ULTRACOLD SUPERFLUIDS

BY JOSEPH H. THYWISSEN

The field of ultracold atoms was born in 1995, when Eric Cornell and collaborators observed Bose-Einstein condensation (BEC) of a gas of magnetically trapped alkali atoms. Today, roughly one hundred laboratories work with quantum degenerate neutral atoms, in seventeen countries [1] including Canada. Theorists who contribute to the field come from a wide range of disciplines, including condensed matter, atomic physics, high energy physics, and quantum information.

It is safe to say that both the growth and the accomplishments of cold atoms have exceeded all expectations of the 1990's. After all, what could a "plain vanilla" Bose condensate contribute to 21st-century condensed matter physics? The study of superfluids and superconductors is a well established field, with impressively advanced techniques and theories, as reviewed throughout this Special Issue.

The power of the cold-atom approach is in its *progressive complexity*. Superconducting heterostructures, such as cuprates and pnictides, are inherently complex. In contrast, cold atom experiments can be confined in simple or sophisticated geometries, and can be tuned from weak to strong interactions. In the next few pages, we explain this approach and give a few examples of its success. We do not attempt to give a complete set of citations here, but we refer the reader to reviews [2–6] and textbooks [7–9] for full references.

SUMMARY

Superconductors are roughly a billion times more dense than neutral gases, but the physical principles of gases and solids have a surprising similarity in their quantum degenerate regimes. In this brief review, we trace a historical path from the early days of weakly interacting Bose condensates to current research in strongly interacting Fermi degenerate gases. Cold atoms can be viewed as quantum simulators able to address open questions about many-body systems. Also tantalizing: if the physics of resonant ultracold superfluids could be reproduced in solids, the critical temperature of superconductivity would be roughly 1000 K, well above room temperature.

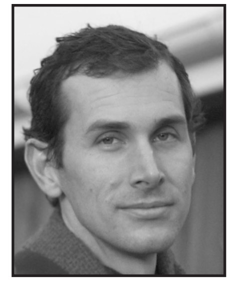
STRONG INTERACTIONS

A student who has taken a course on statistical mechanics can open their textbook, apply Einstein's criterion for Bose condensation, and get quantitative agreement with the critical temperature T_c of the 1995 experiments (see also Fig. 1). A thermal gas is nearly ideal (non-interacting), in contract to liquid helium at its lambda point, where Einstein's criterion gives a T_c that is 50% too high. Even in a Bose-condensed gas, interactions can be treated with a relatively simple approach. The Gross-Pitaevskii (GP) equation [5], a mean-field treatment from the 1960's which never worked very well for liquids or solids, is an excellent description of a Bose-condensed gas of neutral atoms. At low temperature the condensate fraction of a Bose-condensed gas is nearly 100%, in contrast to liquid helium where interactions deplete the condensate to roughly 10% of the total density.

Although this state of affairs was celebrated for its textbook-like clarity, it was unclear at first what contribution ultracold gases could make to the cutting edge of many-body physics. Open questions in condensed matter typically concern systems in which the interaction energy per particle is equal or greater than its single-particle (kinetic plus potential) energy. These strong interactions induce strong correlations between particles, causing mean-field approaches such as the GP equation to fail. In contrast, the first ultracold Bose condensates [10] and Fermi degenerate gases [11] were weakly interacting.

Strongly interacting gases were subsequently created with two basic strategies: decreasing single-particle energy with optical lattices, or increasing interaction strength with Feshbach resonances. In an optical lattice, a spatially periodic potential is created using the Stark effect of a standing wave of laser light. Neutral atoms that move in this potential acquire a band structure, just as free electrons do in a crystalline solid. As the depth of the optical lattice is increased, kinetic energy of the atoms is decreased due to a flatter dispersion relation [12]. In this way, the ratio of interaction energy to kinetic energy can be increased into the strongly interacting regime. Note that the lattice depth is proportional to the laser power, so it can be turned on and off dynamically — unlike the band structure of a solid.

