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Viewpoint

Looking at electrons

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A Viewpoint on:
Experiments with single electrons in liquid helium
W. Guo, D. Jin, G. M. Seidel and H. J. Maris
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How can one photograph the position of a single thermalized electron immersed in a fluid? Better yet, how can one take time-lapse pictures that are able to track the motion of the electron as it moves about? These questions have now been answered, at least for the case of electrons in liquid helium, in *Physical Review B* by W. Guo, D. Jin, G. M. Seidel, and H. J. Maris at Brown University [1]. The genesis of the work actually took place over two decades of experiments by Humphrey Maris and his co-workers studying the properties of bubbles and negative pressures in liquid helium [2], much of it in collaboration with a group led by Sébastien Balibar at the École Normale Supérieure in Paris. Since the electron couples to the flow of the liquid helium, this new technique allows a direct visualization of flow patterns in the liquid, and particularly at low temperatures where the helium is superfluid, it provides a novel way of visualizing quantized vortex lines. The researchers have also been able to resolve a mystery of how cosmic rays can inject electrons into the liquid, and they may be able in further work to understand an "exotic" negative ion in helium whose structure currently remains unknown.

The technique developed by the Brown group relies on the fact that an electron injected into liquid helium forms a tiny bubble around itself, due to a repulsive interaction between the electron and the closed-shell electrons of the helium atoms, which arises from the Pauli exclusion principle. From previous experiments and theory [3] we know that the radius of the bubble is about 2 nm, which is much too small to photograph. The researchers at Brown discovered that they could subject the electron bubble to a high-amplitude acoustic pulse, where the pressure in the pulse oscillates between positive and negative values that can be as high as several bars. A negative pressure applied to a bubble causes it to expand and earlier experiments [3] at Brown University showed that when a negative pressure exceeding -1.9 bars is applied to the electron bubble it literally "explodes," increasing its radius without limit [4]. Since with an acoustic pulse the negative pressure then starts back to positive pressure, the bubble reaches a maximum size of about 10 μm before starting to decrease back to its initial value. At 10 μm in size, however, the bubble strongly scatters light, and, under illumination from a flash lamp synchronized with the acoustic pulse, its position can then be photographed, where it shows up as a bright spot in the photograph. By applying a train of acoustic pulses spaced 30 ms apart, the researchers can explode a single electron multiple times. A 1/4 s shutter speed of the camera yields as many as 7 or 8 bright spots in a picture, allowing the motion of the electron to be tracked as it travels across the cell under the action of electrical or hydrodynamic forces.

Guo *et al.* were able to image the electron bubbles under a variety of conditions. Figure 1 shows an example of one of the photographs of an electron moving through the liquid at a temperature of 2.4 K, where the liquid is in the normal state (helium only becomes a superfluid below 2.18 K). The electron moves upward following the convective fluid flow due to heating by the acoustic transducer at the bottom of the cell, but then is deflected to the left by a repelling -150 V applied to an electrode at the top of the cell. Figure 1 shows an electron moving in the superfluid phase at 1.5 K, where in this experiment the acoustic transducer is placed at the top of the cell, and the motion of the electron is from the top of the cell to the bottom. The zigzag motion evident in this picture is unusual, and means that the electron is not moving freely. It appears likely that this occurs because the electron is trapped on the core of a quantized vortex line, and hence is constrained to follow the meandering of the vortex core across the cell. The electron bubble can become trapped on the vortex because of the Bernoulli force exerted on the bubble that arises from the increasing velocity of the superfluid flow near the vortex core, much as a car gets pulled into the center of a tornado. In Fig. 1 we can see the effect of immersing a radioactive source, a β-emitter, at the bottom of the cell, filling it with a large number of electrons. Note that only the electrons within the central beam of the acous-

