

Control of quantum many-body correlations

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At a glance

This text outlines opportunities arising from the rapidly developing capability to control many-body correlations in solids and in cold atomic gases.

Definition of research

Quantum many-particle systems can exhibit collective phenomena that are inconceivable in their classical counterparts. The spontaneous formation of macroscopic quantum phase coherence in superfluids and superconductors is a particularly striking example, which illustrates that revolutionary applications are conceivable if collective quantum phenomena could be stabilized under ambient conditions. Unfortunately, however, almost all quantum many-particle states known to-date were discovered by pure chance, and it has proven very difficult to manipulate their properties in a controlled fashion. Can we move beyond this haphazard discovery process and into a mode of research that allows purposeful control of quantum many-body correlations? Can we design new collective many-body states and systematically optimize their functionality? Several parallel current developments suggest that decisive progress will be made on these issues within the next decade. They are unfolding in two traditionally separate research fields, namely solid-state physics and atomic physics, which are rapidly building up fruitful interactions and synergies.

Status of the field

The objectives and methodologies of both research fields have traditionally been rather different, but each has left its own imprint on the emerging interdisciplinary field. The idea of *controlling* quantum-mechanical correlations of independent atoms or ions by light fields has its origin in atomic physics. At the frontier of this field, it is now possible to create and coherently manipulate entangled states of photons and atomic excitations inside cavities, and to perform simple quantum computations with arrays of trapped ions. Whereas single atoms are limited in size, electrons in solids naturally allow *many-body physics* in the thermodynamic limit. Collective many-body phenomena of topical interest include unconventional superconductivity in *d*- and *f*-electron materials; “quantum Hall” states in which electrons in semiconductors form fractionally charged composite particles; electronic analogs of liquid-crystals; “spin liquid” states in which the charge of the electrons is localized but their spins condense into a collective singlet wave function; and “spin ice” states that can host magnetic monopole excitations [1]. Tuning external parameters such as pressure and magnetic field has led to the discovery of many new quantum phases in recent years, and zero-temperature transitions between such phases (where the correlation length for critical quantum fluctuations reaches macroscopic dimensions) have grown into a rich field of investigation [2]. The thermodynamic, spectroscopic, and transport properties determined by experiments as well as analytical and numerical calculations have elucidated some of the mechanisms underlying quantum phases and phase transitions, although the resulting understanding is still far from complete.

The nascent field of “quantum engineering” has emerged from recent advances in our ability to control electronic correlations in solids, and to create genuine many-body phenomena with cold atoms. *Control of quantum correlations in solids* has progressed farthest in semiconductors, where decades-long research has produced bulk specimens with extremely low levels of uncontrolled impurities and disorder. Using modern nanostructuring or self-assembly methods, it is now possible to confine electrons to tailored wavefunctions in zero, one, or two dimensions (quantum dots,

quantum wires, and quantum wells). In semiconductor quantum dots (also termed “artificial atoms”), for instance, the electron density and the shape of the confining potential can be tuned to a much greater extent than in real atoms. Research on quantum dots has thus provided an early focus of the interaction between atomic and solid-state physics. It has also proven possible to tune the superposition of several dimensionally confined wavefunctions, by virtue of varying either their spatial separation or the height of the potential barrier between them. This approach has been applied successfully to pairs of quantum wells, wires, and dots, and it has revolutionized our understanding of the Kondo effect, an archetypical many-body phenomenon that arises from coupling of a discrete set of quantum-mechanical degrees of freedom to a bath of conduction electrons. Current research on the Kondo effect illustrates the variety of control strategies that are now being pursued by solid-state physicists: The effect has been realized by coupling semiconductor quantum dots, carbon nanotubes, or single-molecule magnets to metallic leads, and by using scanning probes to couple single magnetic atoms to metallic surface electrons. These strategies offer unprecedented levels of tunability of both the coupling strength and the number of coupling channels. The past few years have also seen rapid progress on the preparation of *d*- and *f*-electron based bulk materials with exceptionally high purity. Atomically sharp heterostructures of complex *d*-electron compounds have recently been synthesized, opening up tantalizing opportunities for wave function engineering along the lines of semiconductor physics [3].

In atomic physics, the realization of Bose condensation 15 years ago has kick-started a new era of genuine *many-body physics with cold atomic gases* [4]. In fact, the Bose condensate of neutral (and hence weakly interacting) atoms was probably the first quantum many-body state “engineered” on the basis of a theoretical blueprint. In the years since then, it has proven possible to control the strength of the interatomic interaction in these gases over a wide range, and into a regime comparable to that of strongly correlated electrons in solids. Another important step towards convergence of both research fields was the development of optical lattices imposing a periodic potential on the cold atoms. Atoms in these lattices were shown to occupy wavefunctions with symmetry properties akin to those of electrons in solids. In this way, many-body phenomena including the Mott-Hubbard superfluid-insulator transition induced by repulsive interactions and the crossover from the Bose condensate to a Bardeen-Cooper-Schrieffer condensate (the many-body state believed to describe the electron system in a superconductor) could be explored in quantitative detail. At the same time, spatially anisotropic optical lattices (the analog of quantum wires in semiconductor physics) allowed detailed tests of concepts in one-dimensional physics.

