The first unequivocal experimental evidence of a superfluid state in 2D 4He films

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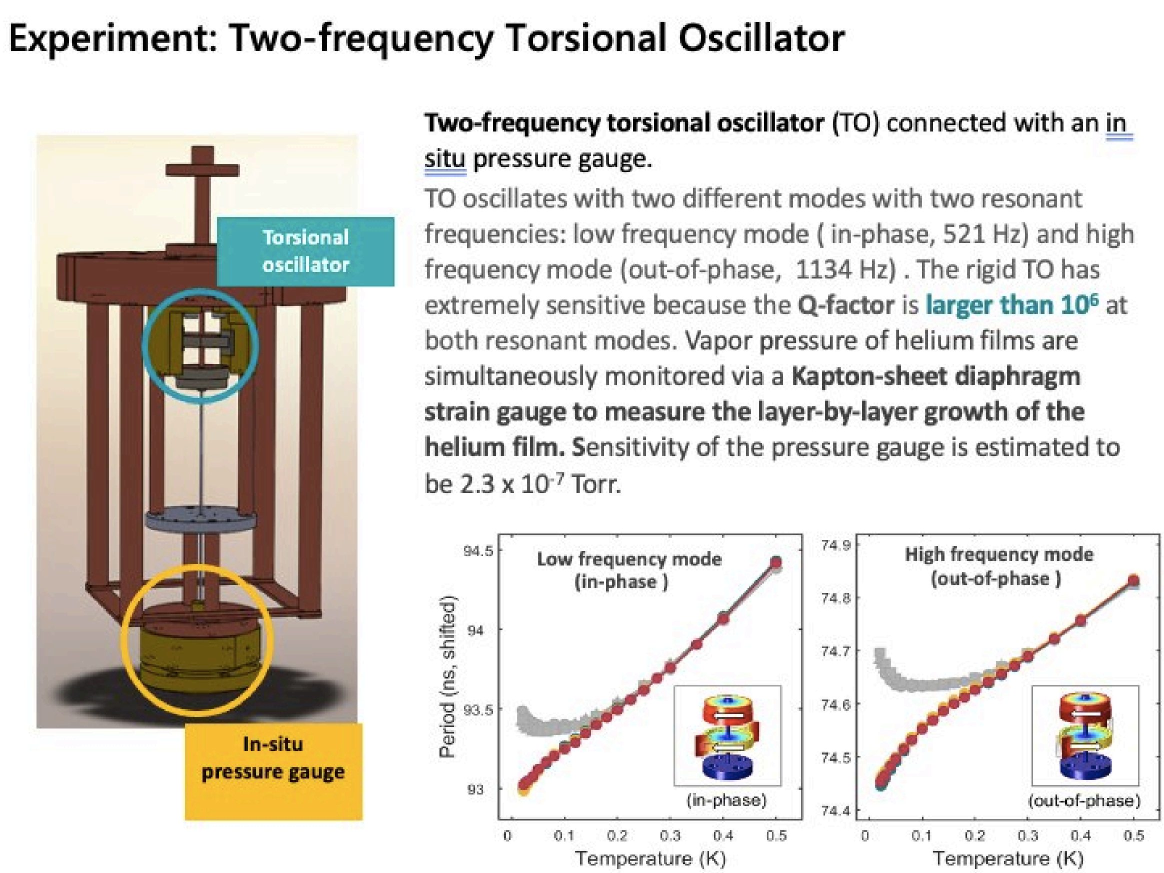

The researchers' experimental set-up. Credit: Choi et al.

Over the past few decades, some physicists worldwide have been trying to use the second layer of ^{4}He films adsorbed on a graphite substrate to study the interplay between superfluid and supersolid phases of matter. Some teams have collected torsional oscillator (TO) measurements on this layer, including P.A. Crowell, F.W. Van Keuls and J.D. Reppy at Cornell University, as well as Dr. Jan Nyeki and his colleagues at Royal Holloway.

Researchers at Korea Advanced Institute of Science and Technology (KAIST) have recently improved on these measurements by gathering the first unequivocal experimental evidence of a superfluid state in 2D ^{4}He films on a graphite substrate. Their findings, published in *Physical Review Letters*, suggest that the second layer of ^{4}He films could be a highly promising candidate for hosting superfluid and supersolid phases.

"Ours is the first successful experiment to present unequivocal evidence of a superfluid phase in the second layer by employing a rigid, two-frequency TO, a radically improved version of the conventional TO," Eunseong Kim, one of the researchers who carried out the study, told Phys.org.

In past studies, a reduction in the TO period within ^{4}He films was interpreted as a signature of superfluidity. However, past studies have found that TO measurements are also sensitive to other non-superfluid effects, such as changes in viscoelastic properties. This means that if an experiment is not carefully designed, TO effects can easily be amplified or overestimated.

"In addition, there has been a recent TO experiment studying viscoelastic property changes of ^{4}He films adsorbed on a disordered substrate," Kim said. "In several different TOs, the elastic anomaly led to a temperature-dependent period reduction with a slow onset behavior, very similar to what was observed in the second layer of ^{4}He on graphite. Thus, one cannot exclude the possibility that the TOs used in the previous studies could be sensitive to this unwanted viscoelastic effect. In this regard, our new measurement is essential to conclusively answer the question "Does superfluid exist in the second layer?" and to carry this research field forward."