The second strategy to create strongly interacting neutral gases is to tune their interaction energy. Interaction potentials between neutral atoms have a length scale of a



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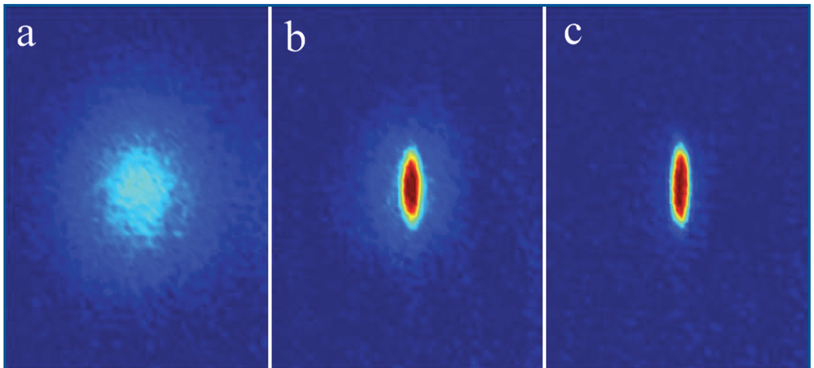

Fig. 1 **Bose-Einstein Condensation.** Absorption images of a cloud of atomic rubidium crossing the critical temperature in Toronto. The color scale (from blue to red) represents integrated density. **a)** At 960 nK, a cloud of 1.2×10^5 atoms is thermal; **b**) At 360 nK, a cloud of 7×10^4 atoms is below the critical temperature, and a Bose condensate appears, mixed with a thermal cloud; **c)** At even lower temperature, no thermal fraction is evident, and thus all 4.5×10^4 atoms are Bose condensed. Images are 0.5 mm across, and taken after 10 ms of free-flight expansion. For further details, see Ref. [13].

nanometer — hundreds of times smaller than the typical inter-particle distance in a gas, and thus interactions can be considered pair-wise. At the sub-microkelvin temperatures of quantum degeneracy, two colliding atoms have too little energy to overcome a centrifugal barrier in their center-of-mass frame, so interactions are restricted to those with no orbital angular momentum, *i.e.* to "s-wave" collisions. Together these two conditions simplify interactions tremendously: the only memory an atom has of a collision is the phase it accumulated. This phase can be parameterized with a "scattering length". Once measured, this single parameter tells a theorist or an experimentalist all they need to know about the interaction. Furthermore, if one can modify that phase, one is able to tune the interaction strength.

In the presence of a magnetic field, free atoms and molecules experience different Zeeman shifts since their magnetic dipole moments are not equal. At certain serendipitous values of the field, this differential Zeeman shift can bring a bound dimer state into resonance with the energy of two asymptotically free atoms. This condition is called a Feshbach resonance [4]. Even though atoms do not actually form a dimer, the phase shift of their s-wave collision is modified by the proximity to the resonance [14]. As a result, by using a magnetic field, the ultracold gas can be tuned from weakly to strongly interacting.

Using these two approaches, several lines of work have been pursued. In the context of this Special Issue, we will focus on conceptual issues concerning superfluidity. However in passing we will mention that other areas of study include magnetism [15], artificial gauge fields, controlled disorder [16], insulating states of bosons and fermions [2,3], few-body bound states, quantum gates, quantum memory, cold molecules [17], low-dimensional systems, and non-equilibrium physics.

RESONANT SUPERFLUIDS

The BCS theory of superconductivity tells us that the critical temperature is proportional to the pairing gap. Although BCS is valid only for weak interactions (compared to the Fermi energy, E_F), it motivates the exploration of high pair energy in search of high-temperature superfluids. With Feshbach control, ultracold fermionic atoms can be tuned to unitarity-limited interactions — the strongest allowed by conservation of probability in a scattering event. In this limit, Deborah Jin [18] and colleagues observed superfluidity that occurs at around $0.2T_F$, where $T_F = E_F/k_B$, and k_B is the Boltzmann constant. If this same behavior could be replicated in solids, where the typical T_F is tens of thousands of kelvin, the critical temperature of superconductivity would be 1000 K. In other words, if the goal of room-temperature superconductivity were scaled to the Fermi energy of the system, it has already been achieved (ironically) in nanokelvin gases.

