Quantum liquid droplets in a mixture of Bose-Einstein condensates

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Quantum droplets are small clusters of atoms self-bound by the balance of attractive and repulsive forces. Here, we report on the observation of droplets solely stabilized by contact interactions in a mixture of two Bose-Einstein condensates. We demonstrate that they are several orders of magnitude more dilute than liquid helium by directly measuring their size and density via in situ imaging. We show that the droplets are stabilized against collapse by quantum fluctuations and that they require a minimum atom number to be stable. Below that number, quantum pressure drives a liquid-to-gas transition that we map out as a function of interaction strength. These ultradilute isotropic liquids remain weakly interacting and constitute an ideal platform to benchmark quantum many-body theories.

Quantum fluids can be liquids—of fixed volume—or gases, depending on the attractive or repulsive character of the interparticle interactions and their interplay with quantum pressure. Liquid helium is the prime example of quantum fluids. For small particle numbers, it forms self-bound liquid droplets: nanometer-sized, dense, and strongly interacting clusters of helium atoms. Understanding the droplets’ properties, which directly reflect their quantum nature, is challenging and requires a precise knowledge of the short-range details of the interatomic potential (1, 2). Very different quantum droplets, more than two orders of magnitude larger and eight orders of magnitude more dilute, have recently been proposed in ultracold atomic gases (3, 4). These ultradilute systems enable a much simpler microscopic description while remaining in the weakly interacting regime. They are thus amenable to well-controlled theoretical studies.

The formation of quantum droplets requires a balance between attractive forces, which hold them together, and repulsive ones that stabilize them against collapse. In helium droplets, the repulsion is dominated by the short-range part of the interatomic potential (1, 2). By contrast, for ultracold atomic droplets several distinct stabilization mechanisms have been proposed, including three-body correlations (3) and quantum fluctuations (4). The latter can be revealed in systems with competing interactions, in which mean-field (MF) forces of different origins almost completely cancel out and result in a small residual attraction. In such systems, beyond MF effects remain important even in the weakly interacting regime. To first order, they lead to the Lee-Huang-Yang (LHY) repulsive energy (5), comparable in strength with the residual MF attraction. Recently, ultracold atomic droplets stabilized by quantum fluctuations have been realized in single-component magnetic quantum gases with competing attractive dipolar and repulsive contact interactions (6–11). In this case, the anisotropic character of the magnetic dipole-dipole force leads to the formation of filament-like self-bound droplets with highly anisotropic properties (9, 12, 13). Given the generality of the stabilization mechanism, droplets should in fact also exist in simpler systems with pure isotropic contact interactions. Even though they were originally predicted in this setting (4), their experimental observation has so far remained elusive.

We observed ultracold atomic droplets in a mixture of two Bose-Einstein condensates with competing contact interactions. Although a single-component attractive condensate with only contact interactions collapses (14, 15), quantum fluctuations stabilize a two-component mixture with intercomponent attraction and intracomponent repulsion (4). There, the repulsion in each component remains large and results in a non-negligible LHY energy. The beyond MF repulsion and the residual MF attraction scale differently with the total density n (in three dimensions, the scaling of the LHY and MF energy densities are $E_{\text{LHY}} \propto n^{5/2}$ versus $E_{\text{MF}} \propto n^2$, respectively). Hence, there is always a density for which these contributions balance each other and droplets are stabilized. Unlike their dipolar counterparts, these mixture droplets originate exclusively from s-wave contact interactions and are therefore isotropic. We demonstrated the self-bound character of mixture droplets and directly measured their ultralow densities and micrometer-scaled sizes. Moreover, through comparison with a single-component condensate with only contact interactions, we confirmed that their stability stems from quantum fluctuations.

We performed experiments with two $^{39}$K Bose-Einstein condensates in states $|\uparrow\uparrow\rangle \equiv |F, m_F = 1, -1\rangle$ and $|\uparrow\downarrow\rangle \equiv |1, 0\rangle$, where $F$ is the total angular momentum and $m_F$ is its projection. An external magnetic field allowed us to control the interactions, which were parameterized by the intracomponent interaction lengths $a_{\uparrow\uparrow}$ and $a_{\uparrow\downarrow}$ (Fig. 1A). These have been computed according to the model of (16). The residual MF interaction is proportional to $\delta a = a_{\uparrow\downarrow} - \sqrt{a_{\uparrow\uparrow}^2 + a_{\uparrow\downarrow}^2}$. The

