Topical: Quantum Bubbles in Microgravity

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Abstract

Progress in understanding quantum systems has been driven by the exploration of the geometry, topology, and dimension of ultracold atomic systems. The NASA Cold Atom Laboratory (CAL) aboard ISS has enabled the study of ultracold atomic bubbles, a terrestrially-inaccessible topology. Proof-of-principle bubble experiments have been done on CAL with an rf-dressing technique; an alternate technique (dual-species interaction-driven bubbles) has also been proposed. Both techniques can drive discovery in the next decade of fundamental physics research in microgravity.

I. Motivation and microgravity justification

The study of ultracold quantum systems is a frontier in physics that has grown in an astonishing fashion in the twenty-five years since the first observation of Bose-Einstein condensation (BEC). With a well-developed toolbox of forces used to confine, guide, and excite ultracold samples, physicists have used quantum gases to test fundamental ideas in quantum theory, statistical mechanics, and many-body physics in general [1–4]. In particular, notions of geometry, topology, and dimensionality have directed the development of quantum-gas physics [5–9]. Quantum gases are typically confined in finite systems of some particular dimensionality and geometric character, such as a harmonic potential [10], a hard-walled "box," [11] or a periodic lattice potential [12]; looking beyond this, novel trapping geometries [13] would permit (as it has in the past) the exploration of new realms of quantum physics and would shed light on the nature of ultracold systems in general. A bubble-shaped trap enabled by microgravity would offer a rich new geometry and topology in which quantum gas phenomena and related systems can be investigated. The collapse, expansion and excitations of such a system are unexplored; the behavior of quantum vortices in an ultracold bubble has many associated open questions, and the nature and consequence of the crossover from a 3D (thick) shell to a quasi-2D (thin) bubble has stimulated significant recent theoretical work [14–21].

Crucially, it is prohibitively difficult to generate ultracold bubbles terrestrially, due to gravitational sag. While in principle levitation techniques exist, they lack the fine-tuning or uniformity to realistically generate bubbles in terrestrial labs. A cold-atom machine in perpetual microgravity, such as the Cold Atom Lab (CAL) [22] and potential successors [23], is required to explore this tantalizing scientific realm. There are two different complementary techniques available to generate ultracold atomic bubbles in orbital microgravity: (i) radiofrequency (rf) dressing of ultracold atoms and (ii) quantum gas mixtures with strong

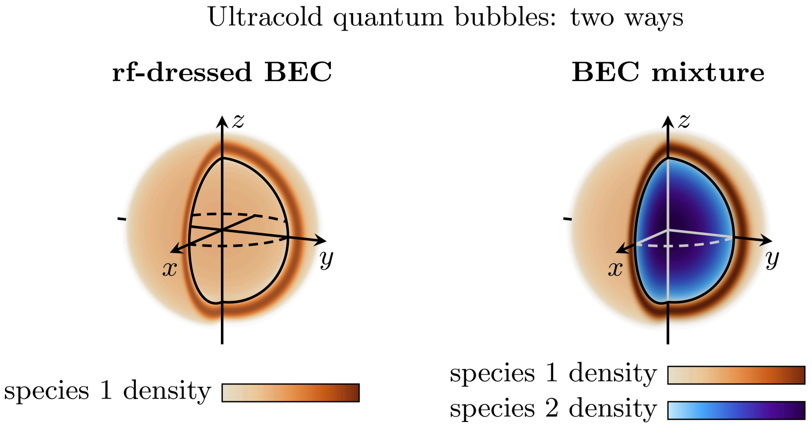

FIG. 1. Schematic sketch of 3D shell density profiles for the rf-dressed and mixture implementations. The darker colors illustrate higher atom density. In the mixture case, the blue color gradient illustrates the second species. Figure taken and modified from Ref. [24] under license: CC BY 4.0

repulsive interactions. Exploring both of these will permit the precise investigation of the many-body quantum physics emerging from the interplay of geometry, curvature, boundaries, and overall topology. The behavior of solitons in a curved geometry could be explored, as could the nature of the Kibble-Zurek mechanism in rapidly inflating (or deflating) bubbles [25]. Additionally, the physics of condensate shells are relevant to some astronomical models, including in neutron stars and other stellar bodies [26].

Current theoretical work suggests that the hydrodynamic modes of an ultracold bubble should show a discontinuity at the transition from a filled system to the hollow shell [27, 28], further evolving into a two-dimensional bubble gas as the transverse confinement increases. Quasi-2D spherical shells should display a phase of Bose-Einstein condensation without superfluidity in the weakly-interacting finite-temperature regime [18]. The phase-space density of a harmonically trapped BEC decreases strongly when it is inflated to bubbles or shells [17], thereby opening studies of finite-temperature effects in the quasi-2D regime such as the thermally-induced proliferation of vortices and Berezinskii-Kosterlitz-Thouless (BKT) physics [16]. The behavior of quantum vortices on the surface of bubbles remains an area of open investigation, with key ideas including the constraints on superfluid flow imposed by topology, the potential creation of vortex lattices, and the lifetime of vortices in a system with periodic boundary conditions.

