PERSPECTIVES

National Science Review
3: 168–173, 2016

PHYSICS

Special Topic: Cold Atoms

Ultracold atomic gases going strong

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The year 2015 marks the 20th anniversary of the achievement of Bose–Einstein condensation (BEC) in atomic vapors. Atomic BEC, realized by Eric Cornell, Carl Wieman and Wolfgang Ketterle in 1995, commenced an exciting wave to explore quantum few- and many-body physics. Different from solid state matter and helium superfluids, atomic condensates in the gas phase come with drastically lower densities and temperatures, which place the systems in a unique regime where the atomic interactions are simple and precisely known. Furthermore, the condensates are typically weakly interacting: the interaction length scale of few nanometers is much shorter than the interatomic separation of hundreds of nanometers. Thus many early experimental observations can be well understood based on mean-field theory. One celebrated model is the Gross-Pitaevskii equation which provides a precise and quantitative description of weakly interacting Bose condensates [1].

Opportunities to extend cold atom research beyond the weak interaction regime emerged in the early 2000s. Several experimental schemes were developed to prepare atoms in the strong correlation and interaction regimes. One approach is loading atoms into an optical lattice, the interference pattern of laser beams. The lattice potential enhances the interactions of localized atoms and quenches their kinetic energy. A variety of lattice configurations are realized that promise novel quantum phases of ultracold atoms. Another route to strong interaction is based on Feshbach resonance, typically induced by magnetically shifting a molecular state near the scattering continuum of atoms. The resonant coupling between scattering atoms and the molecular state leads to a divergence of the atomic interaction length scale. Exactly on Feshbach resonance, the collision cross section reaches the quantum mechanical limit, and the system becomes strongly hydrodynamic with mean-free path as short as interparticle separation.

Fascinating observations in the strong coupling regime soon followed: prominent examples include the superfluid-Mott insulator transition in optical lattices [2], resonantly interacting Fermi gases in the BEC–BCS (Bardeen–Cooper–Schieffer superfluid) crossover [3] and Efimov three-body states [4], and they lead to tremendous research interest into novel quantum states and quantum dynamics. One of the key motivations in these explorations is to uncover new, universal principles that underpin the physics of strongly correlated quantum systems.

A well-studied universal behavior in many-body physics manifests in the critical phenomena near a continuous phase transition. Near the critical point, the system develops a diverging correlation length, which suppresses the dependence on other microscopic length scales. The systems are thus scale invariant and can be universally characterized by a few critical exponents. In cold atoms, divergence of correlation lengthes has been observed near the superfluid phase transition [5,6], as well as the superfluid-Mott insulator quantum phase transition in optical lattices. In the lattice experiments, scale invariance can be tested based on the equation of state measurements [7]. These works complement the transport measurements in condensed matter experiments.

Has a new class of universal physics been discovered in atomic quantum gases? Yes, it turns out that a special class of strongly interacting quantum gas with 'intrinsic' scaling symmetry emerges near a Feshbach resonance [8]. Near the resonance, the scattering length scale diverges $a \to \infty$ [9], unimaginable in classical systems, and the interaction length reaches the maximum value allowed by quantum mechanics as $1/k$, called the 'unitarity limit' and k is the momentum of the scattering state. A famous example is the strongly interacting Fermi gas in the BEC–BCS crossover regime, where the resonant interactions lead to strong pairing and and universal hydrodynamic behavior.

An exciting development in the study of the BEC–BCS crossover focuses on the Fermi gas exactly on Feshbach resonance. Here the system, also called a 'unitary Fermi gas', is the most complex and strongly correlated. The resonant interaction, however, implies a special scaling symmetry of the system. To understand the symmetry, we consider a scale transformation: $x \to \Lambda x$ that stretches the coordinates of all atoms by a factor of Λ, and thus reduces the atomic density n by a factor of Λ^3 in a 3D gas and the kinetic energy $E_k \propto -\nabla^2$ by Λ^2. One can see that both kinetic energy E_k and interaction energy in the unitarity limit $na \rightarrow n/k$ are reduced by the same factor Λ^2. The system is thus hypothesized to be invariant under the scale transformation [8]. Remarkably, similar scaling symmetry also holds for 2D quantum gas with a constant coupling $g = \text{const.}$ [10]. Here stretching the size of the 2D gas by a factor of Λ also reduces both the kinetic E_k and interaction energy $g\sigma$ by Λ^2, where σ is the 2D density. Since the scaling symmetry in these systems comes directly from the form of the interactions, intrinsic scale invariance is robust at all temperatures T and chemical potentials μ and does not rely on the proximity to a phase transition.

