Decadal Survey on Biological and Physical Sciences Research in Space
2023-2032

Topical: Fundamental Physics and Opportunities with Ultracold Quantum Droplets in Space

Principal Author: Name: Prof. Peter Engels
Institution: Washington State University
Email: engels@wsu.edu
Phone: (509) 335-4674

Co-authors:
Prof. Russell N. Bisset, University of Innsbruck, Austria
Prof. Jose D'Incao, University of Colorado, Boulder
Prof. Michael McNeil Forbes, Washington State University
Prof. Maren E. Mossman, University of San Diego

This white paper advocates a research program exploiting self-bound gaseous quantum droplets in a microgravity environment as a new platform to advance our understanding of quantum matter and quantum dynamics. A detailed understanding of few-body and many-body quantum mechanics is essential for the future development of quantum technologies that will enable unprecedented opportunities for fundamental and applied studies relevant from the nanoscale to cosmological scales.

1 Introduction

This white paper advocates a research program exploiting self-bound gaseous quantum droplets in a microgravity environment as a new platform to advance our understanding of quantum matter and quantum dynamics. A detailed understanding of few-body and many-body quantum mechanics is essential for the future development of quantum technologies that will enable unprecedented opportunities for fundamental and applied studies relevant from the nanoscale to cosmological scales.

Ultracold quantum gases, i.e. atomic vapors cooled to near absolute zero temperature, are a highly versatile test bed for the study of quantum phases and dynamics. The rich toolbox of atomic physics presents unprecedented possibilities for the precision manipulation of atomic samples down to a single quantum state. Since the first generation of a dilute-gas Bose-Einstein condensates (BECs) in 1995 [1, 2] earthbound experiments have led to a tremendous advancement of our understanding of complex quantum phases of the matter. To name just a few examples, ultracold quantum gases have provided experimental access to the BEC-Bardeen-Cooper-Schrieffer (BCS) crossover of fermionic superfluidity [3–7], designed topological materials [8] exhibiting quantum-hall physics [9], or supersolid-like states [10–15]. No other experimental platform provides a similarly well-controlled and versatile playground to explore some of the most exotic regimes of modern quantum science.

A common feature of all earth-based experiments is the fact that prolonged interrogation times of a quantum gas require supporting the gas against gravity. In practice, this means confining the atoms in a magnetic or optical trap. This confinement can itself induce perturbations or even instabilities that can obscure the physics under investigation. A microgravity environment, however, alleviates the need for gravity support, and thus avoids such unwanted, perturbing factors allowing for a much cleaner and more stable platform to explore quantum dynamics. This opens new possibilities for experiments that will significantly extend the realm of accessible phenomena. Being far more than just an incremental improvement, the availability of quantum gases in microgravity leads to fundamentally new opportunities. The investigation of quantum droplets as a new form of quantum matter with exotic properties is a particularly promising avenue for research in microgravity: quantum droplets are self-bound objects and do not need any confining potential to remain as an entity without dispersing. From this perspective, microgravity is the natural environment to study this quantum phase in its purest form. A detailed study of quantum droplets will provide essential new insights into the fundamental nature of the interplay between few- and many-body interactions. It is expected that both the experimental and theoretical progress stimulated through a research program involving quantum droplets in microgravity will lead to a significant advancement of quantum science and technology.

2 Current status and microgravity justification

Quantum droplets are an exotic quantum-fluid resulting from the delicate balance between repulsive and attractive interactions that can exist in various physical systems including atomic and nuclear matter. The quantum droplets considered here are a member of a larger family of related exotic quantum states of matter that have been proposed theoretically including fermilets, boselets and ferbolets [16, 17]. Within atomic systems, several approaches for the realization of self-bound quantum droplets have theoretically been suggested. In a seminal paper by A. Bulgac [16], for instance, the mechanism that creates the droplet state is based on a balance between two- and three-body interactions. The proposal put forth by Petrov in 2015 [18], however, explores the attractive and repulsive nature of quantum fluctuations in a two-component BEC. Similar opportunities are available to create self-bound quantum droplets based on atomic species with strong dipolar interactions, most prominently Dy or Er, as proposed by Refs. [19, 20]. From an experimental point of view, earthbound experiments exploiting the ideas from Refs. [18–20] have provided important advances by demonstrating the existence of self-bound droplets and a number of their physical properties [21–24]. Nevertheless, some of their most intriguing properties have remained elusive due to limitations imposed by gravity, and several alternative approaches to droplet physics, including the one described in Ref. [16], are fully unexplored.

