A 'Superglass' State in Solid 4-He?

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The puzzling behavior of solid He^4 under rotation at temperatures below a few hundred millidegrees, first reported by Kim and Chan [1] in 2004, continues to defy agreed theoretical explanation. The original experiments were on a solid sample contained in an annular cavity which formed part of a torsional oscillator, and showed a small but definite increase of the resonance frequency of the oscillator below about 200 mK, which was most naturally interpreted as a decrease of the order of a few per cent in the effective moment of inertia of the helium. Since no such anomaly was observed when the annulus was blocked so as to interrupt its connectedness, the default inference is that the solid is showing effects of the multiply-connected topology similar to those believed to be responsible for the complex of phenomena in liquid He^4 which are collectively known as superfluidity; thus the new phase (if it is one) of solid He^4 in which the anomalous frequency shift occurs is usually called a "supersolid" (a name which some would no doubt claim is inappropriate, since the system appears to be behaving in a rather un-solid-like way!).

Over the past five years, the qualitative features reported in the original experiments have been confirmed by numerous different groups, and a reasonably systematic phenomenology of "supersolidity" has been established; for example, it seems to be uncontroversial that the transition to supersolid behavior is accompanied by a peak in the oscillator dissipation as a function of temperature, that the reduction in the effective moment of inertia decreases as a function of oscillation amplitude and that the onset temperature is strongly increased by the addition of a small amount of He^3 . However, even at the level of phenomenology important questions remain open; in particular, it is unclear whether what is being observed is a genuine thermal equilibrium phenomenon (i.e. whether, if the sample could be cooled through the onset temperature under d.c rotation, it would continue to show a reduced moment of inertia) or whether it is a consequence of a failure to come into equilibrium with the boundary conditions over time scales of the order of the oscillation period. A wide variety of theoretical proposals taking one view or the other have by now appeared in the literature.

The experiments now reported by Hunt et al., while not directly addressing this last question, feed yet another tantalizing ingredient into the puzzle. The system is a torsional oscillator with a geometry qualitatively similar to that of Kim and Chan [1], and as in that case the raw data consists of the period and width of the torsional resonance; in the steady state the authors reproduce the "standard" features of these, with a low-temperature superfluid fraction (relative decrease of moment of inertia) of about 5%. The novel feature is that they study in detail the approach to the steady state, by changing the thermometer temperature rapidly and then monitoring the behavior of the frequency shift and damping as a function of time. When the final thermometer temperature T_f is above the supersolid onset temperature T^*, the shift and damping essentially track the thermometer temperature. However, when $T_f < T^*$, a substantial fraction of the relaxation to the steady-state values takes place after temperature equilibration, with a relaxation time (apparently common to the shift and damping) which at the lowest temperature reached (about 10 mK) can be of the order of days. A further interesting observation is that if the steady-state shift and damping are compared as a function of temperature, their relationship does not fit the hypothesis of a simple Debye relaxation but is more suggestive of ”glassy” behavior, characterized by a wide distribution of relaxation times; study of the way in which the relationship builds up to its steady-state value suggests that the ”glassiness” develops gradually following the initial temperature equilibration. In the light of this behavior the authors propose to call the anomalous state of solid He^4 a ”superglass” state.

What these experiments seem to suggest is that whatever the nature of the ”supersolid” phase (or regime) of solid He^4, it is sufficiently different from the ”normal” (high-temperature) phase that there are rather high free energy barriers between the two regimes; and that the structure of these barriers may perhaps have the sort of ”hierarchical” structure often believed to occur in a structural glass. One obvious question, which is apparently not answered by the results of Hunt et al., is to what extent, if at all, the rotation itself is instrumental in either favoring the anomalous phase or affecting the structure of the barriers. To be sure, since the amplitude of the rotation is presumably very small, it is difficult to think of ways in which it could affect the energetics enough to make a difference, but it might nevertheless be interesting to vary this amplitude systematically as a function of time during the long-time relaxation and see if it had any observable effect.

[1] E. Kim and M.W.H. Chan, Nature 427,225 (2004); Science 305,1941 (2004).