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2014 J. Phys.: Conf. Ser. 568 012016

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Stabilization of Multi-electron Bubbles in Superfluid Helium

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Abstract. Multielectron bubbles (MEBs) in liquid helium were first observed in the late 1970s, but their properties have never been explored experimentally due to their short lifetimes and the difficulty to localize them. We report the observation of long-lived MEBs in a novel cell filled with superfluid helium at static negative pressures. MEBs were extracted from the electron filled vapor sheath of a heated filament loop embedded in the superfluid helium and observed by high-speed photography. MEBs are 2D electron gases on the 3D surface of hollow helium bubbles. Diameters can range from nanometers to millimeters, depending on the number of enclosed electrons. Electrons move in angular momentum states; deformations of the surface are called spherical riplons. The attractive electron-riplon interaction leads to an unusual form of superconductivity. If they can be compressed, Wigner crystallization and quantum melting can be observed, as well as a new phase for localization called the riplon-polaron lattice. MEBs are unstable to tunneling discharge when pressed against a surface. Just as Bose gases are captured in a trap for study, MEBs must also be localized away from walls. We shall discuss methods of capturing them in an electromagnetic trap embedded in the liquid helium.

1. Introduction

An equilibrium multielectron bubble in liquid helium is a spherical cavity containing electrons in a nanometer thin layer on the helium surface of the bubble so as to form a two-dimensional electron system on a spherical surface. MEBs were first observed by Volodin, Khaikin, and Edel'man [1] in the late 1970's. Free electrons were created by thermionic emission in the helium vapor phase; a planar electrode with a positive voltage was placed under the flat surface of bulk superfluid (SF) helium to create a high surface density of electrons, as a two-dimensional electron gas. Above a critical electric field (~ 4 kV/cm) corresponding to a surface electron density of $\sim 2.4 \times 10^9 \text{ cm}^{-2}$, the surface became hydrodynamically unstable and subsided of order $10^7 - 10^8$ electrons in the form of a single bubble. A high-speed camera recorded this. The created bubble flew, opposite to the direction of buoyant forces, to the high voltage plate with a velocity $\sim 10^4$ cm/s where it was annihilated. The lifetime of the bubble was about 1 ms. Shikin [2] analysed and presented a theory for the equilibrium diameter of an MEB. Diameters of nanometers to millimeters were predicted depending on the number of electrons confined in the bubble. A decade later, Albrecht and Leiderer [3, 4] used a similar



geometry to produce MEBs in normal helium. MEBs with $10^5 - 10^7$ electrons were observed by small-angle light scattering using a He-Ne laser, and oscillations and fissioning of the MEBs were observed as well. The velocity of an MEB was about 10 cm/s and the lifetimes were up to 100 ms. They also proposed trapping the MEBs with an electromagnetic quadrupole cage to extend the measurement time, but no experiments were reported.

After MEBs were first observed a few decades ago, a plethora of fascinating properties were predicted including tunable surface electron density, instabilities, superconductivity, vortex states, sonoluminescence, and magnetic properties such as the quantum Hall effect, etc. reviewed in ref. [5]. In order to study these properties, stabilizing an MEB in a long-lived state is crucial. However, none of the earlier reported methods were able to create an MEB with a long enough lifetime. Silvera and Tempere proposed a new method: electrons would be created in the vapor phase of a cylindrical cell having a dome shaped. The cell, which is partially filled with SF helium, incorporated a mechanism to translate the surface of the helium up and down the cell. Single electrons require an energy of ~ 1 eV to penetrate the surface of the bulk helium [6]. Thus, as the helium level is moved up to the dome, the electrons, encircled by helium surfaces, are corralled into a smaller and smaller volume and eventually form an MEB at the top of the dome, localized by buoyancy. Such a system was built using a concave lens for the dome, so that the MEBs could be observed with a low temperature microscope. Large MEBs that were formed in the dome rapidly discharged or collapsed [7]. An analysis showed that the MEBs were attracted to the surface of the dome, mainly by image and buoyant forces so that the superfluid film that separated them from the surface was thinned to $\sim 5-6$ nm so that the electrons could tunnel into the surface, where they were evidently trapped. After a number of attempts to confine MEBs in this manner, the surface of the dome charged up sufficiently creating patch electric fields that repelled the MEBs so that the helium film was not thinned. In this way large MEBs were observed for a few seconds. However, they were not confined in the dome and passed out of the field of view. These bubbles were shown to be filled with electrons, as they could be steered with external electric fields. However they were challenging to control and localize, so another method was developed.