In the frame of the Cold Atom Laboratory (CAL) mission, NASA currently operates a BEC apparatus on board the International Space Station that experiments with rubidium (Rb) and potassium (K) atoms. Significant development work by the Jet Propulsion Laboratory (JPL) has resulted in extensive expertise with handling these two elements, including the laser cooling, trapping, and sympathetic cooling down to nano-Kelvin temperatures. This is a remarkable step in bringing ultracold atom research to space and forms a solid basis on which a program studying quantum droplets can be built. Based on this expertise, one possible avenue towards the realization of quantum droplets in microgravity investigations is based on Petrov's work [18]. In this case, a quantum droplet can be created either from a mixture of two different atomic species, such as two hyperfine states of ^{39}K, or a dual-species mixture of ^{41}K-^{87}Rb atoms. In both cases, to create a droplet an external magnetic field (Feshbach field) is used to fine-tune the intra- and inter-species interactions such that the residual mean-field interaction is slightly attractive. Under normal circumstances, having an attractive mean-field interaction would typically cause a single-component BEC to collapse. However, in a two-component BEC the right balance of the two atomic densities and the right tuning of interactions will allow for higher-order repulsive quantum-fluctuations to prevent the system collapse by favoring the formation of the quantum droplet. Such quantum fluctuations, known as the Lee-Huang-Yang (LHY) corrections [25], can in fact be attractive or repulsive depending on the dimensionality of the system and have a different dependence on density ($n^{5/2}$) than the pure mean-field interaction (n^2). This makes stabilizing the system into a droplet state quite challenging, requiring the precise control of both interactions and densities to satisfy the conditions for the existence of such a delicate quantum state.

Regardless of their particular realization, ground-based droplet studies under free-fall have a maximum observation time of tens of milliseconds in the absence of a trapping potential before the droplet has fallen out of sight or enters regions where the magnetic field becomes significantly inhomogeneous. Existing experimental ground-based investigations of quantum droplets have thus had to use additional fields to compensate for the effects of gravity, introducing further experimental complexity. Potential techniques to mitigate the effect of gravity lead to additional, spurious trapping along one or several directions, compromising the study of untrapped, self-bound droplets. Furthermore, heteronuclear droplets, such as droplets composed of ^{87}Rb and ^{41}K, which differ in mass by more than a factor of two, pose additional challenges for ground-based experiments due to differential gravitational sag. A separation of the clouds in the trap limits their overlap, complicates their sympathetic cooling, and requires special measures for the preparation and study of droplets. When an external potential is applied to compensate for differential gravitational sag, it must be carefully tuned in order to not break a droplet apart, which may prevent the full compensation of gravitational effects.

3 Scope of research program

To enable the best possible progress, it will be highly desirable for NASA to fund a rigorous and strong space-based program that is accompanied by a supporting ground based program involving both experimental and theoretical research. Ground based experiments can provide essential calibrations where possible, such as precision measurements of atomic data that are needed to evaluate the space based results. Theoretical research is needed as the proposed line of investigation will clearly go beyond the current understanding of few-body and many-body quantum dynamics. The development of new theoretical tools and methodologies, concomitant with the expansion of experimental capabilities afforded by the microgravity environment, will be a major outcome of this research. Therefore, the research program should support a strong group of researchers from multiple labs and institutions working together to direct and advise the space based endeavor.

4 Opportunities

Even though quantum droplets are formed from an atomic quantum gas, in many ways their physical characteristics resemble that of a liquid with unusual quantum properties. Here we will list a number of their properties and briefly discuss the opportunities they represent whether they are of a more fundamental or applied nature.

Self-bound quantum objects. Residing within a vacuum chamber, quantum droplets remain self-bound even without any external confinement. A microgravity environment will furnish the next key ingredient for creating pristine, long-lived, quantum test beds with unprecedented levels of isolation and control.

