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Ions and Electrons in Liquid Helium by A. F. Borghesani, Oxford University Press, Oxford, 2007, pp. xv + 542. Scope: monograph. Level: undergraduate and postgraduate.

Unlike all other matter, helium never solidifies under atmospheric pressure, regardless of how cold one makes it. When cooled below 4.2 K, however, the common isotope ^{4}He condenses to form a colourless liquid that has been a source of seemingly endless fascination to physicists since Kamerlingh Onnes first liquefied helum in Leiden in 1908, almost exactly a century ago. Since then, the rare isotope ^{3}He has also been separated and liquefied and found to be equally facinating albeit, in some respects, markedly different from ^{4}He. Both liquids are dominated by quantum mechanics, and both are gas-like in that their atoms are widely separated: the density of ^{4}He is only a third of what it would be for hard spheres in contact (and for ^{3}He the factor is a quarter). The reason lies in a combination of the very weak interatomic forces and the large quantum mechanical zero-point energy, so that the liquid expands to reduce its free energy. Hence London's description of liquid helium as a "quantum liquid blown up by its own zero-point energy". Its gas-like properties, and the fact that it remains liquid right down to the absolute zero of temperature, led London to suggest that the behaviour of liquid helium might be approximated by that of an ideal gas, so that ^{4}He and ^{3}He would be governed by Bose-Einstein and Fermi-Dirac statistics respectively. He was right – though it is the departures from ideal behaviour that are in many ways the most interesting feature of the heliums, as in both cases these give rise to superfluidity and other macroscopic manifestations of quantum mechanics.

How can one study these exotic, but inaccessible, fluids? Their thermodynamic properties can be measured directly, though it is far from trivial given the low temperatures involved. But what about their collective modes, their quantal properties and, in particular their superfluidity? Given that liquid ^{4}He is transparent, colourless, and magnetically inert the answers are far from obvious. Inelastic neutron scattering has been extremely useful e.g. in quantifying the disperion (energy-momentum) relationship of the excitations – and demonstrating the correctness of Landau's inspired guess that the two kinds of excitations, phonons and rotons, would populate different parts of the same dispersion curve. But it is the use of ions as probes that has really opened up the subject to close experimental analysis and examination.

Borghesani has brought together in a single volume the results of several hundred studies of liquid helium, all based on ions. The vast majority of this work has been based on just two types of probe. First, the negative ion is what is created within a few ps after an electron is injected into the liquid. Because of its small mass, and correspondingly its large zero-point motion, the electron carves out a spherical cavity for itself, of radius $\sim 10{-}20$Å, depending on pressure. It possesses a corresponding hydrodynamic effective mass of $\sim 70 - 240$ ^{4}He atomic masses. Secondly, the positive ion is smaller, but also augmented im both mass and hydrodynamic mass when the He$^+$ at its core electrostritively solidifies the ^{4}He around it. Both ions are thus semi-macroscopic objects that can be used to study what goes on within the liquid. They are easily injected e.g. by using the particle tracks around a radioactive source, or by field emission/ionization at a sharp metal point. They can be moved around in the liquid by application of electric fields, and their arrival at an electrode is revealed by the current that they induce.

The book is in three parts, covering results for liquid ^{4}He, liquid ^{3}He, and dense helium gas. Of these, the first is by far the largest, consisting of 17 chapters. It opens with a succinct introduction to superfluidity, covering the 2-fluid and Landau models and explaining how they are effectively equivalent: below its superfluid transition temperature of $T_\lambda = 2.17\,\mathrm{K}$ the liquid behaves in many respects like a mixture of normal fluid (a fairly conventional liquid) and superfluid (with zero viscosity, carrying zero entropy); the first of these corresponds to a gas of elementary excitations i.e. phonons and rotons, and the second is the vacuum-like background within which the excitations move. At $T = 0\,\mathrm{K}$ the liquid is 100% superfluid, and at $T = T_\lambda$ it is 100% normal fluid.

Borghesani describes how ions have been used to probe the excitations via measurements of mobility, to study the patterns of quantized vortex lines created if one tries to rotate the liquid (overall rotation of the superfluid being forbidden), to determine the trapping potential of an ion on a vortex through measurements of capture and escape rates, to investigate excitations of the vortex core through studies of ion motion along vortex lines, to measure the Landau critical velocity at which superfluidity breaks down through roton creation (and the background loses its vacuum-like properties), to show that the process of vortex creation involves a form of macroscopic quntum tunnelling, and to study many many other features of the liquid's exotic properties.

Part II, on ions in liquid ^{3}He, comprises a further seven chapters. At temperatures well below 1 K liquid ^{3}He behaves in a totally different way to liquid ^{4}He because of being described by Fermi-Dirac statistics. This is clearly revealed by the ions. The author covers their behaviour in the normal phase – which in reality is anything but normal, but exhibits characteristic Fermi liquid properties – as well as in the superfluid phases below 2 mK. For liquid ^{3}He, however, there has been far less research involving ion motion than in the case of the common isotope, probably because ^{3}He can be probed in ways that are unavailable for ^{4}He. In particular, the unpaired neutron in its nucleus endows ^{3}He with magnetic properties allowing the use of nuclear magnetic resonance to investigate the liquid. Nonetheless, many of the earlier experiments in ^{4}He, e.g. on ionic mobilities and transport, critical velocities, and interactions with quantized vortices, have their analogues in ^{3}He. This interesting body of work is carefully described.

Finally, the three chapters of Part III describe electrons in dense helium gas. As already remarked, liquid helium is itself gas-like in terms of its density and many other properties, so it was natural to ask what would happen in the dense vapour. Not surprisingly, perhaps, charged bubble states are formed much as in the liquid.

This is a big book, and the only obvious omission is the relatively small amount of work on ion motion in solid helium – but it falls outside the chosen title and it is entirely understandable why the author would have wished to call a halt. He has done an excellent job by encompassing practically everything that has ever been published on ions in liquid helium, from the early debates about the famous (but seemingly mythical) “Careri steps” in the mobility up to the very recent controversy about Maris's “fractional electrons”. Somehow, he has digested this huge body of work and turned it into a coherent whole, and he deserves congratulation and thanks from the entire community of low temperature physicists for doing so.

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