If a fine tungsten filament is heated in superfluid liquid helium a vapor sheath will form around the glowing hot regions of the wire [8]. When such a filament is formed in a loop a large bag-shaped sheath forms around the loop and this is filled with electrons due to thermionic emission from the glowing filament. It turned out that the sheath is tightly tethered to the loop, so an external electric field from a nearby electrode could be used to extract MEBs from the sheath. These MEBs were photographed by high-speed video (up to 10K frames/sec) and seen to be extracted under very turbulent conditions. They underwent large amplitude oscillations, decreasing in size, and finally disappearing after several milliseconds. These MEBs were created under the surface of bulk pumped superfluid helium at a temperature of ~ 1.5 K, so that there was always a positive pressure on the MEBs due to the pressure head of the helium.

Theoretical analysis has shown that for positive pressures MEBs should be dynamically unstable. Surface deformations of MEBs are called spherical ripples; these harmonic modes can be represented by spherical harmonics. The pressure dependence of several of the modes is shown in Fig. 1. It is seen the quadrupole mode ($L=1$) is unstable at zero pressure and that with increasing pressure, all of the higher modes increase in frequency and then drop to zero, so that in principle they should give rise to dynamic instabilities of the MEBs. However, for low negative pressures (negative pressures below the explosion pressure) all of the modes are stable.

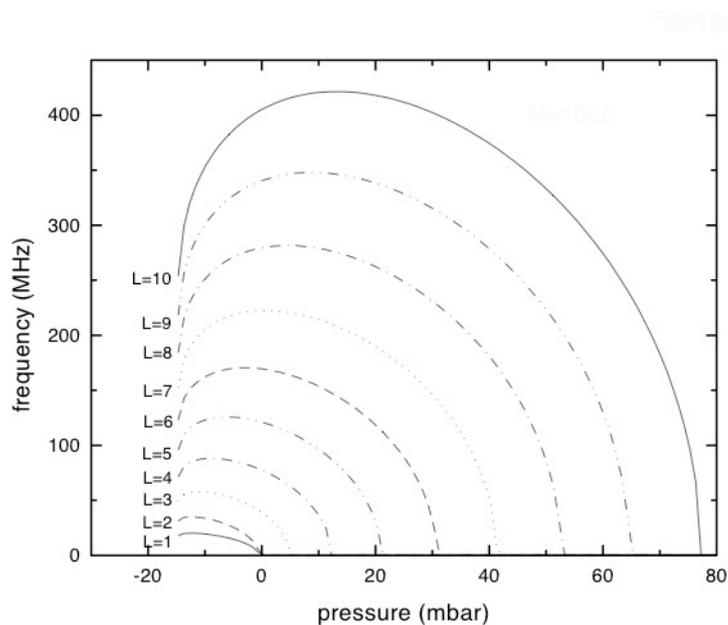


Figure 1. The frequency of ripplon modes of an MEB with $N=1000$ electrons as a function of pressure. L is the index of the spherical harmonics.