Surface effects. Just like the strings of a guitar, the surface of a quantum droplet is excitable according to different harmonics. However, unlike a guitar, the number of harmonics available to a droplet is limited by the binding energy [18, 26]. Intriguingly, it is predicted that by adjusting the number of atoms or inter-particle interactions, even the first harmonic can vanish, producing a novel, unexcitable object that awaits experimental confirmation.

Constant density. Quantum droplets are characterized by a constant density, meaning that adding atoms just makes a droplet wider. Unlike an ordinary liquid, the underpinning stabilization mechanism is instead due to quantum fluctuations, which prevent a runaway implosion [18, 27, 28]. On the one hand, this provides a rare opportunity to investigate quantum fluctuations in a weakly-interacting setting. The theoretical description is still in its infancy and microgravity experiments would provide much-needed precision and insight. On the other hand, the constant density could provide fascinating prospective for interferometry, or be an ideal platform for studying additional quantum gases immersed in these ultra-dilute quantum liquids [29, 30].

Impurity investigations. Quantum droplets, once created, can be utilized in controlled investigations of impurities in a system. By adding a third component to a self-bound two-component droplet – or adding a second component to a dipolar droplet – one can sympathetically cool an impurity [18] or begin to study polaron physics [30, 31]. Not only would this open a novel platform for the study of polaron physics, the impurities themselves are expected to act as important probes to deepen our understanding of quantum droplets.

Self-evaporation. Given that quantum droplets have a finite, controllable number of bound excitations they are predicted to behave as self-cooling objects [18]. Such systems offer an alternative route for advancing the frontiers of ultra-cold temperatures, and may provide a practical means to cool other quantum gases sympathetically by bringing them into thermal contact.

Dynamical studies. Experiments studying collisions between self-bound droplets have begun to shed light on their internal structure and liquid-like properties [32]. Future experiments would clearly benefit from the longer lifetimes afforded by microgravity environments, especially for analyzing the collision products.

Droplet molecules. A single-component dipolar gas can form a self-bound quantum droplet without the need for a second component, and this raises some exciting prospects. Consider two dipolar droplets of different species that are brought into contact. It has been predicted that below a critical inter-component interaction strength the two droplets will be miscible (and co-spatial), while for larger interactions the droplets strongly repel each other [29, 30]. Without dipolar interactions these liquids would fly apart, but remarkably they are predicted to remain bound to one another by their mutual long-ranged attraction to form a kind of immiscible droplet molecule, without any external confinement.

Supersolids. The techniques to generate quantum droplets also offer a path towards the study of supersolidity. Coming from the regime of isolated droplets, a supersolid is formed when droplets sufficiently overlap and superfluidity stretches across a complete droplet assembly, arising due to a quantum delocalization of every atom throughout the 'solid'. A microgravity environment would allow one to consider novel regimes, such as weaker trapping without losing atoms due to gravity, which may allow more-favorable interactions and longer lifetimes. Weaker trapping would also aid evaporative cooling directly into the supersolid regime – a procedure that appears necessary for creating 2D supersolids [33].

Nuclear Physics. Cold-atom platforms realize a type of analog quantum computer capable of simulating aspects of nuclear physics and cosmology. At a quantitative level, a unitary Fermi gas is a good proxy for dilute neutron matter in heavy nuclei and neutron stars. At a more qualitatively level, cold-atom droplets provide a tunable platform to explore phenomena like nuclear fission and heavy-ion collisions. The idea is to use cold atoms to test and validate theoretical techniques such as time-dependent density functional theory (DFT), which are currently the de-facto standard for studying these phenomena in nuclear physics. Quantum droplets provide a compelling analog to nuclei, and droplet dynamics studied in microgravity – e.g. induced fission and collisions – would capture many of the properties affecting their nuclear counterparts such as entanglement between fragments, pairing, projection onto states of definite particle number and angular momentum (see e.g. [34] for a review).