Fig. 1. Observation of quantum droplets. (A) Scattering lengths $a$ (solid lines) and parameter $\delta a = a_{\uparrow\downarrow} - \sqrt{a_{\uparrow\uparrow}^2 + a_{\uparrow\downarrow}^2}$ (dashed line) versus magnetic field $B$ for a $^{39}$K mixture in states $|\uparrow\uparrow\rangle$ and $|\uparrow\downarrow\rangle$. (B) Schematic view of the experiment. Atoms are prepared in a plane of a blue-detuned optical lattice created by two beams intersecting at a small angle and imaged in situ with a high numerical aperture objective [0.97(4) μm measured resolution, 1/e Gaussian width]. The spin composition of the system is verified independently via Stern-Gerlach separation by a magnetic field gradient during time-of-flight expansion. During the preparation sequence, a red-detuned optical dipole trap (not shown) provides radial confinement (17). (C) Typical in situ images taken at time $t$ after removal of the radial confinement but in the presence of the lattice potential. (Top) Expansion of a gaseous mixture $[B = 56.935(9) \text{ G and } a_B = 1.2(1) a_0 > 0]$ and (Middle) Formation of a self-bound mixture droplet $[B = 56.754(9) \text{ G and } a_B = -3.2(1) a_0 < 0]$. (Bottom) Collapse of a single-component $|\downarrow\rangle$ attractive condensate $[B = 42.281(9) \text{ G and } a = -2.06(2) a_0 < 0]$. In our geometry, quantum pressure cannot stabilize bright solitons. Therefore, the existence of self-bound liquid droplets is a direct manifestation of beyond MF effects.
condition $\delta a = 0$ separates the repulsive ($\delta a > 0$) and attractive ($\delta a < 0$) regimes. The experiment starts with a pure condensate in state $|↑⟩$ loaded in one plane of a vertical blue-detuned lattice potential (Fig. 1B). We chose a trapping frequency $\omega_r/2\pi = 635(5)$ Hz large enough to compensate for gravity but small enough for the system to be in the three-dimensional regime (numbers in parentheses indicate experimental error bars). Indeed, the vertical harmonic oscillator length $a_{ho} = 0.68(3) \mu$m exceeds the characteristic length of the most energetic Bogoliubov excitation branch by typically a factor of 3 (17). A vertical red-detuned optical dipole trap provides radial confinement in the horizontal plane. In order to prepare a balanced mixture of the two states, we applied a radio-frequency pulse at $\nu = 57.3$ G, which lies in the miscible regime ($\delta a = 7a_{ho}$ where $a_{ho}$ denotes the Bohr radius) (18). For all measurements, we verified independently the spin composition of the mixture via Stern-Gerlach separation during time-of-flight expansion (Fig. 1B). Subsequently, we slowly ramped down the magnetic field at a constant rate of 59 G/s and entered the attractive regime $\delta a < 0$ (17). We then switched off the vertical red-detuned optical dipole trap while keeping the lattice confinement, allowing the atoms to evolve freely in the horizontal plane. The integrated atomic density was imaged in situ at the lattice confinement, allowing the atoms to be in the three-dimensional regime (numbers in parentheses indicate experimental error bars). Indeed, the vertical harmonic oscillator length $a_{ho} = 0.68(3) \mu$m exceeds the characteristic length of the most energetic Bogoliubov excitation branch by typically a factor of 3 (17). A vertical red-detuned optical dipole trap provides radial confinement in the horizontal plane. In order to prepare a balanced mixture of the two states, we applied a radio-frequency pulse at $\nu = 57.3$ G, which lies in the miscible regime ($\delta a = 7a_{ho}$ where $a_{ho}$ denotes the Bohr radius) (18). For all measurements, we verified independently the spin composition of the mixture via Stern-Gerlach separation during time-of-flight expansion (Fig. 1B). Subsequently, we slowly ramped down the magnetic field at a constant rate of 59 G/s and entered the attractive regime $\delta a < 0$ (17). We then switched off the vertical red-detuned optical dipole trap while keeping the lattice confinement, allowing the atoms to evolve freely in the horizontal plane. The integrated atomic density was imaged in situ at different evolution times. We used a high numerical aperture objective (1 $\mu$m resolution, 1/e Gaussian width) along the vertical direction and a phase-contrast polarization scheme (19) that detects both states with almost equal sensitivity (Fig. 1) (17).