The physics of this *resonant superfluid* has an interesting kind of universality because its properties do not depend on the particular type of interaction in question. The same thermodynamics, critical temperature, etc. would occur in neutrons stars or metals, if their interactions (whose microscopic origins differ from neutral atoms) could be tuned to resonance. Perhaps the most provocative connection is to the dense quark-gluon plasma, currently being studied at RHIC (relativistic heavy ion collider). Both systems may be creating perfect fluids that probe the quantum limits of viscosity, as conjectured by string theory [19].

The resonant regime also provides an important conceptual unification between fermionic and bosonic superfluids. Sweeping across the Feshbach resonance, experimentalists can dynamically transform a paired BCS superfluid to a Bose-Einstein condensate of molecular dimers. This shows us that the only distinction between Cooper pairs and molecules is the ordering of the interatomic and inter-pair length scales, but the physics is continuous across the BEC-BCS crossover [9].

What could break such a strong superfluid? Since composite bosons require fermions of distinct spins, one can certainly prevent superfluidity by polarizing the sample: a Fermi gas of one spin state is simply noninteracting. However a question debated in the literature was whether a critical polarization (called the Chandrasekhar-Clogston limit) existed, beyond which superfluidity could not occur [20]. This question was answered by Wolfgang Ketterle and collaborators, observing a Chandrasekhar-Clogston limit of 36% [21]. Above this limit, the Fermi surfaces are too far apart to be bridged by the pairing interaction.

However not all superfluids need to find the same number of up- and down-spin partners. Forty years ago, Fulde and Ferrell,

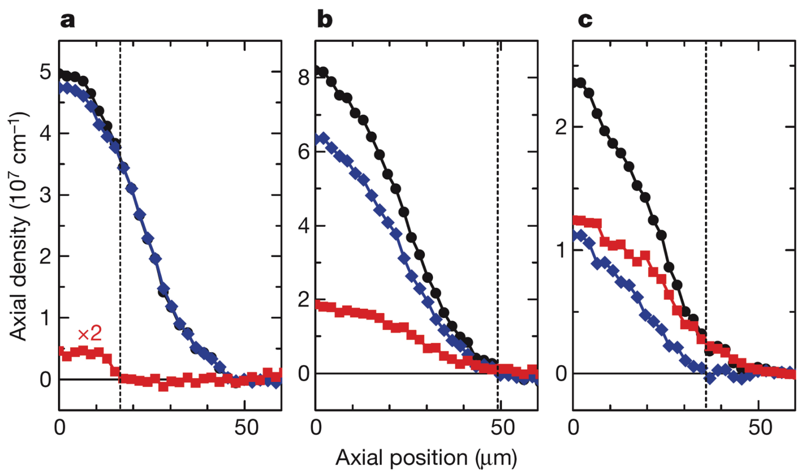

Fig. 2 **Observation of a partially polarized Fermi superfluid.** Cold atoms in one-dimensional tubes show density profiles that are consistent with a FFLO-type pairing. Integrated axial density profiles of the tube bundles (black circles represent the majority, the blue diamonds represent the minority, and the red squares show the difference) are shown as functions of central polarization P. **a**) At low P (= 0.015), the edge of the cloud is fully paired and the density difference is zero. The centre of the cloud is partially polarized. The density difference has been multiplied by two for better visibility of the phase boundary (dashed black line); **b**) Near P_c (P = 0.10), where almost the entire cloud is partially polarized; **c**) Well above P_c (P = 0.33), where the edge of the cloud is fully polarized and the minority density vanishes. For further details, see Ref. [23].

and Larkin and Ovchinnikkov (FFLO) proposed an exotic pairing mechanism in which the superfluid itself is spin-imbalanced and overcomes the difference in Fermi energies by creating pairs with finite momentum [22]. The FFLO state has been elusive in condensed matter systems and occupies little of the phase diagram in three-dimensional cold atom systems. However in *one-dimensional* systems, the FFLO state is prevalent. Randy Hulet and collaborators have studied strongly interacting one-dimensional Fermi gases and found partially polarized superfluids in which the FFLO paring mechanism may be at work (see Fig. 2) [23]. This exciting regime paves the way for direct observation of FFLO pairing.

