Scientific background for the 2025 Micius Quantum Prize: A brief history of quantum simulation with ultracold atoms in optical lattices

The field of quantum simulation has made remarkable strides in tackling problems that even the most powerful classical computers cannot solve. These advancements have a history spanning over four decades.

The concept of quantum simulation was first put forward by Feynman in 1982 [1]. He envisioned the use of "quantum machines" — systems constructed from quantum-mechanical components that obey quantum laws — to simulate any other quantum system, including the physical world itself. Essentially, quantum simulation harnesses a highly controllable quantum system to investigate complex, less manageable ones. The ultimate goal is to develop quantum simulators capable of solving intractable problems such as many-body problems in condensed matter physics and electronic structure problems in quantum chemistry.

The creation of the Bose-Einstein condensate in 1995 by Cornell, Wieman [2] and Ketterle [3], followed by the creation of the quantum degenerate Fermi gas by Jin in 1999 [4], ushered in a new era for atomic, molecular, and optical (AMO) physics. These ultracold atoms offer exceptional controllability: their internal quantum states and interparticle interactions can be precisely manipulated using lasers, magnetic fields, and radio/microwave fields. Such distinctive properties render ultracold atoms an ideal platform for building quantum simulators.

In 1998, a theoretical proposal by Jaksch, Bruder, Cirac, Gardiner, and Zoller at Innsbruck suggested using cold bosonic atoms in optical lattices to simulate the Bose-Hubbard model [5]. This model, introduced in 1989 in condensed matter physics, had proven challenging to study using conventional methods. Inspired by this groundbreaking idea, Greiner, Mandel, Esslinger, Hänsch, and Bloch at Munich experimentally realized the Bose-Hubbard model in 2002 [6]. Employing ultracold rubidium atoms in optical lattices, they observed the quantum phase transition from a superfluid to a Mott insulator. This pivotal achievement opened the door to using cold atoms in optical lattices as analog simulators to explore strongly-correlated many-body physics, effectively bridging AMO physics with condensed matter physics.

Subsequent breakthroughs emerged in 2008 when Esslinger's group at ETH and Bloch's group at Munich independently realized the Fermi-Hubbard model by employing fermionic potassium atoms in optical lattices [7,8]. The Fermi-Hubbard model is particularly important in condensed matter physics, as it is believed to capture the essential physics of high-temperature superconductivity. This accomplishment enabled the simulation of electrons in solids using fermionic atoms, opening an exciting avenue to explore strongly-correlated electron systems using ultracold atoms.

In 2009, Greiner's group at Harvard and, in 2010, Bloch's group independently developed the quantum gas microscope for bosonic atoms in two-dimensional optical lattices, allowing for single-site-resolved imaging of atoms [9,10]. In 2015, this technique was extended to fermionic atoms by several groups, including those of Zwierlein at MIT, Kuhr at Glasgow, Thywissen at Toronto, as well as the Greiner and Bloch groups [11-15]. These advancements enabled the direct observation of strongly-correlated many-body states and their correlation functions at the single-atom level.

Over the past two decades, quantum simulation with ultracold atoms in optical lattices has undergone dramatic expansion. A series of landmark experiments has demonstrated how the analog quantum simulator can be employed to comprehensively investigate quantum phases, transport phenomena and topological effects. For instance, in 2011 DeMarco's group observed three-dimensional Anderson localization of quantum matter using fermionic atoms in optical lattices [16]. In 2012, Bloch's group integrated Rydberg long-range interaction into a two-dimensional neutral atom array and later observed the quantum crystal structures in Rydberg excitations [17,18]. These experiments largely inspired the quantum simulations with Rydberg atoms in reconfigurable atom arrays. In 2014, Esslinger's group realized the topological Haldane model [19], a topological model related to anomalous quantum Hall effects introduced in 1988, by periodically modulating ultracold atoms in optical lattices. Subsequently, they realized supersolid states by combining atoms in optical lattices with optical cavities [20]. In 2015, Sengstock's group engineered the Berry curvature of the Bloch bands and observed a full momentum-resolved measurement of the Berry curvature [21]. Bloch's group observed many-body localization in both bosonic and fermionic atoms in optical lattices [22,23]. In 2017, Pan's group demonstrated four-body ring-exchange interactions and observed fractional statistics of anyonic excitations within a toric-code Hamiltonian [24]. In the same year, Greiner's group observed antiferromagnetic long-range order in the two-dimensional Fermi-Hubbard model [25] and subsequently realized fractional quantum Hall states using two bosonic atoms in optical lattices [26]. In 2020, Pan's group achieved extremely low entropy Mott insulator samples in two-dimensional optical lattices by employing a novel cooling method with removable superfluid reservoirs [27]. In 2023, Zwierlein's group observed nonlocal fermionic pair in an attractive Fermi-Hubbard gas [28]. Most recently, Pan's group observed antiferromagnetic phase transition in a three-dimensional fermionic Hubbard model [29].

Besides simulating condensed matter physics, quantum simulation with atoms in optical lattices has expanded into other domains, such as simulating lattice-gauge models in high-energy physics [30]. There are also proposals to employ quantum simulations with atoms in optical lattices to tackle the electronic structure problem [31], a central challenge in quantum chemistry. Quantum simulation in optical lattices has also been extended to more complex quantum systems such as polar molecules, enabling the simulation of quantum magnetism [32,33].

The pioneering research led by Immanuel Bloch, Tilman Esslinger, and Markus

Greiner has laid the foundations for the rich and rapidly evolving field of quantum simulation with atoms in optical lattices. In recognition of their contributions, the selection committee has awarded them the 2025 Micius Quantum Prize.

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