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Remarks on Solid Helium

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In this Special Issue, some of the fundamental and practical challenges and questions that appear to us to exist concerning the possibility of supersolidity or other unusual phenomena that may be present in solid helium are presented. The work of Kim and Chan stimulated a major rebirth of significant investigation of the properties and behavior of solid ^{4}He. In the intervening ten or so years, a number of discoveries have been made, but a number of early questions remain, and a number of new questions have emerged in recent years. Here, a number of issues that remain outstanding are presented. This list could no doubt be increased by other scientists active in these fields, but these ideas come to mind, stimulated by the recent work reported at LT27 and at this Workshop.

A major question is, of course, is there a supersolid? And, if so, is it anything like the supersolid predicted in the early 1970s to exist? The community has moved from excitement, that such state of matter exists, to very serious skepticism. The original interpretation that seemed obvious from the torsional oscillator results has been retracted, and most in the community believe that the torsional oscillator effects were due to the temperature dependence of the shear modulus. The community has not come into complete agreement on how to fully interpret double-frequency torsional oscillator experiments. So, there needs to be a clarification of the torsional oscillator work. At the moment, there appears to be no convincing evidence for supersolidity from torsional oscillator experiments. But, this needs to be definitively settled by the scientific community.

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There are now experimental results emerging in addition to the results from the University of Massachusetts that show evidence for mass transport through an experimental cell filled with solid helium. This needs to be fully understood. A robust temperature dependence to the mass flux is observed. We need to understand the origin of the sharp reduction in the flow at a low temperature that depends on the ^{3}He concentration and just why the presence of the ^{3}He blocks the flow. We need to understand the temperature dependence at higher temperatures, a dependence that appears to be universal (in the sense that the functional dependence is common to many samples), and we need to understand why no flow is evident at temperatures above about 650 mK and pressures above about 28 bar—at least for the geometries studied to date. Also we need to learn just what the mechanism of conduction through a cell filled with solid helium is. We can grow solid samples from the superfluid, but this growth seems to show an interesting temperature dependence, which needs to be understood. Is superclimb present?

There is some evidence in the flow experiments that a Luttinger liquid model might be appropriate to describe the characteristics of the flow. We need further evidence that this interpretation is correct. Can theory provide us with the necessary parameters and from comparison with the experiments can we learn more details about the manner in which flow depends on the driving chemical potential?

We would like to know in more detail the differences between the behavior of solid ^{4}He and solid ^{3}He. In what ways do the dislocations in these two quantum solids differ? And, what similarities and differences exist between the helium quantum solids and solid hydrogen?

We need a better understanding of defects in quantum solids. Even in the absence of supersolidity, there might possibly be new purely quantum effects associated with defects in helium, e.g., delocalized/zero-point kinks, superfluid dislocation cores, superclimb, and ^{3}He motion and drag. If so, how can we observe them clearly and conclusively? The theoretically predicted superfluid cores of dislocations that may explain the results from the University of Massachusetts need to be directly tested, perhaps by flow measurements, but perhaps also by developing ways to look for phenomena like superclimb.

In addition to such possible new quantum phenomena in solid helium, it is clear that quantum corrections to defect properties are large. Helium is a unique model system for studying fundamental material science issues of dislocation creation, structure, motion, etc., but it is important to understand the specific properties of dislocations in solid helium. For instance, which dislocations are split into partials? Is this critical to their mobility? What is the stacking fault energy and resulting splitting? What is the difference in the binding energy for ^{3}He to screw versus edge dislocations and to partials? At what temperatures will kinks and kink motion be thermally activated? Can we calculate the kink energy by including quantum fluctuations and quantum tunneling so that one gets some prediction for the existence of zero-point kinks? Can we better calculate the binding energy of ^{3}He to ^{4}He dislocations, and in particular to their intersections? Can we calculate the damping in the dislocation motion due to the binding of ^{3}He impurities? It may be that first-principles Monte Carlo calculations will be able to address some of these issues.

In a number of the experiments, there is an irreversible behavior. What is responsible for this and just how does annealing or stress influence this irreversibility? There are only a few rotation experiments that have been directed to the study of solid helium and the behavior that these experiments reveal is complex and not at all understood. What is the relevance of vortices to solid helium?

Can we exploit some of the superfluid vortex experimental technology to study dislocations? A disadvantage of solid helium as a material science model system is the inability to directly image and count dislocations. For example, can He_2* or other excited stable states (or dopant impurities) be excited and imaged in solid helium? Could you decorate and light up dislocations? Could a charge be injected and currents used to learn something about dislocations, e.g., see a current moving down a single dislocation?

There is a host of interesting questions and directions that need to be explored before we can say that we really understand the quantum solids ^{3}He and ^{4}He. There is plenty of work to do.