PERSPECTIVE

In order to trap and cool atoms to sub-microkelvin temperatures, an ultracold gas experiment combines a wide range of technologies and techniques. Typical experimental systems include a half-dozen lasers frequency stabilized to 1 part in 10^9, far-off-resonant lasers with tens of watts of power, CCD cameras operating at photon-shot-noise sensitivity, nested magnetic traps requiring µT stability and sub-ms time response, ultra-high vacuum systems operating at 10^{-12} Torr, microwave and RF manipulation systems, and real-time sequencing control involving several hundred time steps and up to one hundred channels. The majority of these systems are not available commercially, so must be designed, built, and tested in-house.

However, these difficult experiments provide an exciting perspective on superfluids and other quantum many-body systems. In the traditional condensed matter approach, the voyage of discovery begins with the observation of a new phenomenon — such as the observation of superconductivity 100 years ago, or of superconductivity in pnictides a few years ago. Theoretical physicists search for a Hamiltonian, or a ground state, that might explain the phenomenon. In contrast, the cold atoms approach starts with well known ingredients. The system is then tuned to explore a specific regime, to test whether the Hamiltonian might explain a certain class of behaviour, or to find a postulated but as-yet unobserved phase.

Another way to see this approach is as a *quantum simulation*. For instance, strongly interacting fermions pose a 'sign problem' for numerical Quantum Monte-Carlo calculations. Whereas tens of thousands of bosons can be simulated on supercomputers, these same machines can handle only ten or so fermions – insufficient to characterize a macroscopic phase at low temperature. From this perspective, a cold atom experiment with a well known Hamiltonian is a quantum simulator, exceeding the abilities of a classical computer. Experimental realizations of universal quantum computers are currently limited to several (less than ten) qubits. Although non-universal, a cold atom system can already perform a quantum simulation requiring thousands of qubits. These quantum simulators are now being applied to solve problems involving strongly correlated fermions, such as whether the Hubbard model can explain d-wave superconductivity [2,3].

In conclusion, a program of progressive complexity is underway in the ultracold atom community. Starting from textbook-like illustrations of the basic principles of condensed matter physics, we progress towards open questions by tuning Hamiltonians, controlling internal states, and engineering environments. Although quantum degenerate neutral gases were realized 84 years after Kamerlingh Onnes observed superconductivity, they are providing powerful new insights into superfluidity and other topics of quantum many-body physics.