The long-term goal of this research program is to reach the threshold of understanding for the production, control and explication of the quantum physics of superfluids on curved manifolds, either open or closed. This is of fundamental interest because quantum many-body systems have most often been studied in flat geometries, and characterizing the complex interplay of curvature, interactions and topology of a quantum gas will open new research directions in quantum systems generally. For instance, controlling and understanding the curvature of a 2D quantum gas will enable interesting applications in quantum simulation, with the local curvature constituting an additional tunable degree of freedom, thus contributing to our understanding of fundamental physics, all enabled by orbital microgravity.

II. Approach 1: Quantum bubbles via radiofrequency-dressed potentials

The recent achievement of ultracold bubbles in orbital microgravity [29] proves that the ISS is able to support cutting-edge investigations in this budding area (CAL was recently commissioned as an orbital BEC facility aboard the ISS [22]). This novel work was based on a microgravity implementation of longstanding theoretical proposals to use rf-dressed magnetic traps to create a bubble-shaped trap for ultracold atoms [13, 30]. Such bubble traps are dynamically adjustable in their size and shape due to their dependence on common experimental quantities like trap currents and rf frequencies. While terrestrial shell structures have been observed [31–33], they have always been radically deformed by the presence of terrestrial gravity, which causes the ultracold atoms to collect at the bottom of the bubble. This prevents their application to any physics requiring significant curvature or fully connected bubbles with cold atoms distributed over the entire surface.

The rf-dressed approach to bubble creation boasts its demonstrated flight heritage as well as versatile tunability of shell size and thickness. Rf-dressed traps have extremely low spurious heating rates as spontaneous emission is negligible, and they have very good lifetimes (approaching the vacuum-limited regime) when used with sufficiently strong coupling [34]. While in principle rf-dressed bubbles are vulnerable to residual smooth sag of order $0.001g$ due to inhomogenous rf coupling, this can be mitigated through careful rf-coil modeling and design. The technique is entirely insensitive to alignment as there are no elements to manipulate into position; this is helpful given the remote operation of CAL or similar facilities. The potentials are extremely smooth, standing out from other cold-atom technologies in this regard; optical potentials can suffer from wavelength-scale fringing imperfections, and even the residual roughness of static magnetic field traps is augmented by a smoothing effect associated with the rf-dressing.

The underpinning rf technology allows considerable flexibility in controlling parameters of the shell and its deformations (when needed). Multiple frequencies can produce multiple concentric shells [33], the rf can be chirped or modulated to perform expansion, or breathing oscillations; rf polarization can be used for spatially varying surface effects, and the underlying magnetic field structure can be adjusted. Furthermore, in mixture experiments the bubbles for different species can be controlled in an independent manner [35]. The bubble can be collapsed on demand by switching off, or adjusting the rf field strength, with the idea that bubble collapse physics is an unexplored avenue. In general, rf is a well-developed mature technology with a proven space track record, and as such it is sensible to rely on it as a key tool in this new domain of remotely-operated ultracold atomic-physics experiments. Future experiments in space would benefit through consideration of advancing these rf-dressing methods, as well as bubble generation through ultracold mixture interactions, discussed below.

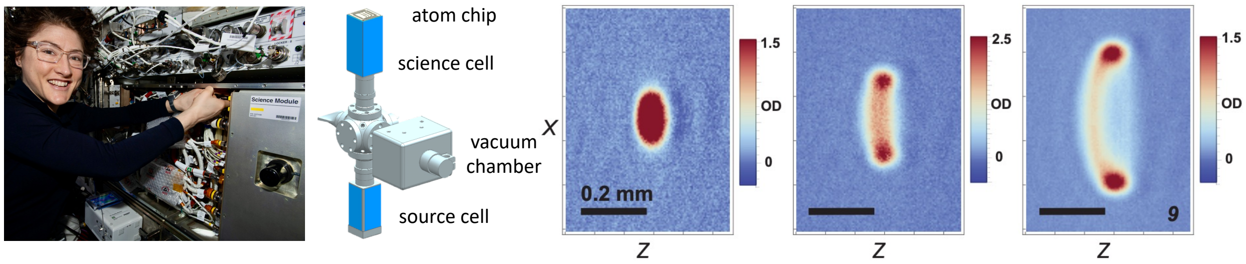

FIG. 2. Recent observations of rf-dressed bubble structures in orbital microgravity with NASA CAL. Left photo shows astronaut Christina Koch installing a CAL upgrade on the ISS, and adjacent is an illustration of the vacuum chamber at the heart of the instrument. Absorption image at left is of initial ultracold sample; images at center and right are of bubbles inflated to intermediate and large radii. Images are absorption column densities in false-color optical depth, which exaggerates residual shell tilts that slightly preference atoms pooling at left and at top/bottom of bubble. A terrestrial equivalent would have atoms strongly pinned to the leftmost 5% of the bubble surface. Figure taken and modified from Ref. [29].

