

A new state of matter of quantum droplets

Mingyang Guo[†], Tilman Pfau

5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany
E-mail: [†]guo@pi5.physik.uni-stuttgart.de

Since the realization of Bose–Einstein condensation (BEC) [1–3] and degenerate Fermi gases [4], ultracold quantum gases have become important platforms to study quantum phenomena and novel states of matter with precise control over both internal and external degrees of freedom. While quantum gases are typically dilute and weakly interacting, the interactions intrinsically determine their essential properties, such as the superfluidity of a BEC. Most of the realized ultracold quantum gases, like the ones consisting of alkali atoms, are dominated by the short-range and isotropic contact interaction that can be tuned from repulsive to attractive via the so-called Feshbach resonances [5]. A BEC with effectively attractive interactions at the mean-field level was predicted to be unstable and undergo collapse after exceeding a critical atom number, which has been experimentally observed in purely contact interacting clouds [6, 7] and dipolar quantum gases of Chromium with additional long-range and anisotropic dipolar interaction [8].

For an improved description of quantum gases, quantum fluctuations, a beyond mean-field quantum effect, should be taken into account, leading to modified ground-state energy. The leading-order correction due to quantum fluctuations was first calculated in 1957 by Lee, Huang and Yang, and called LHY correction [9]. Unlike strongly interacting superfluid Helium, quantum fluctuations are typically negligible for weakly interacting quantum gases and the mean-field approximation can precisely capture the features of a condensate. However, for a quantum gas with two competing mean-field interactions with opposite sign, resulting in a combined effective interaction that is weakly attractive, the repulsive quantum fluctuations can stabilize the cloud from collapsing and lead to a exotic novel state of matter, the quantum droplet. Such a new phase was first predicted by Petrov in 2015 for Bose–Bose mixtures with competing inter- and intra-species contact interactions [10] while shortly afterwards the first experimental realization was independently observed in

a different platform, dipolar quantum gases of Dysprosium [11, 12] in Stuttgart with competing contact and dipolar interactions. In 2018 quantum droplets in Bose–Bose mixtures were also realized experimentally [13, 14].

Although observed in two distinct platforms, the underlying mechanism for the formation of these quantum droplets is the same, namely the stabilization of the precisely tuned attractive mean-field interactions by the repulsive quantum fluctuations. The main features of the droplets in both systems can be well captured with the corresponding extended Gross–Pitaevskii equations (eGPEs) by incorporating additional quantum fluctuation corrections. However, the different nature of the mean-field interactions result in isotropic droplets in Bose–Bose mixtures while the anisotropic dipolar interaction leads to elongated droplets along the magnetic field.

The realized quantum droplets feature a density that is more than seven orders of magnitude lower than classic liquids, but more than an order of magnitude higher than a BEC. The hallmark feature of the droplets is their liquid property of self-maintaining shape even without external confinements, like a classic drop of water and distinct from normal expanding quantum gases. The self-bound nature is a direct result of the balancing between the attractive mean-field interaction and the repulsive quantum fluctuations when the condensate atom number exceeds a critical value. Self-bound quantum droplets have been observed in both platforms including spin mixtures of ³⁹K [13, 14], heteronuclear mixtures of ⁴¹K and ⁸⁷Rb, dipolar condensates of ¹⁶⁴Dy and ¹⁶²Dy [15, 16], and slowly expanding dipolar gases of ¹⁶⁶Er close to the self-bound region [17]. Another liquid feature of incompressibility was also observed in ¹⁶²Dy [16] by *in-situ* detection of the saturated density distribution. When the peak density reaches a critical value, adding more atoms into the droplet will lead to a flat-top density distribution while maintaining the peak density constant.

Shortly after the realizations of quantum droplets, collective excitations of these novel quantum liquid are investigated to understand the underlying physics both theoretically and experimentally. As predicted in the original theoretical work by Petrov [10], one fascinating feature of the droplets in Bose–Bose mixture is that there exists a region where the energies of all the collective modes are above the chemical potential, which means exciting the droplets will lead to emission of particles instead of populating any excitation modes. Therefore the droplets can self-evaporate to zero temperature. The self-evaporation effect is unique in Bose–Bose mixtures and not exists in dipolar case [18], but has not yet been observed due to the

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lack of temperature probes. Experimental measurements of the collective modes are limited by the lifetime of the droplets due to the three-body loss, and have been focused on the quadrupole mode across the BEC to droplet crossover in ^{166}Er [17] and the unique scissors mode of elongated dipolar droplets with ^{164}Dy [19]. Recently, the monopole mode of the quantum liquid was also observed in a spin mixture of ^{39}K with in-phase oscillating of both spin species in the quantum fluctuations dominated region where the effective mean-field interaction is tuned to zero [20].

