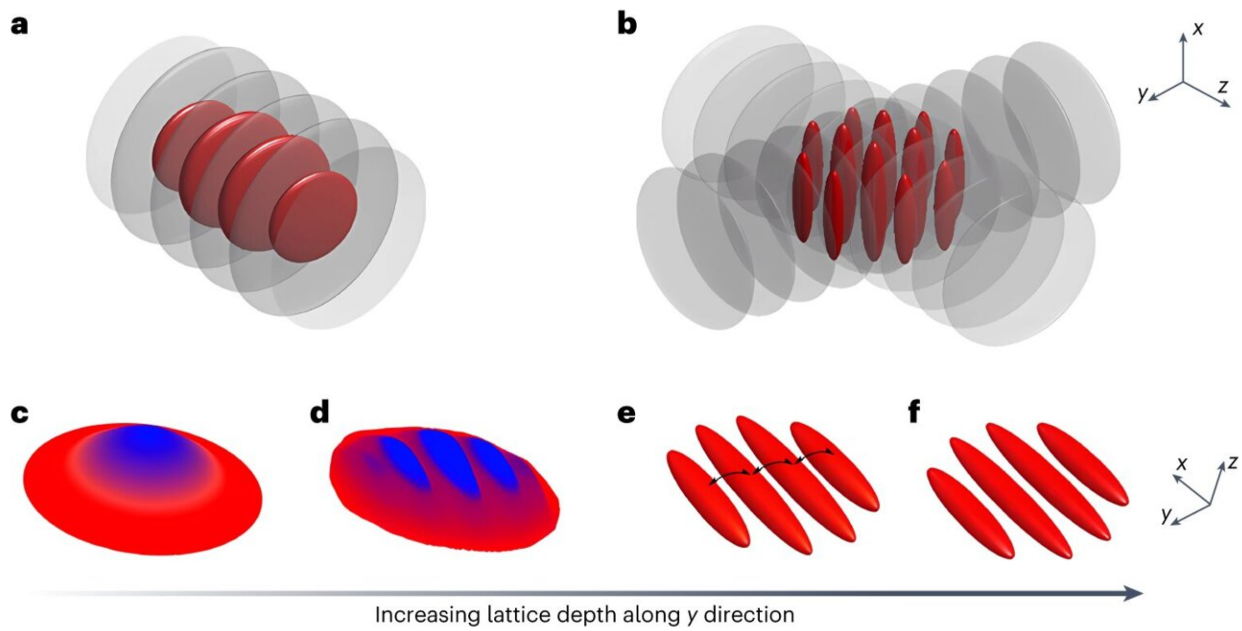
Physicists track how continuous changes in dimensionality affect collective properties of a superfluid

April 10 2024



Conceptual sketch of the experiment. a,b, Starting from a 3D BEC, we generate an ensemble of low-dimensional units, namely, 2D layers (a) and 1D tubes (b). c–f, Schematic plots for the evolution of one particular layer during the dimensional crossover, where the quantum gas goes from being 2D (c), to being modulated 2D (d), to being coherently coupled 1D (e) and then to being 1D (f) by continuously increasing the lattice depth. The blue color in c and d indicates the high-density regime where superfluid regions appear. Credit: *Nature Physics* (2024). DOI: 10.1038/s41567-024-02459-3

An international research team from Innsbruck and Geneva has, for the first time, probed the dimensional crossover for ultracold quantum matter. In the regime between one and two dimensions, the quantum particles perceive their world as being 1D or 2D depending on the length scale on which they are probed: For short distances, their world is 1D, but it is 2D for long distances.

The results obtained from correlation measurements have just been published in *Nature Physics*.

Inhabitants of the inner cities of Manhattan or Miami have known it all along: For short distances, up to the length of a block, the world inside the "urban canyons" of the city appears to be one-dimensional. Only one direction is preferred. However, with the cross streets present for longer distances, the world is two-dimensional: It is possible that one explores the transverse direction when traveling far enough.

Quantum particles, confined at ultralow temperatures to "optical canyons" with the possibility to quantum tunnel to neighboring canyons, also "know" what their dimensionality is: They are 1D for short distances, but 2D for long distances. Such behavior has recently been revealed in a joint experiment-theory work by researchers from the Department of Experimental Physics at the University of Innsbruck and in the Department of Quantum Matter Physics at the University of Geneva.

Quantum systems in reduced dimensionality and at ultralow temperatures in the regime of superfluidity and quantum degeneracy have become a rich field of research. Two-dimensional superfluids may contain topological excitations, and interacting one-dimensional systems feature a multitude of unusual properties, of which fermionization of bosons is one of the most striking ones.

Little is known about the regime of the dimensional crossover: How do strongly interacting 2D bosonic superfluids connect to fermionized bosons in 1D? Using cold atoms as a research platform, the dimensional crossover can now be studied directly in the experiment.

In a first test, the physicists probed the correlation properties of interacting bosons confined to variable crystals of light. In mixed dimensionality, they found a characteristic two-slope decay for the one-body correlation function, mirroring the fact that the particles are 1D and 2D at the same time.

"Our system is 1D and 2D simultaneously," says one of the lead authors of this work, Yanliang Guo, who is a postdoc in Innsbruck. "It depends on how we interrogate the system."

Hepeng Yao, a postdoc in Geneva who has carried out the numerical simulation and analysis by state-of-the-art quantum Monte Carlo methods, agrees. "We can now directly track how the continuous change of a system's dimensionality affects the collective properties of a superfluid."

"Our experiments had a surprise for us in store," says Yanliang Guo. "In view of our high-quality numerical modeling, we can now use the correlation measurements to determine the temperature of our quantum liquids in 1D, 2D, and in between, with very high precision. This might open the avenue to new discoveries, for example for the exploration of the elusive Bose-glass phase."

Hepeng Yao concurs, "The correlation measurements, when done for bosons at very low temperatures in the presence of a random potential, should show signatures of the Bose glass."

The results will serve as a starting point for further research on low-dimensional quantum matter and its dimensional crossover.

More information: Yanliang Guo et al, Observation of the 2D–1D crossover in strongly interacting ultracold bosons, *Nature Physics* (2024). DOI: 10.1038/s41567-024-02459-3

Provided by University of Innsbruck