Typical images of the mixture time evolution in the repulsive and attractive regimes are displayed in Fig. 1C. For $\delta a = 1.2(1) a_{ho} > 0$ (Fig. 1C, top row), the cloud expands progressively in the plane, as expected for a repulsive Bose gas in the absence of radial confinement (20). In contrast, in the attractive regime $\delta a = -3.2(1) a_{ho} < 0$ (Fig. 1C, middle row), the dynamics of the system are remarkably different, and the atoms reorganize in an isotropic self-bound liquid droplet. Its typical size remains constant for evolution times up to 25 ms. In an analogous experiment with a single-component attractive condensate $|↓⟩$ of scattering length $a = 2.00(2) a_{ho} < 0$, the system instead collapses (Fig. 1C, bottom row). In our experimental geometry, quantum pressure can never stabilize bright solitons because of the presence of weak anticonfinement in the horizontal plane (17). At the MF level, the two-component attractive case has a description equivalent to the single-component case, provided that the scattering length $a$ is replaced by $-\delta a/2$ and the density ratio between the two components is fixed at $n_0/n_1 = \sqrt{\alpha_{11}/\alpha_{22}}$ (17). However, the role of the first beyond MF correction is very different in the two systems, explaining their very different behavior. In the single-component case, the LHY energy depends on $a_1$ and, in the weakly interacting regime, constitutes a negligible correction to the MF term. Therefore, its contribution is most easily revealed in strongly interacting systems (21). By contrast, in the mixture the MF and LHY energy densities scale as $E_{MF} \propto \delta a n^2$ and $E_{LHY} \propto (\sqrt{\alpha_{11}+\alpha_{22}})^2 \approx \delta a$ for typical experimental parameters they balance at accessible atomic densities and stabilize liquid droplets (4). Therefore, the existence of liquid droplets is a striking manifestation of beyond MF effects in the weakly interacting regime.

To further characterize the mixture, we performed a quantitative analysis of the images fitting the integrated atomic density profiles with a two-dimensional Gaussian (17). We extracted the atom number $N$ and radial size $\sigma_r$ and inferred the peak density $n_0 = N/(\pi^{3/2}\sigma_r^3)$ by assuming a vertical size $\sigma_z$ identical to the harmonic oscillator length $a_{ho}$. Shown in Fig. 2A, top and middle, are the time evolutions of $N$ and $\sigma_r$ measured for the interaction parameters of Fig. 1C. For $\delta a > 0$ (Fig. 2A, red circles), the gas quickly expands, and its atom number does not vary. Instead, for $\delta a < 0$ (Fig. 2A, blue circles), the system is in the liquid regime, and the radial size of the droplet remains constant at $\sigma_r = 6 \mu$m. Initially, its atom number is $N = 24.5(7) \times 10^5$, corresponding to a peak density of $n_0 = 1.97(8) \times 10^{14}$ atoms/cm$^3$. We attribute the subsequent decrease of the atom number (Fig. 2A, top) to three-body recombination. The observed time scale is compatible with the measured density and effective three-body loss rate (17). By directly measuring the density of our droplets, we confirmed that they are more than eight orders of magnitude more dilute than liquid helium and remain very weakly interacting. Indeed, the interaction parameters of each component are extremely small $(n_0a_{11}^2, n_0a_{22}^2) \approx 10^{-5}$.

A closer view of the droplet size is displayed in Fig. 2A, bottom. At $t \approx 25$ ms, $\sigma_r$ starts to increase, and the system behaves like the $\delta a > 0$ gas. Following (4, 9, 22, 23), we attribute the dissociation of the droplet to the effect of quantum pressure, which acts as a repulsive force. As the atom number decreases, the relative weight between kinetic ($E_K$) and interaction energies ($E_{MF}, E_{LHY}$) changes, for each term scales differently with $N$: $E_K \propto N, E_{MF} \propto N^2$, and $E_{LHY} \propto N^{5/2}$. Below a critical atom number, kinetic effects become sufficiently strong to drive a liquid-to-gas transition. To support this scenario, the radial size and atomic density as a function of atom number is depicted in Fig. 2B. For $\delta a < 0$ (Fig. 2B, blue circles), we observed that both size (Fig. 2B, top) and density (Fig. 2B, bottom) remain constant at large $N$. For a decreasing atom number, we observed a point at which the size diverges and the density drops abruptly. This indicates a liquid-to-gas transition, which takes place at the critical atom number $N_c$. Below this value, the attractive gas is still stabilized by quantum fluctuations.

![Fig. 2. Liquid-to-gas transition. (A) Atom number $N$ and radial size $\sigma_r$ of the mixture for different evolution times $t$. The measurements are taken in the repulsive ($\delta a = 1.2(1) a_{ho} > 0$, red circles) and attractive ($\delta a = -3.2(1) a_{ho}$, blue circles) regimes. (Top) Whereas for $\delta a > 0$, the atom number in the gas remains constant, for $\delta a < 0$, it decreases on a time scale compatible with three-body recombination (17). (Middle) The radial size of the droplet remains constant at $\sigma_r = 6 \mu$m, demonstrating its self-bound nature. By contrast, the size of the gas increases continuously with time. (Bottom) Closer view of $\sigma_r$ for $\delta a < 0$. For $t > 25$ ms, the droplet dissociates, and a liquid-to-gas transition takes place. (Inset) Images taken at $t = 25$ to 35 ms in 2-ms increments, corresponding to the points in the gray area. (B) Radial size $\sigma_r$ (top) and peak density $n_0$ (bottom) versus $N$. For $\delta a < 0$ and large atom number, both remain approximately constant, as expected for a liquid. For a critical atom number, $\sigma_r$ rises suddenly, and $n_0$ plunges, signaling the liquid-to-gas transition. In the gas phase, the $\delta a < 0$ system behaves like the $\delta a > 0$ one. (Inset) Sketch of the phase diagram. In the liquid phase (blue region), observing the mixture at variable evolution times gives access to different values of $N$ (black arrow). For (A) and (B), error bars represent the standard deviation of 10 independent measurements. If not displayed, error bars are smaller than the size of the symbol. Additionally, $N$ has a calibration uncertainty of $25\%$ (17).]
but expands because of kinetic effects, similarly to the repulsive mixture ($\delta a > 0$) (Fig. 2B, red circles).