Cosmology. Droplets also provide an intriguing platform to study aspects of cosmology. This idea was originally explored in helium [35], but cold atom provides substantial improvements in flexibility compared to the helium platform, especially tunable interactions and miscible superfluid mixtures. Ideas in this direction include exploring surface effects which manifest as a boundary-sensitive "cosmological constant" [36], topological defect formation (Kibble-Zurek transition) and the fragmentation of clouds into small droplets. The latter could help model the formation mechanism for axion quark nuggets (AQNs), a promising condensed-matter candidate for dark matter that simultaneously explains baryogenesis through the separation of matter and antimatter into quark nuggets at the quantum chromodynamics (QCD) phase transition (see [37, 38] and references therein).

5 Conclusion

The extensive list of opportunities enumerated above clearly indicates that the time is ripe for a research program focused on self-bound droplets in microgravity. We expect that an investment in this direction will lead to a tremendous pay-off on both fundamental and technological levels and should be considered a high priority of NASA's fundamental physics research focus.

References

[1] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell. Observation of Bose-Einstein condensation in a dilute atomic vapor. Science, 269:198, 1995. `doi:10.1142/9789812813787_0062`.

[2] K. B. Davis, M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, and W. Ketterle. Bose-Einstein condensation in a gas of Sodium atoms. Phys. Rev. Lett., 74(22):3969–3973, November 1995. `doi:10.1109/eqec.1996.561567`.

[3] C. A. Regal, M. Greiner, and D. S. Jin. Observation of Resonance Condensation of Fermionic Atom Pairs. Phys. Rev. Lett., 92(4):040403, jan 2004. `doi:10.1103/PhysRevLett.92.040403`.

[4] M. W. Zwierlein, C. A. Stan, C. H. Schunck, S. M. F. Raupach, A. J. Kerman, and W. Ketterle. Condensation of Pairs of Fermionic Atoms near a Feshbach Resonance. Phys. Rev. Lett., 92(12):120403, mar 2004. `doi:10.1103/PhysRevLett.92.120403`.

[5] C. Chin, M. Bartenstein, A. Altmeyer, S. Riedl, S. Jochim, J. Hecker Denschlag, and R. Grimm. Observation of the Pairing Gap in a Strongly Interacting Fermi Gas. Science, 305(5687):1128–1130, aug 2004. `doi:10.1126/science.1100818`.

[6] T. Bourdel, L. Khaykovich, J. Cubizolles, J. Zhang, F. Chevy, M. Teichmann, L. Tarruell, S. J. J. M. F. Kokkelmans, and C. Salomon. Experimental Study of the BEC-BCS Crossover Region in Lithium 6. Phys. Rev. Lett., 93(5):050401, jul 2004. `doi:10.1103/PhysRevLett.93.050401`.

[7] J. Kinast, S. L. Hemmer, M. E. Gehm, A. Turlapov, and J. E. Thomas. Evidence for Superfluidity in a Resonantly Interacting Fermi Gas. Phys. Rev. Lett., 92(15):150402, apr 2004. `doi:10.1103/PhysRevLett.92.150402`.

[8] N. Goldman, J. C. Budich, and P. Zoller. Topological quantum matter with ultracold gases in optical lattices. Nat. Physics, 12(7):639–645, jun 2016. `doi:10.1038/nphys3803`.

[9] B. K. Stuhl, H.-I. Lu, L. M. Aycock, D. Genkina, and I. B. Spielman. Visualizing edge states with an atomic Bose gas in the quantum Hall regime. Science, 349(6255):1514–1518, sep 2015. `doi:10.1126/science.aaa8515`.

[10] Jun-Ru Li, Jeongwon Lee, Wujie Huang, Sean Burchesky, Boris Shteynas, Furkan Çağrı Top, Alan O. Jamison, and Wolfgang Ketterle. A stripe phase with supersolid properties in spin-orbit-coupled Bose-Einstein condensates. Nature, 543(7643):91–94, mar 2017. `doi:10.1038/nature21431`.

[11] Julian Léonard, Andrea Morales, Philip Zupancic, Tilman Esslinger, and Tobias Donner. Supersolid formation in a quantum gas breaking a continuous translational symmetry. Nature, 543(7643):87–90, mar 2017. `doi:10.1038/nature21067`.

