Electrons Meet Helium

Dr. Keiya Shirahama meets Sir Martin Wood

Dr Keiya Shirahama, is the winner of the 2001 Sir Martin Wood Prize. Sponsored by Oxford Instruments Superconductivity, the Millennium Science Forum annually awards the Sir Martin Wood Prize to a young Japanese scientist carrying out his/her research in Japan, who has performed outstanding research in Condensed Matter Science. Dr Shirahama's prize winning research using 2D electron systems is presented below.

Liquid ^{3}He Free Surface Probed by the Wigner Crystal

Two-dimensional (2D) electron systems have contributed greatly to developments in fundamental physics, for example, in the discovery of the Quantum Hall effect. Electrons trapped on a free surface of liquid helium (He) offer an excellent high mobility 2D electron system.

Since the free surface of liquid He is extremely smooth, the mobility of electrons increases enormously at low temperatures. Due to this highly mobile nature, the electrons are very sensitive to elementary excitations, which disturb electron transport, and can be a powerful probe for the study of the He surface.

Due to strong Coulomb repulsion, surface electrons undergo a phase transition to a crystalline state called the Wigner crystal, predicted theoretically by the famous American physicist, Eugene Wigner, in 1934. The Wigner crystal is one of the possible ground states of strongly correlated electron systems.

Quantum Liquids

The Wigner crystal on liquid He has a unique feature; the electrons localised within the lattice put pressure on the liquid surface resulting in periodic corrugations (Figure 1). This is called the "dimple" structure. Not only does the dimple structure play a key role in the dynamic properties of the Wigner crystal, but it can be used as a tool for understanding liquid He, the fascinating quantum liquid.

The free surface of liquid He is an intriguing object of study. In particular, we have been interested in the surface of superfluid ^{3}He. The superfluid ^{3}He is a typical *anisotropic* Fermi superfluid, in which the Cooper pairs have nonzero spin- and orbital- angular momenta. Near the boundaries of the liquid, the anisotropic nature may be greatly enhanced. A boundary is made by, for instance, a solid wall of a liquid helium container. The wall is usually very rough in a mesoscopic length scale, however, so it does not provide a good boundary. Conversely, the free surface of liquid helium is extremely flat in atomic length scale, with no impurities or defects. This offers an almost ideal boundary of the anisotropic Fermi superfluid where one may expect some peculiar elementary excitations called *quasiparticles*.

The superfluidity of liquid ^{3}He was discovered by Osheroff et al 30 years ago. Its surface properties have never been studied, because suitable experimental means were not available. Our study has established the utility of the surface electrons for understanding the surface properties of liquid ^{3}He.

We have conducted measurements of electron mobility on both liquid ^{3}He, and ^{4}He, a boson isotope, under various experimental conditions, in particular, for temperatures spanning four orders of magnitude from 1 Kelvin down to 200 microKelvin. The mobility measurement is a simple method, but it has provided a great deal of important information on electronic and surface properties.

The mobility shows a peculiar temperature dependence (figure 2). The most important is that mobility of the Wigner crystal is determined by the scattering of ^{3}He quasiparticles to the

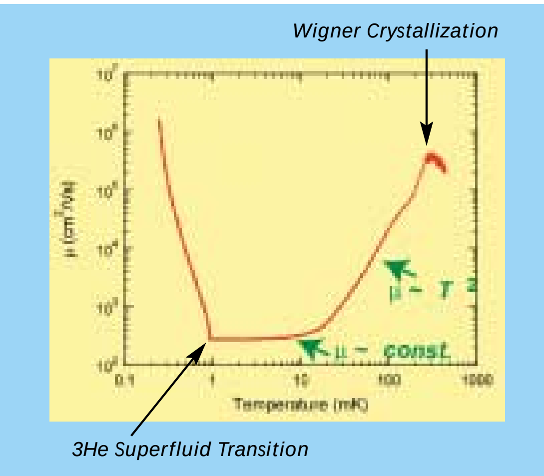

Figure 2: The electron mobility shows a peculiar temperature dependence

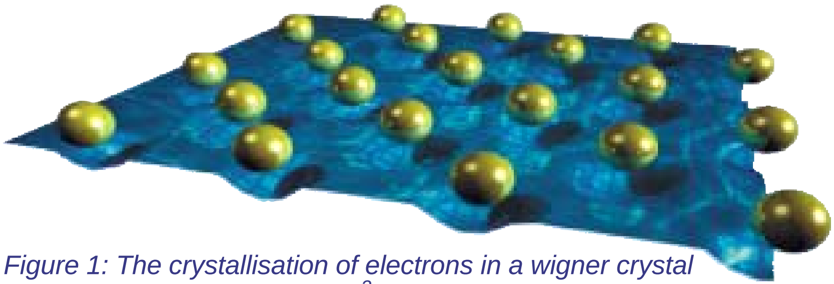

Figure 1: The crystallisation of electrons in a wigner crystal structure at the surface of the ^{3}He superfluid

surface dimples. Below 930 microKelvin (the superfluid transition temperature of ^{3}He) the mobility greatly increases, obeying the Arrhenius law. This behavior is explained by the scattering of quasiparticles, which are thermally excited over the superfluid energy gap, and hit the corrugated surface in a ballistic way. This interpretation has been confirmed for the two different superfluid phases, the B phase, which possess an isotropic energy gap, and the A phase, in which the energy gap is highly anisotropic.

Novel physics in quasiparticle dynamics

Our study shows that the Wigner crystal and the dimples are sensitive to the quasiparticles of liquid ^{3}He. This fact enables us to study novel physics in quasiparticle dynamics and the gap structure of anisotropic superfluid, such as the Andreev type quasiparticle reflection. It also enables us to study quasiparticle states bound to the surface, and novel surface collective oscillation called surface zero sound.

Another intriguing property is nonlinear (nonohmic) electron transport, which appears only in the Wigner crystal state. We attribute the nonlinearity to the complicated collective dynamics both of the crystal and surface dimples. Above a certain driving force, the dimples may not follow the crystal motion, and this results in the collective sliding of the electrons out of the dimples. The Wigner crystal with surface dimples provides us with a model system exhibiting fascinating nonlinear electron transport phenomena.

In conclusion, the Wigner crystal on liquid helium acts as an excellent surface probe for quantum liquid He. The meeting point of the electrons and the helium is fertile, and it will produce a new interdisciplinary research field of ultralow temperature physics, low dimensional electron physics, and nonlinear physics.

*Contact: **K. Shirahama**,*
Department of Physics, Keio University,
Yokohama 223-8522, Japan
keiya@phys.keio.ac.jp

Sir Martin Wood Prize

The 2002 Sir Martin Wood Prize giving will take place on 30th October.

For further details on how to apply for the 2003 prize, please view: www.oxford-instruments.jp or www.msforum.jp/index.htm

The Prize consists of a ¥500,000 cash sum, and a certificate and gift awarded at a prize ceremony at the British Embassy. The prizewinner is also invited to lecture at British Universities.

Sponsored by Oxford Instruments Superconductivity, the Millennium Science Forum was launched in 1999 with the aim of motivating young scientists in the area of condensed matter science and to increase scientific dialogue between the UK and Japan. Each year it awards the Sir Martin Wood Prize to a young Japanese scientist performing outstanding research into Condensed Matter Science in Japan.