The liquid-to-gas transition is expected to depend on $\delta a$, as sketched in Fig. 2B, top, inset. We explored the phase diagram by tuning the interaction strengths with magnetic field (Fig. 1A). The measured size is displayed in Fig. 3A as a function of atom number $N$ for different magnetic fields $B$, from strong to weak attraction (top to bottom). The critical atom number $N_c$ increases as attraction decreases. Solid lines display the phenomenological fit $a_c(N) = a_0 + A/(N - N_c)$ used to locate the liquid-to-gas phase transition.

The critical number $N_c$ shows a strong dependence on the magnetic field. Our experimental determination of the phase transition line is presented in Fig. 3B, top, which increases when the attraction decreases, confirming that weakly bound droplets are more susceptible to kinetic effects and require a larger atom number to remain self-bound. Figure 3A also yields the droplet size as a function of atom number and magnetic field. In Fig. 3B, bottom, we display the measurements obtained at a fixed atom number $N = 1.5(1) \times 10^4$, which is always larger than $N_c$ for our interaction regime. As expected, the droplet size decreases as the attraction increases.

We theoretically describe the system using a simple zero-temperature model based on an extended Gross-Pitaevskii equation that includes both the vertical harmonic confinement and an additional repulsive LHY term. The latter was obtained by assuming the Bogoliubov spectrum of a three-dimensional homogeneous mixture (17). In Fig. 3B, we compare the experimental results with the predicted critical atom number and droplet size (Fig. 3B, solid line). We found qualitative agreement for the complete magnetic field range, with no adjustable parameters. The strongly attractive regime, the agreement is even quantitative, similar to the dipolar erbium experiments of (9). By contrast, when increasing the effective attraction, the droplets are more dilute than expected. In particular, their size exceeds the theoretical predictions by up to a factor of 3. This is almost one order of magnitude larger than our imaging resolution, excluding finite-resolution effects. Furthermore, the critical atom number is a factor of 2 smaller than the theoretical value. A similar discrepancy was reported for dipolar dysprosium droplets, with a critical atom number one order of magnitude smaller than expected (9). There, the deviation was attributed to an insufficient knowledge of the background scattering length. This explanation seems unlikely in the case of potassium (17), in which excellent interaction potentials are available (16, 24, 25).

Other physical mechanisms might be responsible for the diluteness of the observed droplets. Although our system is three-dimensional, the confinement along the vertical direction might affect the LHY energy, modifying its density and interaction dependence or introducing finite-size effects; however, a description of quantum fluctuations in the dimensional crossover between two and three dimensions is challenging. The almost perfect cancellation of the MF energy could reveal corrections other than the LHY term. Higher-order many-body terms might play a role, as proposed in (3) for single-component systems. Taking them into account analytically requires knowledge of the three-body interaction parameters of the mixture, which are nonuniversal and difficult to estimate in our interaction regime. Alternatively, our results could be compared with ab initio quantum Monte Carlo simulations (26).

Given the ultradilute character and simple microscopic description of our system, a direct comparison with different theoretical approaches could provide insights on yet-unmeasured many-body effects.

Future research directions include studying the spectrum of collective modes of the droplets (8). Their unconventional nature not only provides a sensitive testbed for quantum many-body theories but should also give access to zero-temperature quantum systems (4) not present in the dipolar case (27). Our experiments could also enable the exploration of low-dimensional systems, in which the enhanced quantum fluctuations make droplets ubiquitous (28). Last, a coherent coupling between the two components (29) is expected to yield effective three-body interactions (30) and provide control over the density dependence of the LHY term (31).

Note added in proof: After submission of this work, related experiments have been performed by the European Laboratory for Non-Linear Spectroscopy (LENS) group (32).

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SUPPLEMENTARY MATERIALS

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Supplementary Text
Figs. S1 and S2
Tables S1 to S3
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