In lower dimensional BECs, there exists another type of self-bound object, the so-called soliton. However distinct from quantum droplets, soliton is a product of the interplay between the kinetic dispersion and the nonlinear two-body mean-field interactions while the droplets result from additional nonlinearity of the beyond mean field many-body quantum fluctuations, featuring a distinct density dependence. Furthermore, while a soliton is only stable in one-dimensional contact interacting clouds as well as one- and two-dimensional dipolar systems, droplets can exist in three-dimensional free space. On the other hand, connections between the solitons and droplets have been studied with spin mixture of ^{39}K in an optical waveguide [21], where the system evolves from solitons to droplets with increasing atom number and the crossover can be smoothly connected or remained distinct in a bistable region depending on the interaction strength.

In the spirit of the coalescence of Helium clusters to reveal the superfluid features of the liquid, collisions of the quantum droplets have been studied. In Bose–Bose mixtures, separated droplets are typically prepared from separate condensates, say in a double-well potential. As expected, the outcome of two colliding droplets, merging or separating, depends on the collision velocity [22]. The dependence of the critical velocity on the atom number behaves differently for small and large droplets, corresponding to the crossover from a compressible to an incompressible region where the dynamics is dominated by the droplet binding energy and the surface tension respectively [22]. In dipolar gases, multiple droplets state can be reached even in a harmonic trap and colliding droplets repel each other without even contacting each other due to the repulsive dipolar interaction [23].

Uniquely in the dipolar case, the systems can also develop into multiple droplets ground states even in harmonic confinements as an intrinsic result of the long-range and anisotropic dipolar interaction [24]. Indeed the first experimental observation of the quantum liquid is a two-dimensional array of droplets by quenching the contact interaction [11]. The emergence of such a droplet array naturally raises the question whether it can be the long-sought supersolid state, which is an exotic state of matter possessing both the frictionless flow of a superfluid and the periodic structure of a crystal, therefore simultaneously breaking the gauge symmetry

and the translation symmetry. Distinct from the initially proposed candidate of strongly interacting superfluid Helium, the intrinsic interactions inducing the crystalline structure in the droplet arrays is much weaker but still leads to a similar rotonic excitation spectrum as in Helium [25]. Recent experiments realized in three independent groups proved the periodic density structure of the droplet arrays and the global phase coherence between the droplets in one-dimensional droplet arrays of Dysprosium and Erbium [26–28]. Together with the measured low-lying collective excitations [29–32] including the Goldstone modes which are closely related to the genuine superfluidity and the two broken symmetries, these hallmark features confirm the supersolidity of the droplet arrays close to the phase transition. Other properties of the supersolid states like the out-of-equilibrium dynamics [33], high-energy Bragg spectroscopy [34], rotation of the arrays [35], as well as the density fluctuations and structure factors [36], are also studied.

The recently discovered quantum droplets and droplet arrays are attracting great interests both from theoretical and experimental aspects (see recent reviews [37, 38]). These include but are not limited to quantum droplets in lower dimensions, droplets in other platforms like Bose–Fermi mixtures and dipolar mixtures, supersolidity of two-dimensional droplet arrays, and vortices in the droplets and droplet arrays (see references in the reviews [37, 38]). On the other hand, there are many open questions that need to be solved. Although the eGPEs well capture features of the droplets qualitatively, the corrections due to quantum fluctuations are derived under the local density approximations which is not always valid in the droplet region. Consequently there are some quantitative discrepancies with experimental measurements [16, 37]. Moreover, the effects of finite temperature and the particle correlations, which cannot be described by the eGPEs, are still not clear. To answer these questions and gain better understanding on the novel and exotic quantum droplets, a close collaboration between theoretical and experimental research is needed.

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