[12] Thomas M. Bersano, Junpeng Hou, Sean Mossman, Vandna Gokhroo, Xi-Wang Luo, Kuei Sun, Chuanwei Zhang, and Peter Engels. Experimental realization of a long-lived striped Bose-Einstein condensate induced by momentum-space hopping. Phys. Rev. A, 99(5):051602, may 2019. `doi:10.1103/PhysRevA.99.051602`.

[13] L. Tanzi, E. Lucioni, F. Famà, J. Catani, A. Fioretti, C. Gabbanini, R. N. Bisset, L. Santos, and G. Modugno. Observation of a Dipolar Quantum Gas with Metastable Supersolid Properties. Phys. Rev. Lett., 122(13):130405, apr 2019. `doi:10.1103/PhysRevLett.122.130405`.

[14] Fabian Böttcher, Jan-Niklas Schmidt, Matthias Wenzel, Jens Hertkorn, Mingyang Guo, Tim Langen, and Tilman Pfau. Transient Supersolid Properties in an Array of Dipolar Quantum Droplets. Phys. Rev. X, 9(1):011051, mar 2019. `doi:10.1103/PhysRevX.9.011051`.

[15] L. Chomaz, D. Petter, P. Ilzhöfer, G. Natale, A. Trautmann, C. Politi, G. Durastante, R. M. W. van Bijnen, A. Patscheider, M. Sohmen, M. J. Mark, and F. Ferlaino. Long-Lived and Transient Supersolid Behaviors in Dipolar Quantum Gases. Phys. Rev. X, 9(2):021012, apr 2019. `doi:10.1103/PhysRevX.9.021012`.

[16] Aurel Bulgac. Dilute Quantum Droplets. Phys. Rev. Lett., 89(5):050402, jul 2002. `doi:10.1103/PhysRevLett.89.050402`.

[17] Paulo F. Bedaque, Aurel Bulgac, and Gautam Rupak. Quantum corrections to dilute Bose liquids. Phys. Rev. A, 68(3):033606, sep 2003. `doi:10.1103/PhysRevA.68.033606`.

[18] D. S. Petrov. Quantum Mechanical Stabilization of a Collapsing Bose-Bose Mixture. Phys. Rev. Lett., 115(15):155302, oct 2015. `doi:10.1103/PhysRevLett.115.155302`.

[19] D. Baillie, R. M. Wilson, R. N. Bisset, and P. B. Blakie. Self-bound dipolar droplet: A localized matter wave in free space. Phys. Rev. A, 94(2):021602, aug 2016. `doi:10.1103/PhysRevA.94.021602`.

[20] F. Wächtler and L. Santos. Ground-state properties and elementary excitations of quantum droplets in dipolar Bose-Einstein condensates. Phys. Rev. A, 94(4):043618, oct 2016. `doi:10.1103/PhysRevA.94.043618`.

[21] Matthias Schmitt, Matthias Wenzel, Fabian Böttcher, Igor Ferrier-Barbut, and Tilman Pfau. Self-bound droplets of a dilute magnetic quantum liquid. Nature, 539(7628):259–262, nov 2016. `doi:10.1038/nature20126`.

[22] L. Chomaz, S. Baier, D. Petter, M. J. Mark, F. Wächtler, L. Santos, and F. Ferlaino. Quantum-Fluctuation-Driven Crossover from a Dilute Bose-Einstein Condensate to a Macrodroplet in a Dipolar Quantum Fluid. Phys. Rev. X, 6(4):041039, nov 2016. `doi:10.1103/PhysRevX.6.041039`.

[23] C. R. Cabrera, L. Tanzi, J. Sanz, B. Naylor, P. Thomas, P. Cheiney, and L. Tarruell. Quantum liquid droplets in a mixture of Bose-Einstein condensates. Science, 359(6373):301–304, dec 2017. `doi:10.1126/science.aao5686`.

[24] G. Semeghini, G. Ferioli, L. Masi, C. Mazzinghi, L. Wolswijk, F. Minardi, M. Modugno, G. Modugno, M. Inguscio, and M. Fattori. Self-Bound Quantum Droplets of Atomic Mixtures in Free Space. Phys. Rev. Lett., 120(23):235301, jun 2018. `doi:10.1103/PhysRevLett.120.235301`.