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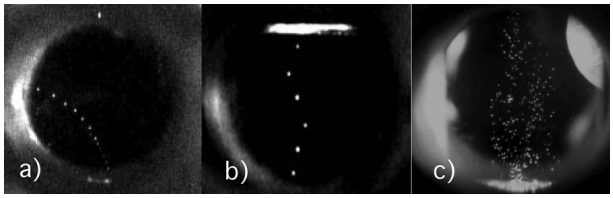

FIG. 1: Electrons moving through liquid helium, imaged by repeatedly exploding the helium bubbles with the camera shutter open. (a) A single electron in normal helium at 2.4 K moves upward, carried by convective heat flow in the liquid, and then is repelled to the left by a negative voltage applied to an electrode at the top of the cell. (b) A single electron in the superfluid helium at 1.5 K moves in a zigzag path from the top to the bottom of the cell, apparently from being trapped on the core of a quantized vortex line that extends from the top of the cell to the bottom. (c) Many electrons are injected into the liquid by immersing a radioactive β source at the bottom of the cell, but only the bubbles directly in the acoustic beam are subject to sufficient negative pressure to "explode" and become visible. (Illustration: Adapted from Guo *et al.*[1])

tic transducer light up, while those outside the acoustic beam are subjected to less than the critical negative pressure, and do not "explode" and become visible.

The advantage of being able to visualize a physical process is well illustrated by an initial mystery confronting the Brown researchers: in Figs. 1 and 1 there was no electron source in the cell to provide the charged particles, so where did the electrons come from? Of course, ionizing cosmic rays are constantly passing through the liquid helium, but the electrons and ions created in the cosmic-ray tracks almost immediately thermalize in the surrounding fluid and recombine, leaving behind no free electrons. From the pictures, the experimenters found that most of the electrons seemed to originate from positions very close to the gold film on the surface of their acoustic transducer, as seen in Figs. 1 and 1. This clue allowed them to formulate a plausible scenario, that the electrons are being photoemitted from that metallic surface. When an electron and a helium ion recombine in a cosmic-ray track an ultraviolet photon is emitted with an energy of about 16 eV. The gold surface is thus under constant bombardment by these photons, which have plenty of energy to photoexcite an electron in the metal, overcoming the 5 eV work function of the metal (and the Pauli-principle repulsive barrier of about 1 eV) to inject the electron into the helium.

It is clear that this new technique for looking at electrons should be applicable to a host of interesting further research projects, both in superfluid helium and in other noble gas liquids that are known to form a bubble state around electrons. In superfluid helium, it would be interesting to try to trap multiple electrons onto the core of a vortex line, allowing a visualization of the entire line, and its subsequent motion through the helium. The trapping of multiple electrons has already been accomplished for the vortex array in rotating helium [5], but in that case only a two-dimensional representation of the vortex positions could be photographed, while the present technique would allow for a full three-dimensional picture [6]. If the temperature of the helium can be reduced below 1 K, then more complicated structures such as vortex loops could be accessible to the technique, although getting to such temperatures will require development of a more efficient acoustic transducer that dissipates less power into the liquid. One further application may be to studies of a mysterious "exotic" negative ion that has been observed to exist in superfluid helium [7], which has a considerably higher mobility than the electron bubble. The nature of this ion is still unknown, but there is some speculation that it may also involve a bubble state, though one smaller than the 2 nm radius of the electron bubble. If that is the case, then it may be possible to "explode" the "exotic" ion in a similar manner and track it through the liquid.

References

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[4] This is somewhat reminiscent of the old bubble chamber technique where the pressure on a superheated liquid is suddenly reduced, producing expanding bubbles that nucleate preferentially along the track of an ionizing particle.
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Gary A. Williams is a Professor of Physics at UCLA, specializing in low-temperature physics. His recent experimental and theoretical work has been concerned with the role of quantized vortices in the superfluid phase transition, particularly for thin helium films adsorbed in porous materials and on nanotubes, and a further line of research has studied the luminescence emitted by collapsing laser-induced bubbles in liquid nitrogen and other liquids. He was named an Outstanding Referee by the American Physical Society in 2008.

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