Probing strongly-interacting quantum matter atom-by-atom in velocity space

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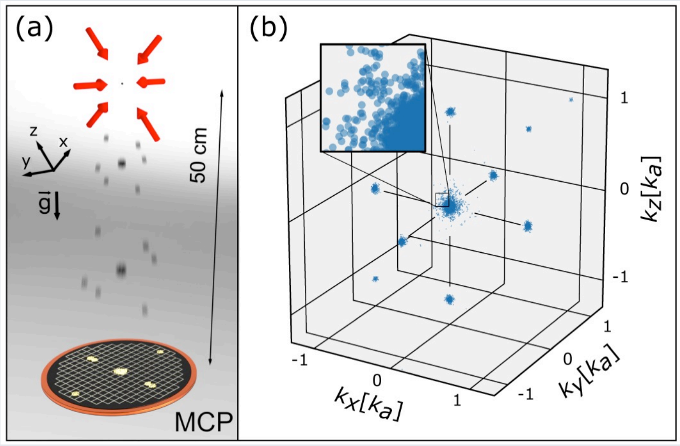
Solving problems regarding systems made of a large number of interacting quantum particles - many-body problems - is notoriously challenging. When both numerical and analytical theoretical methods fail to provide us with a satisfying answer, an alternative approach consists in finding an experiment simulating the many-body problem and allowing one to obtain information from a measurement. It requires an extreme control of the experiment to adequately implement many-body problems. To collect all the information about the system, it also needs detecting quantum particles individually, a pre-requisite to evaluate particle correlations at any order.

In this respect, the past decade has seen tremendous progress over the control of individual quantum objects like trapped ions, superconducting qubits and neutral or Rydberg atoms. All these platforms are capable of measuring spatial distributions and correlations between individual particles. But some paradigmatic manifestations of many-body peffects are elusive in spatial correlations, and multi-particle correlations between other degrees of freedom play a fundamental role. Our approach consists in investigating the velocity degree of freedom by measuring the momentum distribution of individual particles in quantum gases.



Our work exploits the properties of Helium-4 atoms brought to quantum degeneracy in a metastable state. In particular, the large internal energy of metastable Helium-4 yields the unique possibility to detect individual atoms in three-dimensions after a long time of free-fall with Micro-Channel Plates (MCP, see figure (a)). To benchmark the capabilities of this technique, we have loaded Bose-Einstein condensate of Helium-4 atoms into a three-dimensional crystal of light of relatively large amplitude and measure their momentum distribution (see figure (b)). In this situation, the celebrated Bose-Hubbard Hamiltonian that can be numerically solved with Quantum Monte-Carlo (QMC) describes the many-body groundstate. We have shown that the measured distributions perfectly match the QMC calculations. This work opens a new route to investigate interacting lattice systems through momentum correlations.

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