Superfluid transition of helium films in one-dimensional nanopores

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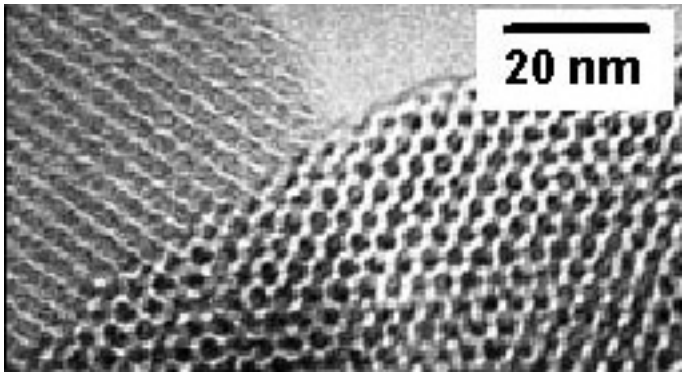
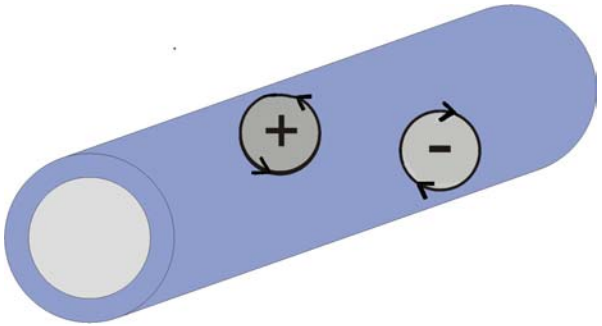
We have measured the superfluid density of of very thin helium films contained in long cylindrical channels that are only 2.0 nanometers in radius. Measurements over a wide range of temperature and film thickness have allowed us to study the superfluid to normal phase transition in this geometry, which results from thermally excited vortices. We find that as the films become thinner the vortex core radius increases, but finally limits at the 2.0 nanometer radius of the cylinder. In this limit superfluidity disappears, because the system crosses over to become purely one-dimensional, and a one-dimensional system cannot be superfluid. The large vortex cores essentially block any superflow in the channel.



Electron microscope picture of MCM-41 nanoporous ceramic, showing the array of cylinders; the inside surfaces of these cylinders are coated with films of liquid helium in our experiments.



Vortex pair of opposite circulation in the cylindrical helium film. If the size of the vortex cores become comparable to the cylinder radius they will block any superfluid flow in the channel.

In the superfluid state liquid helium is able to flow along a wall with no friction at all, since its viscosity is identically zero. This only occurs at very low temperatures, however, below 2 degrees on the Kelvin scale of temperature (-456 degrees Fahrenheit) for the bulk liquid. As the helium is warmed up the increasing thermal energy causes small whirlpools, or vortices, to appear in the liquid, and these reduce the superfluid properties, and finally at a critical temperature they completely kill the superfluidity. Above this temperature the liquid helium has viscosity like any other normal fluid.

In our experiments we study this transition between superfluid and normal fluid for the case of very thin films of helium, less than a few atomic layers thick. Even such extremely thin films can still be superfluid and flow without friction, but this requires even lower temperatures, down to 0.05 Kelvin in our measurements. As we warm up it is again the vortices which cause the phase transition to the normal state. Since our helium films coat the inside surface of the narrow ceramic cylinders, we find an an additional constraint on the phase transition in this geometry. As we decrease the thickness of the films we find that the core size of the vortices increases, and when the core size becomes equal to the radius of the cylinders the superfluidity disappears at all temperatures, since the vortices completely block any superflow down the channel.

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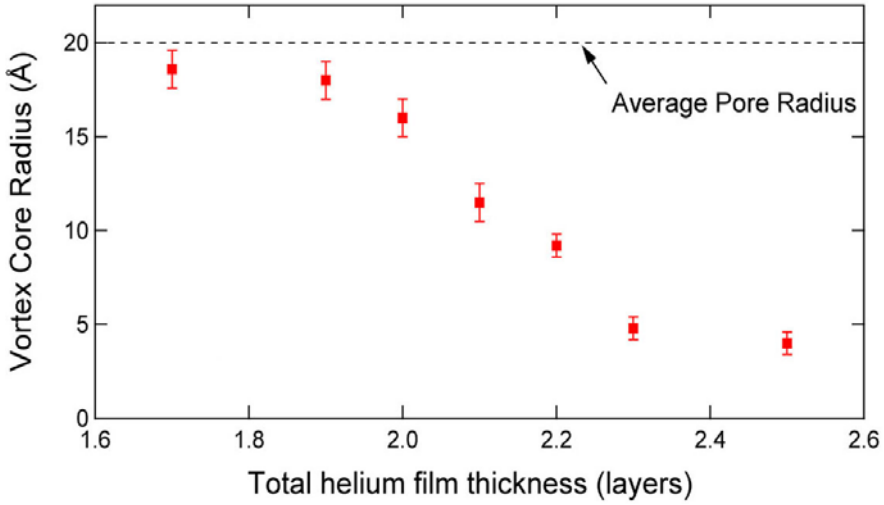

Plot showing the increase in vortex core radius as the film thickness is decreased, and the crossover to 1D as the core radius becomes equal to the pore radius. The films are no longer superfluid below 1.6 atomic layers.

Impact of the research:
The superfluid transition of helium films forms an important test of renormalization-group theories of phase transitions, and illustrates the fundamental importance of dimensionality in these theories.

Education:
Two graduate students, Heetae Kim and Han-Ching Chu (a woman), contributed to this work. Heetae graduated with his Ph.D. and is now a postdoc at Harvard. Han-Ching will finish her Ph.D thesis this summer and has accepted a postdoc position in a UCLA nanotechnology lab. Three undergraduates gained experience working in the lab (including a Latino woman), and three high school students completed summer projects.