2. The Negative Pressure Cell.

In order to stabilize MEBs a cell was built in which MEBs could be produced under negative pressure of the helium. A hollow cubic cell was constructed out of copper with indium sealed fused silica windows on the four vertical walls. Electrical feedthroughs on the bottom flange were used to activate or monitor a tungsten filament, provide electric fields, capacitance pressure gauge, etc. On the top of the cell were mounted a superfluid tight valve made of Torlon and a bellows that is incorporated as part of the volume of the cell; this bellows could be manually expanded or contracted. The cell was submerged in a pumped bath of SF helium and then filled so that there was no vapour phase in the interior when the Torlon valve was closed. By expanding or compressing the bellows the pressure in the cell could be made negative or positive. This was detected with a capacitance gauge that also insured that the Torlon valve was SF tight: the pressure remained stable at a fixed extension of the bellows. The loop tungsten filament could be viewed through the windows and illuminated for high-speed video photography. Electrodes could also be mounted in the cell for extraction of MEBs.

3. Observations.

Because the cell is isochoric, compressing the bellows creates a positive pressure; in this case a sheath could not be formed when the tungsten loop filament was heated. The explanation is that it is energetically unfavorable to create a vapor sheath that will further compress the helium. On the other hand with negative pressures, below a certain threshold, vapor sheaths were easily formed as this relieves the negative stress in the fluid. At low temperatures of ~ 1.5 K, MEBs could be formed by several methods. With a sheath present a sudden change in the negative pressure released MEBs, observed with an external microscope and high-speed video. MEBs could also be extracted from the sheath using electrodes either below (with negative voltage) or above the loop (with positive voltage).

However, in all of these cases the MEBs had large turbulent oscillations and disappeared within a few milliseconds, just as with positive pressures in an isobaric cell.

Our idea was that in order to create a stable MEB it should be created “adiabatically”, or we should find conditions to damp the oscillations. We produced shaped loops that would allow an MEB to gently slide off of the filament, but this was unsuccessful, as the sheath remained tethered to the loop. We then produced MEBs just below the lambda point of the SF helium with the idea that this might damp the oscillations. This procedure succeeded in producing long-lived MEBs. In Fig.2 we