Future directions

Despite the very different “hardware”, quantum many-body physics in solids and cold atoms has thus reached a high degree of synergy and complementarity. On the one hand, the virtually unlimited variety of compounds and lattice architectures made possible by the periodic table of elements continues to provide a highly fertile ground for discovery of new many-body states. These phenomena can be experimentally explored over a wide range of external conditions (in some cases already including room temperature) and are thus potentially amenable to technological applications. On the other hand, cold-atom physicists can tune both the strength of the interatomic interaction and the depth and shape of the optical lattice potential to a much greater extent than it is possible in solids. This offers the opportunity to experimentally realize systems which are exactly described by simple model Hamiltonians invented by theorists in order to elucidate the principles underlying electronic many-body phenomena in solids, where complications arising from uncontrolled disorder or uncontrolled coupling to lattice distortions are nearly always present. The resulting insights can then feed back into the quantitative description of observations in the solid state.

This approach has been tested and validated for bosonic systems, whose many-body correlations had already been well known from prior analytical and numerical work [4]. A major current

challenge is to extend it to fermionic systems, whose correlation functions and physical properties are notoriously difficult to compute. Even for elementary fermionic many-body Hamiltonians, such as the two-dimensional Hubbard model, the ground state and excitation spectra are thus still largely unknown, despite much progress in recent years. Yet it is models such as these that are widely believed to hold the key to some of the most fascinating phenomena in solid-state physics, including unconventional superconductivity. Over the next decade, experimental atomic and solid-state physicists together with many-body theorists (many of whom already pursue projects bridging both areas) will mount a concerted attack on these deep and challenging scientific problems. The outcome will comprise a largely enhanced understanding of the physical properties of quantum many-particle systems, and building on this, a rapidly increasing ability to control their physical properties.

Motivated by the intriguing fundamental questions posed by research on quantum magnetism, and by the growing consensus that spin fluctuations are the key driving force of unconventional superconductivity in metals, many-body correlations between *quantum spins* will be a strong focus of this synergistic effort. As atomic physicists are beginning to be able to design and control spin Hamiltonians on optical lattices and to probe their excitation spectra, cold-atom systems are expected to serve as “quantum simulators” of many-body problems that have thus far defied analytical or numerical solution, including especially correlated fermions in low-dimensional and/or geometrically frustrated networks (Fig. 1). Owing to the continuous tunability of the model parameters, investigation of these systems promises to greatly advance our understanding of the influence of spin correlations on the equilibrium phase behavior. In solid-state physics, the ability to build up magnetic nanostructures on solid surfaces atom-by-atom and to probe magnetic correlations by spin-polarized scanning probes opens up novel opportunities to study and control quantum spin correlations. Further, high-quality heterostructures of complex *d*- and *f*-electron materials offer a clear path towards controlling the exchange interactions of a macroscopic number of electrons. In particular, the occupation of *d*-orbitals that controls the superexchange interaction in metal oxides can be tuned through epitaxial strain and/or covalent bonding at heterointerfaces (Fig. 2). Advances in many-body theory combined with modern ab-initio computational methods that account for the chemical specificity may then allow systematic design of spin Hamiltonians in metal oxide heterostructures and superlattices [3]. A long-term vision of this concerted effort is to use the enhanced understanding and control in order to stabilize collective quantum phenomena such as superconductivity at room temperature.

Another long-term vision that will continue to inspire research on quantum many-body physics is that of a *quantum computer* that takes advantage of non-local correlations in order to solve computational problems (such as the factorization of large numbers) that are currently intractable. Individual quantum bits (“qubits”) can now be realized in the form of atoms, molecules, or ions either confined to optical traps or implanted in solids, or in the form of solid-state micro- or nanostructures. While it seems unlikely that experiments designed to control the coupling of multiple qubits and to eliminate decoherence will scale up to a bona-fide quantum computer within the next decade, there is no doubt that more limited devices will lead to novel applications in quantum communication and cryptography [4]. Operation of such devices will also yield important new insights into quantum information theory, which may in turn stimulate the development of novel computational methods for many-body problems [5]. Another approach to quantum computation that is just beginning to be explored takes advantage of the topological structure of certain many-body wavefunctions (including those describing some quantum Hall states and unconventional superconductors, and possibly cold-atom systems designed for this purpose) in order to avoid decoherence [6]. Independent of its promise for quantum computation, “quantum engineering” of topologically nontrivial wavefunctions opens up completely new perspectives for many-body physics.

