rel} is also smooth (Fig. 3c). It is calculated from gaussian fits to the density after time of flight: $E_{\text{rel}} = m(2\sigma_y^2 + \sigma_x^2)/2\tau^2$, where σ_i is the rms

width along i , and τ is the time of flight [30]. The release energy presents a plateau for $B \leq 750$ G, and then increases monotonically towards that of a weakly interacting Fermi gas. The plateau is not reproduced by the mean field approach of a pure condensate (dashed line). This is a signature that the gas is not at $T = 0$. It can be understood with the mean field approach we used previously to describe the behavior of the thermal cloud. Since the magnetic field sweep is slow compared to the gas collision rate [21], we assume that this sweep is adiabatic and conserves entropy [31]. We then adjust this entropy to reproduce the release energy at a particular magnetic field, $B = 720$ G. The resulting curve as a function of B (solid line in Fig. 3c) agrees well with our data in the range $680 \text{ G} \leq B \leq 800 \text{ G}$, where the condensate fraction is 70%, and the temperature is $T \approx T_C^0/2 = 1.2 \mu\text{K}$. This model is limited to $n_m a_m^3 \lesssim 1$. Near resonance the calculated release energy diverges and clearly departs from the data. On the BCS side, the release energy of a $T = 0$ ideal Fermi gas gives an upper bound for the data (dot-dashed curve), as expected from negative interaction energy and a very cold sample. This low temperature is supported by our measurements on the BEC side and the assumption of entropy conservation through resonance which predicts $T = 0.1T_F$ [31].

On resonance the gas is expected to reach a universal behavior, as the scattering length a is not a relevant parameter any more. At 820 G, we compare $E_{\text{rel}} = E_{\text{kin}} + E_{\text{int}}$ with the kinetic energy E_{kin} measured in a time of flight without interaction obtained by switching the magnetic field off as in [22]. We find $\beta = E_{\text{int}}/E_{\text{kin}} = -0.55(10)$. This value is larger than the Duke result $\beta = -0.26 \pm 0.07$ at 910 G [28], but agrees with that of Innsbruck $\beta = -0.68^{+0.13}_{-0.10}$ at 850 G [2], and with the most recent theoretical prediction $\beta = -0.56$ [10].

Around 925 G, where $a = -270$ nm and $(k_F|a|)^{-1} = 0.35$, the release energy curve displays a change of slope. This is a signature of the transition between the strongly and weakly interacting regimes. It is also observed near the same field in [13] through *in situ* measurement of the trapped cloud size. Interestingly, the onset of resonance condensation of fermionic atom pairs observed in ^{40}K [12] and ^6Li [23], corresponds to a similar value of $k_F|a|$ [11].

In summary, we have explored the whole region of the ^6Li Feshbach resonance, from a Bose-Einstein condensate of fermion dimers to an ultra-cold interacting Fermi gas. The extremely large scattering length between molecules, that we have measured leads to novel BEC conditions. The long lifetime and very low temperatures in the BEC-BCS regime will be key to future study of superfluidity in this intriguing system.

We are grateful to Y. Castin, C. Cohen-Tannoudji, R. Combescot, J. Dalibard, G. Shlyapnikov, and S. Stringari for fruitful discussions. This work was supported by CNRS, Collège de France, and Région Ile

de France. S. Kokkelmans acknowledges a Marie Curie grant from the E.U. under contract number MCFI-2002-00968. Laboratoire Kastler Brossel is *Unité de recherche de l'École Normale Supérieure et de l'Université Pierre et Marie Curie, associée au CNRS*.

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