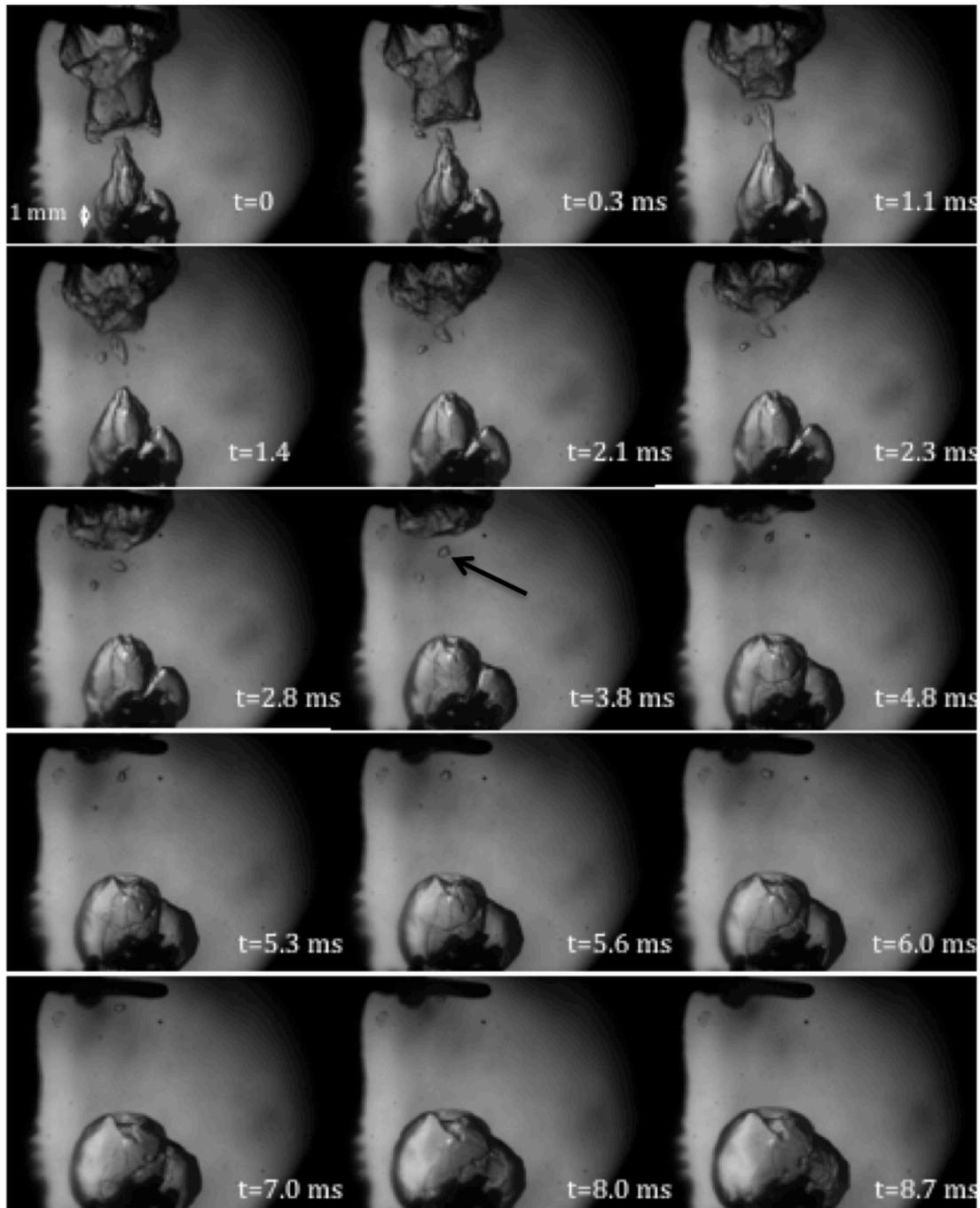


Figure 2 Selected frames from a high-speed video of stabilized MEBs. The arrow at 3.8 ms indicates one of the MEBs.

show a sequence taken at 10,000 frames/s. The filament itself was somewhat pear shaped and hottest at the top. The filament was biased at -3 KV and was below a ring electrode biased at +2 KV. We also attached metallic carbon nano tubes to the filament that produce more electrons in the sheath by field emission. In the figure one sees large hollow “cloud” that breaks loose and rises above the filament. Smaller MEBs are seen below this cloud that rapidly relax towards a spherical shape. These MEBs eventually rise out of the field of view in the superfluid helium. However, these are of a substantially different nature than earlier ones created at lower temperatures, i.e. these have smooth surfaces without oscillations and are approaching spherical shapes. This procedure was reproducible, and in one case an MEB was observed for ~30 ms, before it rose out of the field of view of our microscopy.

We have successfully produced long-lived MEBs that will rise in the SF fluid. The next step is to capture such MEBs with a radio frequency quadrupole trap that has been designed to be somewhat robust in that it can trap MEBs with a rather broad distribution of the number of electrons. To operate such a trap an electric pulse will be used to stop the MEBs as they enter the trap, to remove their kinetic energy. After capture detailed studies can be carried out on the MEBs. We note that Joseph et al [9] have reported observation of MEBs above the lambda point.

In conclusion, we have found that MEBs created around the lambda point of SF helium rapidly relax towards a spherical, and stable condition. The special properties of SF helium near the lambda point are a large heat capacity and large density of superfluid vortices that may play a role in the observed damping of large amplitude oscillations. These MEBs were produced in a negative pressure environment. It is not yet clear that this is an absolutely necessary condition, as earlier experiments showed that MEBs were produced for a few seconds of observation in a positive pressure environment.

Partial support for this research was provided by a grant from Alby and Kim Silvera. JT received support from the Fund for Scientific Research – Flanders, FWO projects G. 0115.12N and G.0122.12N. The high-speed video camera was provided by the Center for Nanoscale Systems (CNS), which is supported by the NSF award no. ECS-0335765. CNS is part of Harvard University.

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