Whereas current experimental and theoretical methodology is mostly based on the notion of thermodynamic equilibrium, research in the next decade will also increasingly exploit the possibility to modify the external conditions *dynamically*, on a timescale comparable to or shorter than the natural response time of the internal quantum variables. In cold-atom systems, for instance, the optical potential can be adjusted faster than it takes interatomic interactions to establish equilibrium [7]. And in modern pump-probe experiments on solids, the relaxation of the electron system back to equilibrium after a particular collective mode (such as a lattice vibration or spin wave) has been launched can be coherently monitored on a femto- (and in the future perhaps atto-) second timescale. These dynamical control methods provide access to a multitude of new collective many-body states far from equilibrium that can be studied in detail and may offer completely new functionalities. The development of experimental methods to probe these states and theoretical methods to describe them is an intriguing research challenge for the next decade.

Realizing the tremendous potential of quantum many-body correlations for fundamental and applied research will require a significant investment in research infrastructure. For instance, new experimental methods have to be developed and implemented to cool gases of fermionic atoms or molecules and to probe their correlation functions; to develop hybrid devices comprising solid-state nanostructures and cold-atom systems; to synthesize new correlated-electron materials and structure them with atomic precision; and to detect and analyze the massive amount of data expected from the next generation of large-scale facilities for condensed matter research (such as neutron spallation sources and x-ray free-electron lasers). In addition, new ways to communicate and collaborate among the traditionally separate research centers concentrated on atomic and solid-state research will have to be explored in order to fully develop “quantum engineering” as a truly interdisciplinary research field.

Scientific reviews with references to original research papers

[1] Concepts in solid-state many-body physics: R. Moessner and K.S. Raman, *Quantum dimer models*, Lecture Notes Trieste 2007, available at www.arXiv.org/abs/0809.3051

[2] Quantum criticality: P. Gegenwart, Q. Si, and F. Steglich, *Quantum criticality in heavy-fermion metals*, Nature Physics **4**, 186 (2008)

[3] Transition metal oxides: B. Keimer, *Perspectives in orbital physics*, Proceedings of the 24th Solvay conference on physics (World Scientific, Singapore, in press)

[4] Many-body physics with cold atoms: I. Bloch, J. Dalibard, and W. Zwerger, *Many-body physics with ultracold gases*, Reviews of Modern Physics **80**, 885 (2008)

[5] Quantum information theory and computational many-body physics: F. Verstraete, V. Murg, and J. I. Cirac, *Matrix product states, projected entangled pair states, and variational renormalization group methods for quantum spin systems*, Advances in Physics **57**, 143 (2008)

[6] Quantum information processing: P. Zoller *et al.*, *Quantum information processing and communication*, Eur. Phys. J. D **36**, 203 (2005)

[7] Topological quantum computation: C. Nayak, S. H. Simon, A. Stern, M. Freedman, and S. Das Sarma, *Non-Abelian anyons and topological quantum computation*, Rev. Mod. Phys. **80**, 1083 (2008).

Figures

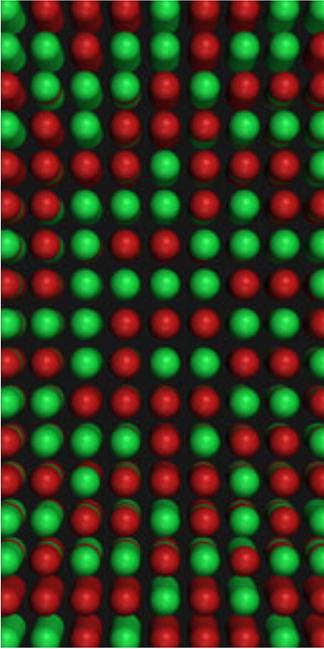


Fig. 1 Mott-insulating state generated by strong many-body correlations between cold fermionic atoms on an optical lattice. The colors denote different spin states of the fermions. Researchers at the MPI for Quantum Optics and their collaborators have shown that this system shows promise as an efficient "quantum simulator" of many-body problems that are intractable by current computational methods (U. Schneider *et al.*, *Science* **322**, 1520 (2008)).

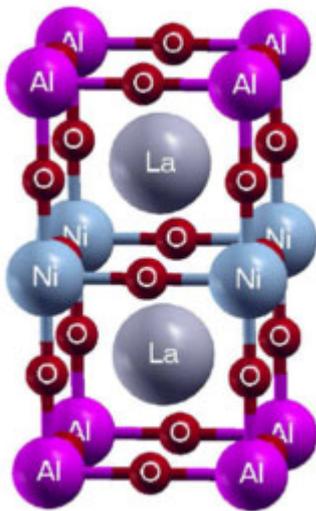


Fig. 2 Heterostructure of the correlated-electron metal LaNiO₃ and the wide-gap band insulator LaAlO₃. According to analytical and numerical many-body calculations by researchers at the MPI for Solid State Research, this system is a candidate for "engineered" high-temperature superconductivity (J. Chaloupka and G. Khaliullin, *Phys. Rev. Lett.* **100**, 016404 (2008); P. Hansmann *et al.*, *Phys. Rev. Lett.* **103**, 016401 (2009)). Experimental work to test this prediction is in progress at the same institute.