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REFERENCES

1. For a list of groups that work on quantum degenerate neutral atoms, see UltraCold Atom News, at http://ucan.physics.utoronto.ca .
2. I. Bloch, J. Dalibard, and W. Zwerger, "Many-Body Physics with Ultracold Gases", *Rev. Mod. Phys.* **80**, 885 (2008).
3. T. Esslinger, "Fermi-Hubbard Physics with Atoms in an Optical Lattice", *Annu Rev. Condens. Matter Phys.* **1**, 129 (2010).
4. C. Chin, R. Grimm, P.S. Julienne, and E. Tiesinga, "Feshbach resonances in ultracold gases", *Rev. Mod. Phys*. 82, 1225 (2010); and references therein.
5. F. Dalfovo, S. Giorgini L.P. Pitaevskii, and S. Stringari, "Theory of Bose-Einstein condensation in trapped gases", *Rev. Mod. Phys.* **71**, 463 (1999).
6. S. Giorgini L.P. Pitaevskii, and S. Stringari, "Theory of ultracold atomic Fermi gases", *Rev. Mod. Phys.* **80**, 1215 (2008).
7. A.J. Leggett, *Quantum Liquids*, Oxford, (2006).
8. C.J. Pethick and H. Smith, *Bose-Einstein Condensation in Dilute Gases*, Cambridge, (2008).
9. A. Griffin, T. Nikuni, and E. Zaremba, *Bose-Condensed Gases at Finite Temperatures*, Cambridge, (2009).
10. M.H. Anderson, J.R. Ensher, M.R. Matthews, C.E. Wieman, and E.A. Cornell, "Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor", *Science* **269** 198 (1995); K.B. Davis, M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle, "Bose-Einstein Condensation in a Gas of Sodium Atoms", *Phys. Rev. Lett.* **75**, 3969 (1995); C.C. Bradley, C.A. Sackett, J.J. Tollett, and R.G. Hulet, "Evidence of Bose-Einstein Condesation in an Atomic Gas with Attractive Interactions", *Phys. Rev. Lett.* **75**, 1687 (1995); see also C.A. Sackett, C.C. Bradley, M. Welling, and R.G. Hulet, "Bose-Einstein condensation of lithium", *Appl. Phys. B* **65**, 433 (1997).
11. B. DeMarco and D.S. Jin, "Onset of Fermi degeneracy in a trapped atomic gas", *Science* **285**, 1703(1999); A.G. Truscott, K.E. Strecker, W.I. McAlexander, G.B. Partridge, and R.G. Hulet, "Observation of Fermi pressure in a gas of trapped atoms", *Science* **291**, 2570 (2001); F. Schreck *et al.*, "Sympathetic cooling of bosonic and fermionic lithium gases towards quantum degeneracy", *Phys. Rev. Lett.* **87**, 080403 (2001).
12. At the same time, the interaction energy increases because the Wannier wave function is more strongly localized. However the quenching of kinetic energy is dominant – exponential instead of polynomial – in the large lattice depth limit.
13. S. Aubin, S. Myrskog, M.H.T. Extavour, L.J. LeBlanc, D. McKay, A. Stummer, and J.H. Thywissen, "Rapid sympathetic cooling to Fermi degeneracy on a chip", *Nature Phys.* **2**, 384 (2006).
14. The reader might be familiar with other situations in physics where the reflected phase is changed near a resonance, for example light reflecting off a cavity near its resonance.
15. G.-B. Jo, Y.-R. Lee, J.-H. Choi, C.A. Christensen, T.H. Kim, J.H. Thywissen, D.E. Pritchard, and W. Ketterle, "Itinerant Ferromagnetism in a Fermi Gas of Ultracold Atoms", *Science* **325**, 1521 (2009).
16. A. Aspect and M. Inguscio, "Anderson localization of ultracold atoms", *Physics Today* **62**, 30 (2008); and references therein.
17. T. Köhler, K. Góral, and P. S. Julienne, "Production of cold molecules via magnetically tunable Feshbach resonances", *Rev. Mod. Phys.* **78**, 1311 (2006); K.-K. Ni, S. Ospelkaus, M.H.G. de Miranda, A. Pe'er, B. Neyenhuis, J.J. Zirbel, S. Kotochigova, P.S. Julienne, D.S. Jin, and J. Ye, "A High Phase-Space-Density Gas of Polar Molecules", *Science* **322**, 231 (2008).
18. C.A. Regal, M. Greiner, and D.S. Jin, "Observation of resonance condensation of Fermionic atom pairs", *Phys. Rev. Lett.* **92**, 040403 (2004).
19. C. Cao, E. Elliott, J. Joseph, H. Wu, J. Petricka, T. Schäfer, and J.E. Thomas, "Universal Quantum Viscosity in a Unitary Fermi Gas", *Science* **331**, 58 (2010); also J.E. Thomas, "The nearly perfect Fermi gas", *Physics Today* **63**, 34 (2010).
20. Polarized electrons are difficult to achieve in a real superconductor, since the Meissner Effect shields out the magnetic field that would otherwise imbalance the electron spin population. However no such constraint exists for cold neutral atoms, and in fact initial polarizations are preserved due to an absence of spin-orbit depolarization.
21. Y.I. Shin, C.H. Schunck, A. Schirotzek, and W. Ketterle, "Phase diagram of a two-component Fermi gas with resonant interactions", *Nature* **451**, 689 (2008).
22. R. Casalbuoni and G. Nardulli, "Inhomogeneous superconductivity in condensed matter and QCD", *Rev. Mod. Phys.* **76**, 263 (2004).
23. Y. Liao, A.S.C. Rittner, T. Paprotta, W. Li, G.B. Partridge, R.G. Hulet, S.K. Baur, and E.J. Mueller, "Spin-imbalance in a one-dimensional Fermi gas", *Nature* **467**, 567 (2010).