Speed limit on a superfluid helium nano-highway

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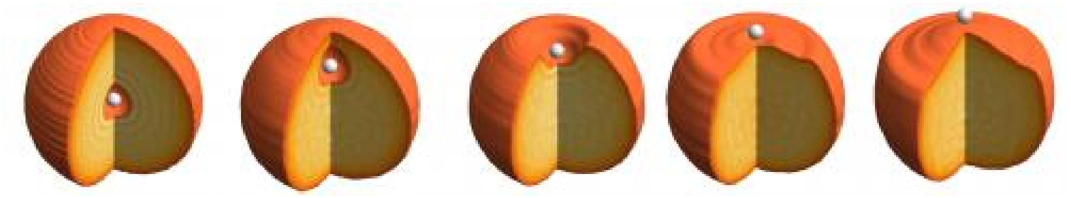

These computer simulations show how a silver atom is launched from a helium nanodroplet. The moment the silver atom is 'spat out' is a spectacle in its own right, as it is accompanied by various other processes such as excitation of 'riplons' (surface waves). Credit: Fundamental Research on Matter (FOM)

Scientists from the University of Amsterdam (UvA), the Ecole Polytechnique Fédérale de Lausanne (EPFL) and the Universitat de Barcelona have been able to determine the so-called Landau velocity for helium nanodroplets down to a radius of 2.5 nanometer, containing only a thousand helium atoms. Their results, confirming the existence of superfluidity at the nanoscale, are published this week by *Physical Review Letters*.

The fact that helium becomes superfluid at extremely low temperatures is a well-known quantum mechanical phenomenon. Objects do not experience any friction when they move through superfluid helium – at least, as long as they move slower than the critical Landau velocity. So far, scientists have only been able to verify this for bulk helium. The new research has now shown that even in tiny nanodroplets, helium still exhibits superfluidity.

Pioneering experiment

The pioneering experiment is the result of a collaboration between dr. Marcel Drabbels (EPFL, former postdoc at FOM Institute AMOLF) and FOM workgroup leader and UvA researcher prof.dr. Wybren Jan Buma. The experiment starts with the production of extremely cold helium nanodroplets having a temperature of 0.4 K and a size that can be varied from a few million to less than thousand helium atoms. Subsequently, the researchers place one single metal atom or one single molecule in such a nanodroplet.

Due to the weak attractive interactions it experiences with helium, the 'impurity' will initially be located at the center of the nanodroplet. Next, the researchers activate the impurity with a nanosecond laser pulse. The electronically excited particle now experiences a repulsive interaction with the helium. As a result the atom or molecule is launched out of the droplet. There its speed is determined.

Speed limiter

The result of the experiment was quite astonishing: the measured velocity is always the same. It does not matter whether the impurity is a metal atom, a diatomic molecule or a polyatomic molecule with a cage structure: they all leave the droplet with the same speed. Mass or size thus does not matter. Even the repulsive force (which could be tuned with the laser pulse) turned out not to be of any influence.

"We thus observe that a speed limiter is at work when the atoms or molecules travel from the center to the outside of the helium droplet", says Buma. In more scientific terms: for these kind of nanosystems a critical Landau velocity exists. "From this we can conclude that superfluidity can be maintained not only in bulk helium but also at these tiny length scales", according to Drabbels.

To support this conclusion, theoretical physicist prof.dr. Manuel Barranco and his team of the Universitat de Barcelona performed simulations based on the experimental data. Their work confirms that the impurity leaves the helium nanodroplets with a critical velocity.

Practical relevance

The results are not only important from a fundamental theoretical perspective. They also have a practical relevance. Buma explains that the critical Landau velocity is a manifestation of Bose-Einstein condensation, a quantum effect which lies at the basis of superfluidity. "The critical Landau velocity is in essence a macroscopic property associated with superfluid helium. This is also how it has been determined experimentally: in vessels with zillions of atoms. However, nowadays all kinds of techniques make use of helium nanodroplets. For example to study chemical reactions at ultralow temperatures, to determine the structure of proteins, or to synthesize special metal alloys. For these applications it is essential that we know exactly the viscosity properties of the helium nanodroplets".

So far it had not been possible to achieve unambiguous results in this area, according to Drabbels. "Spectroscopic experiments on molecular probes in helium nanodroplets led to a conflicting picture. Moreover, in those experiments superfluidity is probed only indirectly. The most direct experiment one can do is the experiment that we have performed. Actually, everybody knew and agreed on this since a long time, but until now nobody had been able to do it."

EXPLAINING THE LANDAU VELOCITY

The critical Landau velocity finds its origin in the fact that superfluid helium is a so-called Bose-Einstein condensate. This is a quantum system in which - quantized - energy exchange with other objects can only proceed via a collective excitation of the helium atoms.

For moving objects the Russian physicist Lev Landau predicted already more than seventy years ago that this energy exchange is only possible above a certain velocity – the critical Landau velocity. For bulk helium this was demonstrated by experiments in the seventies. The helium remains superfluid at the Landau velocity, but changes quantum state because of the energy it has absorbed from the moving particle. The particle, in turn, loses its energy and travels at a lower velocity. However, due to the repulsive interaction with the helium, it will accelerate again - until it once again reaches the critical Landau velocity. This repeating process is the mechanism underlying the 'speed limiter' observed by Drabbels and Buma.

Provided by Fundamental Research on Matter (FOM)

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