III. Approach 2: Quantum bubbles via ultracold mixture interactions

A complementary approach [24] for generating quantum bubbles in microgravity exploits optically trapped dual-species atomic mixtures and their tunable interaction. The conceptual idea is the following: The shape of the ground-state-density distribution of a mixture of two BECs [36, 37] strongly depends on the interplay between the intra-species and inter-species interaction. In an optical trap [38], at least one interaction strength can be tuned with Feshbach resonances [9] in a way that both species either spatially overlap, if the intra-species interactions dominate, or separate, if the repulsive interaction between the two species dominates over the intra-species interaction. In the second, immiscible regime and crucially in the absence of gravity one atomic species is located at the center of the trap while the other one forms a symmetric hollow shell around it, as displayed in Fig. 1 (right). It is shown in Ref. [24] that the wave function of the outer shell of the mixture displays similar features to an rf-dressed shell BEC, in particular with respect to its ground-state density, collective excitation spectrum, and free expansion dynamics. Hence, the various studies of quantum many-body effects on curved manifolds discussed above could also be performed with quantum bubbles realized with dual-species BECs.

In addition to the similarities with the rf-dressed scheme, the mixture approach [24] offers several experimental advantages or alternatives and unique applications that balance the technical challenges of dealing with a second species. For instance, the mixture can be directly condensed into a shell state without any needs for adiabatic transition, which may improve the experimental cycle rate and reproducibility of the shell. Moreover, the mixture approach could enable ideal spherical symmetric configurations, where the an isotropic potential of optical trap is generated by a set of three orthogonal laser beams. In this way, fundamental physical effects on the shell could be studied more cleanly compared to ellipsoidal traps.

Another feature which naturally occurs in mixture-based shells is the ability to dynamically magnify the shell [24] via its expansion. If the interaction between the two species is switched off after release from the trap, then the shell structure undergoes a drastic change and propagates both inwards and outwards resulting in an interference pattern, which would similarly occur in the rf-dressed case. However, if the strong repulsion between the two species is kept on during expansion, the spherically symmetric structure of the shell is conserved and both species expand simultaneously. This regime provides an easy way to magnify the dynamics on the shell and to better observe initially rather small structures like vortex cores. Furthermore, the possibility to tune the interactions of the mixture together with the usual mass imbalance between the two atomic species opens up new avenues for few body-physics and molecule formation on curved manifolds. Finally, the response of the interacting mixture on the rotation of one of its components or the whole system would be fascinating to study from a fundamental point of view.

IV. Outlook and conclusion

Current investigations aboard CAL (the 'SM3' generation) are focusing on reaching the Bose-condensed state in ultracold bubbles, having demonstrated in the first CAL science campaigns ('SM2') that such bubbles are feasible. Additional efforts are investigating mixtures of two species and applying alternative dressing techniques (including microwave transitions, or dual microwave/rf transitions) to broaden the scope of available configurations. The atom-interferometer capabilities of CAL are also employed in the service of shell physics in the form of Bragg spectroscopy of dressed samples. Ambitions for the upgraded CAL machine ('SM4') are aimed at initiation of vortex studies, potentially using a 'stirring' tweezer beam or dynamic trap control of increased complexity; elimination of all residual 'accidental' inhomogeneities (as observed in Fig. 2) through careful field coil design would be ideal.

Aside from the ongoing progression of rf-dressing techniques within CAL's current capabilities, development of more advanced designs to achieve highly uniform and controllable bubbles would benefit from ground-based campaigns to mature essential technologies and define requirements for future space hardware. Generally, such hardware will need improved reliability and reduction of the size, weight, and power of ultra high vacuum chambers and pumps, as well as the many integral optical and electrical devices, such as lasers, fiber optics, and modulators. Specific development areas for quantum bubbles research include advanced RF and microwave sources, emitters, waveguides and/or cavities to improve coupling efficiency with trapped atoms and provide enhanced control of the dressing methods through precise control of rf polarization, frequency and power. To support shell experiments with mixtures, space-proven optical dipole traps and shielding capabilities for large magnetic fields should be developed further. In addition, extending the range of space-usable isotopes beyond rubidium and potassium would open up new opportunities for bubble mixtures.

We envision topical investigations on CAL 'SM4' and beyond using both rf-dressing and inter-species interaction as bubble generators. In the next decade, the NASA/DLR joint project BECCAL will operate aboard ISS and serve as a next-generation microgravity cold-atom machine, featuring design heritage from multiple terrestrial drop-tower and sounding-rocket architectures. Following CAL upgrades and BECCAL, the use of cold-atom facilities in future space stations or on dedicated free-flyer missions could expand the scope and fidelity of quantum bubble study and its topological analogs in fundamental physics research. We foresee quantum behavior on curved manifolds with ultracold atomic bubbles—formed in at least two different ways as described here—becoming a featured physics 'factory' of the orbital environment. Such a factory would explore further questions: can dynamically-evolving bubbles give insight into cosmological Hubble physics [39]? Can we construct quantum-coherent bubbles at the millimeter scale, and what would their properties be? Can the microgravity-enabled insights into the effects of topology and geometry be extended to new shapes like nested torii, Möbius strips, or lattice physics on bubbles? The evolution from drop-tower, to sounding rocket, to CAL in orbit cements spaceborne cold-atom physics as a field ripe for exploration in the coming decade and beyond.

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