[25] T. D. Lee, Kerson Huang, and C. N. Yang. Eigenvalues and Eigenfunctions of a Bose System of Hard Spheres and Its Low-Temperature Properties. Physical Review, 106(6):1135–1145, jun 1957. `doi:10.1103/PhysRev.106.1135`.

[26] D. Baillie, R. M. Wilson, and P. B. Blakie. Collective Excitations of Self-Bound Droplets of a Dipolar Quantum Fluid. Phys. Rev. Lett., 119(25):255302, dec 2017. `doi:10.1103/PhysRevLett.119.255302`.

[27] F. Wächtler and L. Santos. Quantum filaments in dipolar Bose-Einstein condensates. Phys. Rev. A Rapid Comm., 93(6):061603, jun 2016. `doi:10.1103/PhysRevA.93.061603`.

[28] R. N. Bisset, R. M. Wilson, D. Baillie, and P. B. Blakie. Ground-state phase diagram of a dipolar condensate with quantum fluctuations. Phys. Rev. A, 94(3):033619, sep 2016. `doi:10.1103/PhysRevA.94.033619`.

[29] Joseph C. Smith, D. Baillie, and P. B. Blakie. Quantum Droplet States of a Binary Magnetic Gas. Phys. Rev. Lett., 126(2):025302, jan 2021. `doi:10.1103/PhysRevLett.126.025302`.

[30] R. N. Bisset, L. A. Peña Ardila, and L. Santos. Quantum Droplets of Dipolar Mixtures. Phys. Rev. Lett., 126(2):025301, jan 2021. `doi:10.1103/PhysRevLett.126.025301`.

[31] L A Peña Ardila and T Pohl. Ground-state properties of dipolar Bose polarons. J. Phys. B: At. Mol. Opt. Phys., 52(1):015004, dec 2018. `doi:10.1088/1361-6455/aaf35e`.

[32] Giovanni Ferioli, Giulia Semeghini, Leonardo Masi, Giovanni Giusti, Giovanni Modugno, Massimo Inguscio, Albert Gallemí, Alessio Recati, and Marco Fattori. Collisions of Self-Bound Quantum Droplets. Phys. Rev. Lett., 122(9):090401, mar 2019. `doi:10.1103/PhysRevLett.122.090401`.

[33] Matthew A. Norcia, Claudia Politi, Lauritz Klaus, Elena Poli, Maximilian Sohmen, Manfred J. Mark, Russell N. Bisset, Luis Santos, and Francesca Ferlaino. Two-dimensional supersolidity in a dipolar quantum gas. Nature, 596(7872):357–361, aug 2021. `doi:10.1038/s41586-021-03725-7`.

[34] Aurel Bulgac. Time-dependent density functional theory for fermionic superfluids: From cold atomic gases – to nuclei and neutron stars crust. Phys. Status Solidi B, 256(7):1800592, 2019. URL: `https://onlinelibrary.wiley.com/doi/abs/`

`10.1002/pssb.201800592`, `arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1002/pssb.201800592`, `doi:https://doi.org/10.1002/pssb.201800592`.

[35] Grigory E. Volovik. The Universe in a Helium Droplet, volume 117 of The International Series of Monographs on Physics. Carendon Press, Oxford, 2003.

[36] Ariel Zhitnitsky. Superfluid helium ii as the QCD vacuum. Nucl. Phys. B, 916:510–549, 2017. URL: `https://www.sciencedirect.com/science/article/pii/S0550321317300330`, `doi:https://doi.org/10.1016/j.nuclphysb.2017.01.019`.

[37] Ariel Zhitnitsky. Axion quark nuggets. dark matter and matter-antimatter asymmetry: Theory, observations and future experiments. Mod. Phys. Lett. A, 36(18):2130017, May 2021. URL: `https://doi.org/10.1142%2Fs0217732321300172`, `doi:10.1142/s0217732321300172`.

[38] Ariel Zhitnitsky. Multi-modal clustering events observed by horizon-10t and axion quark nuggets. Universe, 7(10), 2021. URL: `https://www.mdpi.com/2218-1997/7/10/384`, `doi:10.3390/universe7100384`.