The scaling symmetry suggests that the only independent variables are the ratios of the length scales or the equivalent energy scales. In a grand canonical ensemble, the independent ratio can be chosen as μ/k_BT. This realization greatly simplifies theoretical description as well as the experimental characterization of the system. Theoretically, a new set of universal thermodynamic relations are expected to be insensitive to the microscopic details; experimentally, measurements are expected to collapse into universal functions that only depend on μ/k_BT. Measurements on unitary Fermi gas and the 2D Bose gas are consistent with the scaling hypothesis, shown in Fig. 1(a) and (b). Remarkable quantitative agreement between measurements and calculations has greatly advanced our understanding of the 'unitary Fermi gas' and 2D atomic gas.

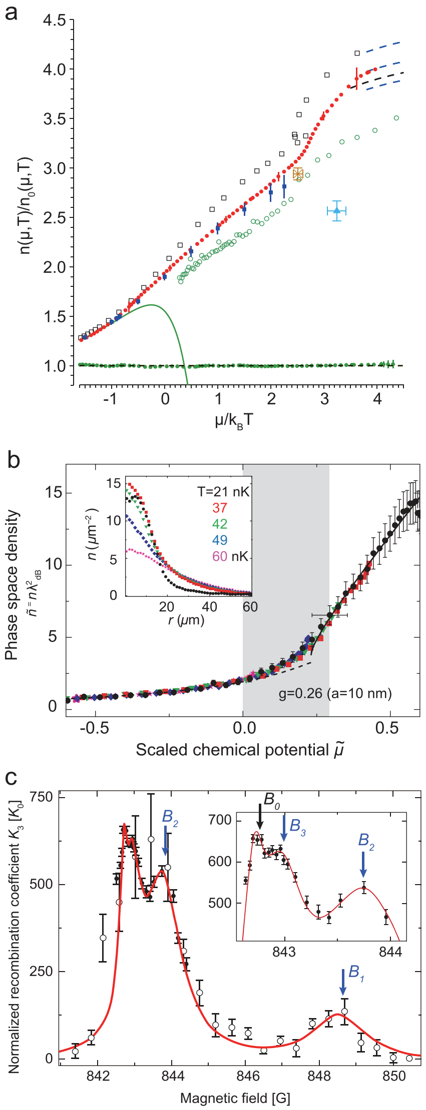

Figure 1. Ultracold atomic gases which are intrinsically scale invariant: (a) unitary Fermi gas, (b) 2D Bose gas and (c) unitary Bose gas. The scaling symmetry suggests that thermodynamic observables only depend on the ratio of chemical potential and thermal energy $\tilde{\mu} = \mu/k_BT$. In (a), thermodynamic pressure of a unitary Fermi gas is compared with calculations and other measurements. Figure courtesy of M. Zwierlein [11]. In (b), the collapse of the density measurement at various temperatures (inset) confirms the scaling symmetry. Figure adopted from [12]. Panel (c) shows the three-body loss spectrum in a ^{6}Li^{133}Cs mixture. The geometric progression of the Efimov resonance positions at $B = B_1$, B_2 and B_3 toward the Feshbach resonance at B_0 results from the discrete scaling symmetry of Efimov physics. Figure adopted from [13].

