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Quantum theory verified by experiment

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Abstract

Systems of quantum objects can be characterized by the correlations between the objects. A technique that precisely measures even the most delicate of these correlations allows models of quantum systems to be tested.

The laws of nature are inferred through the observation of correlations, which distill information about the properties of physical systems. Such correlations can be determined by studying systems in their natural state, or by performing controlled experiments in which certain quantities are deliberately manipulated. Observing correlations in quantum systems is challenging because quantum objects are fundamentally altered by the process of taking measurements, and available measurement tools do not probe the quantities of interest. But on page 323, Schweigler *et al.*¹ report a method that overcomes these problems and allows correlations to be measured for a quantum system comprising thousands of rubidium atoms at ultracold (nanokelvin-scale) temperatures. The authors show that this system is accurately described by a mathematical framework called the sine-Gordon quantum field theory², confirming a previous proposal³. Crucially, their technique could be applied to many types of quantum system — including those that have strong interactions, in which the underlying physics is not well established⁴.

In quantum systems, matter behaves like a wave and has an associated phase — defining the position of the crest of the wave. The type and degree of correlation between the phases of two quantum objects can be expressed using a set of statistical parameters called correlation functions (CFs). For example, the first-order CF is simply the average relative phase between the objects at a particular position along the length of the waves. Conversely, the second-order CF expresses the similarity of the relative phases at two different positions: if the relative phases have the same sign, the CF will be positive (correlated); if they have opposite signs, the CF will be negative (anti-correlated); and if they sometimes have the same sign and at other times have opposite signs, the CF will be negligible (uncorrelated).

For quantum systems that have a constant relative phase (after taking the average of multiple measurements), the fluctuations around this average look like experimental background noise when observed in a single measurement. In these systems, the interplay between two types of noise contains information about higher-order CFs (those of order greater than one). First, there is quantum-measurement noise — individual quantum measurements have a fundamental noise owing to relations similar to the Heisenberg uncertainty principle, which constrains the precision with which the position and momentum of quantum objects can be measured. Second, there is thermal noise, which results from extra motion present in

systems at non-zero temperatures. Schweigler *et al.* generated a huge amount of data to evaluate the combination of these sources of fluctuations. This allowed the authors to calculate higher-order CFs that are required for testing theoretical models of such quantum systems.

Schweigler and colleagues' experiment consisted of a pair of weakly interacting one-dimensional quantum fluids — comprising thousands of ultracold rubidium-87 atoms — that behave in a wave-like manner (Fig. 1). The authors used a measurement technique known as matter-wave interferometry⁵ to determine the CFs of the system; the interference between the two waves produced an interference pattern whose fringes (bright or dark bands) corresponded directly to the relative phase between the waves.

The authors calculated 'disconnected' CFs, in which the information present in lower-order CFs was removed. In many systems — for example, atomic gases ultracooled to a phase of matter known as a Bose-Einstein condensate⁶ — only first- and second-order disconnected CFs contain useful information. However, Schweigler *et al.* evaluated disconnected CFs up to tenth order. They found that these contain information that is not present in any combination of lower-order CFs, highlighting the complexity of their system. Furthermore, the authors showed that the CFs were in agreement with predictions of the sine-Gordon quantum field theory³, rather than with those of more-conventional and simple models of 1D quantum fluids⁷.

Although Schweigler and colleagues' study represents a powerful first demonstration of their technique, only a tiny fraction of the information present in their CFs was used. An n th-order CF is an n -dimensional function of the positions at which the measurements are taken, but the authors fixed all but two of these quantities — they restricted their study to 2D parameter spaces or, even more restrictively, looked at simple averages over all the positions. These simplifications made the authors' data easily tractable, but simultaneously erased most of the information present in their CFs. A crucial next step will therefore be to develop the theoretical and numerical tools required to interpret all the data present in these CFs and to fully characterize the corresponding quantum systems.

Moreover, the physics describing the authors' weakly interacting 1D quantum fluid was not under debate. However, their methodology might in future be applied to strongly interacting systems in which the underlying physics is not established. In particular, their technique is broadly applicable to 1D systems including disordered quantum systems of interacting atoms far from thermal equilibrium, in which the unknown physics of many-body localization⁴ is likely to be in play.

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Figure 1. Observing correlations in a quantum system

Schweigler *et al.*¹ report a method to probe the underlying physics of quantum systems. Their experiment consists of a pair of weakly interacting one-dimensional quantum fluids — thousands of rubidium-87 atoms at ultracold (nanokelvin-scale) temperatures. Each fluid acts like a wave whose shape can be described by a fluctuating phase (defining the position of the crest of the wave). The authors use a measurement technique called matter-wave interferometry⁵ to determine the relative phase between the fluids at various positions (dotted lines) along the length of the waves. They then use these measured correlations to test theoretical models of such systems.