"Two 'recipes' were suggested to search for the genuine superfluidity: (i) a TO with a rigid design that can filter out the unwanted viscoelastic contribution and (ii) a TO with multiple resonant frequencies to test the frequency dependence of the detected signal," Kim explained. "The TO experiments that satisfy the above two criteria played a pivotal role in reconciling the conflicting observations and led to the conclusion that the viscoelastic property change of solid ^{4}He gives rise to the superfluid-mimicking signal."

In their study, Kim and his colleagues collected a rigid two-frequency TO measurement that unequivocally confirms the existence of the superfluid phase in the second layer of ^{4}He films on a graphite substrate. According to the researchers, this is the first truly 'successful' TO measurement on the second layer, as it is the only one so far that satisfied the two criteria for reliably detecting superfluidity.

"The two pioneering works by Crowell & Reppy and Nyeki & Saunders opened up a new research direction and provided new insights," Kim said. "However, their TOs were not designed to disentangle the superfluid signal from other effects. What they commonly observed is a mismatch between the empty-TO period data and the vertically adjusted TO period with nonsuperfluid ^{4}He films (which they called a "composite" background)."

Based on past studies focusing on bulk solid ^{4}He, the absence of a 'composite' or tilted background is a key characteristic of rigid TO measurements. As a result, 'composite' backgrounds observed in previous studies might be the result of viscoelastic coupling between the samples analyzed and the TO methods used to examine them.

Kim and his colleagues measured the temperature dependence of the TO, which included a helium film with two different resonant periods (i.e., frequencies). The temperature dependence would ultimately reveal a monotonic change with decreasing temperature if there is no superfluid.

"When superfluid helium appears, it decouples from the oscillation and, accordingly, reduces the resonant period (or increases the resonant frequency—oscillates faster due to the reduced mass in the TO). It is straightforward that the superfluid response is independent of the driving frequency since superfluid completely decouples from the oscillation," Kim said. "However, non-superfluid mechanisms, such as viscoelastic response, show frequency dependence because the coupling of the helium to the TO depends on the driving frequency."

The shift in frequency observed by Kim and his colleagues was found to be independent from the measurement frequency, which suggests that the anomaly they spotted is truly associated with superfluidity. The findings thus represent a substantial advancement in the study of low-dimensional ^{4}He adsorbed on ordered substrates, as well as of quantum fluids and solids in general.

"Another unique contribution of our work is that we add new understanding on the relationship between superfluid and structural order," Kim said. "To this end, it is essential to make a phase diagram with an accurate determination of film coverage. In our work, we carried out simultaneous TO and vapor pressure measurements using an in situ pressure gauge to accurately measure the coverage and, for the first time, proposed a region where the superfluid and solid order coexist."

Interestingly, the region at which the superfluid and solid order coexist delineated by Kim and his colleagues is consistent with the latest diffusive Monte Carlo study. Based on these findings, the researchers concluded that two exotic quantum phases emerge in the second layer of ^{4}He films.

In their previous experiments, other teams had measured vapor pressure in their sample while it was outside of the fridge and then defined their coverage scale by setting the second-layer promotion at 11.4 atoms/nm^2. This makes it difficult to determine the absolute coverage scale of their system. Kim and his colleagues, on the other hand, were able to clearly identify the coverage where both superfluid and solid orders coexist, which is a necessary condition for reliably detecting the supersolid phase.

Thanks to the radical improvement of existing TO techniques, this study gathered unequivocal evidence of the superfluid phase, which has never been successfully achieved before. In addition, it experimentally confirmed past theoretical predictions suggesting that the superfluid and solid order coexist at a specific coverage range.

"Our work opens a new era of by reconciling different experimental and theoretical studies," Kim said. "Even though the second layer has been extensively studied, the shape of its phase diagram did not converge into a single conclusion. For example, the coverage where superfluidity was found in Crowell & Reppy was not consistent with the region where the heat capacity anomaly was reported. The coverage region for the supersolid candidate suggested by Nyeki & Saunders did not coincide with the region where the superfluid and solid order coexist in numerical calculations. However, our study suggests the possibility to reconcile all these results in an integrated fashion."

The coexistence of the superfluid and solid phase, a necessary condition for supersolidity, has become a popular research topic in numerous fields, ranging from condensed matter to AMO physics. In the future, he two exotic and intertwined quantum phases observed by Kim and his colleagues are thus likely to inform both experimental and theoretical research rooted in different areas of physics.

"The next obvious question is whether the helium film has structural order in the areal density where the superfluid appears," Kim added. "This is crucial because it is a direct evidence of the supersolid state: the coexistence of superfluidity and crystalline order. We are currently designing a new mechanical oscillator that can probe the structural order at this stage."

More information: Spatially modulated superfluid state in two-dimensional ^{4}He films. *Physical Review Letters*(2021). DOI: 10.1103/PhysRevLett.127.135301

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