We may expect the same scaling symmetry for a resonantly interacting Bose gas. Here, however, the scaling symmetry is more subtle because of the presence of three-body physics. Predicted by Vitaly Efimov in the context of nuclear physics [14], an infinite number of three-body bound states exist for resonantly interacting bosons and their energies follow a discrete scaling law, breaking the otherwise continuous scaling symmetry. Identical fermions do not form such three-body states due to Pauli's exclusion principle. Theoretically the three-body bound states are supported by the 'Efimov potential' $V(R) \propto -1/R^2$, where R is the characteristic length scale of the three interacting atoms. While the Efimov potential does not break the continuous scaling symmetry, the presence of discrete three-body states does break the symmetry. An alternative picture based on renormalization group limited cycles [15] also explains the discrete scaling symmetry of the system, a scenario that rarely happens in electronic systems. Experimentally, Efimov states have been observed in cold gases of alkali atoms, as well as in helium-4. The geometric scaling symmetry of Efimov states is reported in a recent experiment, shown in Fig. 1(c). The same discrete scaling symmetry is expected for unitary quantum gas of bosons, which, if confirmed, will establish a unique and fascinating class of strongly interacting quantum systems.

While in this article, we focus on atoms in optical lattices and unitary atomic gases as primary examples of universal physics that have been actively investigated, efforts in many new research frontiers have shown promising prospects to uncover new universal physics in the strongly correlated and interacting systems. Non-equilibrium dynamics is one of the hottest directions. Ultracold atoms are particularly suited for the study of quantum dynamics due to their slow evolution time scales of miniseconds to seconds. Dynamics near a quantum phase transition and the thermalization of isolated quantum systems are two research topics with many unanswered questions. Cold atom experiments may provide new universal insights that go beyond current theoretical framework.

Another exciting direction is quantum many-body systems with long range or very strong interactions. Examples include trapped ions, and condensates of exotic atoms with huge magnetic dipole moments, polar molecules, as well as those with Rydberg excitations. These systems possess various long range interactions. Novel universal dynamics, for example, propagation of information and entanglement, are predicted to depend solely on the asymptotic form of the interaction and the dimension of the systems.

ACKNOWLEDGEMENTS

The author thanks Yijun Wang for discussion and careful reading of the article.

FUNDING

This work was supported by National Science Foundation (PHY-0747907) and Army Research Office-Multiple University Research Initiative (W911NF-14-1-0003).

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doi: 10.1093/nsr/nwv073
Advance access publication 9 November 2015

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Quantum-gas microscopes: a new tool for cold-atom quantum simulators

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Imagine a new generation of computers that dramatically surpasses the most powerful supercomputers, being able to tackle the most challenging of computational problems. These problems arise, for example, in quantum physics where the computational power required to model a many-particle system increases exponentially with the number of its constituents, and as a consequence the calculations become prohibitively time-consuming. Nobel laureate Richard Feynman proposed this new type of computer in the early 1980s: 'Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws.'

Such a quantum simulator would allow researchers to tackle challenging problems in condensed-matter physics. In particular many-body fermionic quantum systems are very difficult to compute due to the antisymmetric nature of the wave function, and the resulting sign problem for quantum Monte Carlo methods. This is why a quantum simulator will be an excellent test bed to investigate phenomena and properties of strongly correlated fermionic quantum systems.

A powerful experimental platform to realize a quantum simulator is laser-cooled atoms [1] held in an artificial crystal of light, generated by superimposing laser beams. The atoms are kept in this optical lattice similar to marbles in the hollows of an egg carton, and they can mimic the behaviour of electrons in a real crystal. These systems interface atomic physics with condensed matter physics in a new way, as the tools of atomic physics allow for exquisite control of many experimental parameters, which are often inaccessible in solid state experiments.

In-situ imaging techniques [2] using 'quantum-gas microscopes' constitute a new approach to the study of many-body quantum systems in an optical lattice with unprecedented resolution at the single-particle and single-site level [3,4]. This new method is complementary to earlier optical lattice experiments measuring distributions in momentum space after a time-of-flight expansion. A quantum-gas microscope uses an optical imaging system (Fig. 1a) for collecting the fluorescence light of ultracold atoms in an optical lattice with high spatial resolution comparable to the lattice spacing of ≈ 500 nm.

Fluorescence imaging of atoms in a quantum-gas microscope has made it possible to directly observe bosonic Mott insulators with single-atom resolution [4–6], giving access to *in-situ* measurements of temperature and entropy distributions. Subsequently, ground-breaking experiments in many-body quantum dynamics have been performed, such as