Bose-Einstein condensation in dilute atomic gases

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ABSTRACT

We summarize all experimental studies of Bose-Einstein condensation (BEC) in dilute atomic gases reported thus far and discuss the experimental techniques used to produce, manipulate and observe nanokelvin samples of atoms.

Keywords: Bose-Einstein condensation, optical cooling and trapping, atom laser

1. INTRODUCTION

The work on Bose-Einstein condensation (BEC) in dilute atomic gases has greatly extended the temperature and density range of atomic samples. Nanokelvin temperatures are among the lowest temperatures ever achieved, and densities of 10^{15} cm^{-3} exceed previous densities for ultracold atoms by two to three orders of magnitude. The observation of BEC in such systems [1-3] has created a subfield which is interdisciplinary between atomic and condensed matter physics. It uses experimental methods of AMO physics, but many formalisms to describe the phase transition and the novel many-body physics have been developed in the condensed matter physics community. It is amazing that a condensed matter phenomenon can be observed at number densities which are similar to a room temperature gas at a pressure of 10^{-2} mbar! So maybe one should categorize this work as ultralow density condensed matter physics! The low density is crucial for the (meta-) stability of the cold atomic gas against inelastic collisions, in particular three-body recombination. The system develops correlations at such low density because the thermal de Broglie wavelength at nanokelvin temperatures exceeds 1 µm, more than the average distance between atoms. The realization of such quantum degenerate gases provides a test-ground for many-body theories of the dilute Bose gas which were developed many decades ago [4] but never tested experimentally.

In the last two years, we have published several review papers which summarized the developments in the field. Ref. [5], written early in ‘96, described the first experiments with Bose condensates, Refs. [6-8] contained a more complete account on the cooling and trapping techniques and described the progress during the summer of 1996, Ref. [9] of Oct. ‘97 included the more recent experiments on sound propagation and the atom laser. The technique of evaporative cooling, key to the accomplishment of BEC, was reviewed in [10]. Refs. [11-14] are more popular papers, with Ref. [13] containing many animated movies of experimental data and Ref. [14] discussing the concept of an atom laser.

In this paper, we will give a short overview over all experiments done so far with Bose condensates and the experimental techniques used. This compact presentation displays the key techniques and concepts in an almost tabular form and refers to relevant original and review papers for more detailed explanations. A modified and shortened version of this review will appear in the Proceedings of the SPIE conference Photonics West 1998.

2. CAST OF CHARACTERS: NANOKELVIN TOOLS TO PRODUCE, OBSERVE AND MANIPULATE BOSE-EINSTEIN CONDENSATES

2.1 Laser cooling and trapping

In this section, we want to briefly describe the techniques used to perform experiments with Bose-Einstein condensates. The first step is cooling atoms from the temperature of an atomic beam oven or a vapor cell to sub-microkelvin temperatures. To reduce the temperature of a sample by nine orders of magnitude the sequential application of several cooling techniques is required (see [15] for general discussion of laser cooling):

- Zeeman slowing
  Atomic beams can be decelerated by resonant radiation pressure. Among the many methods of slowing atomic beams ([16, 17] and references therein), Zeeman slowing (first demonstrated by Phillips et al. [18]) gives the highest fluxes of

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slow atoms, more than 10^{12} atoms/s [19]. Typically, a Zeeman-slowed beam has a velocity of 30 m/s, corresponding to a kinetic energy of 1 K.

- Doppler molasses
  The slow atomic beam is stopped by optical molasses, first reported in Ref. [20] and reviewed in [21]. This reduces the temperature of the atoms to 1 millikelvin or below.
- Magneto-optical trap
  Cooling in optical molasses is one feature of the magneto-optical trap. In addition to cooling the atoms, it also confines the atoms and compresses them to higher densities (typically between 10^{10} cm^{-3} and 10^{12} cm^{-3}). The magneto-optical trap was first realized in 1987 [22] (for a review, see [23]).
- Dark SPOT trap
  High densities for a large number of atoms are reached in a variant of the magneto-optical trap, where the atoms are kept in a dark hyperfine state which does not absorb the laser light necessary for cooling and trapping [24]. This avoids the limitations of the ordinary magneto-optical trap due to light absorption and trap loss caused by laser-induced collisions.
- Polarization gradient cooling
  Even colder temperatures (between 1 and 50 μK) are reached in polarization gradient cooling (first demonstrated in [25] and reviewed in [26]). This cooling mechanism is already present in the center of the magneto-optical trap, but colder temperatures are usually reached by switching off the magneto-optical trap and adding a short cycle (a few ms) of optimized polarization gradient cooling.
- Vapor cell trap
  In many experiments, the first step (atomic beam slowing) is replaced by directly loading atoms from the low energy tail into the magneto-optical trap [27, 28].

In these conventional cooling and trapping techniques, temperatures are limited by heating due to spontaneous emission and densities by radiation trapping effects and trap loss due to excited-state collisions. More sophisticated cooling methods ("sub-recoil" techniques) have been developed [15], but they have not been used so far for realizing BEC. The closest approach to BEC achieved with the standard techniques is short in phase-space density by five orders of magnitude, while sub-recoil cooling was used to come within a factor of 400 [29].

2.2 Magnetic trapping and evaporative cooling

In the BEC experiments, the phase of optical precooling is followed by evaporative cooling in magnetic traps. Since no light is involved in both the trapping and cooling, the density limitations due to strong optical absorption are absent.

- First magnetic traps
  Ref. [16] discusses early suggestions and magnetic confinement of neutrons. Magnetic trapping of neutral atoms was first observed in 1985 [30]. Shortly afterwards, orders of magnitude improvements in density and number of trapped atoms were achieved at MIT and in Amsterdam using superconducting traps and different loading schemes [31-33]. Important aspects of magnetic trapping are discussed in [10, 16, 34-36].
- Evaporative cooling
  The technique of evaporative cooling was developed by Doyle, Greytak, Hess, Kleppner and collaborators at MIT as a method for cooling atomic hydrogen which had been precooled by cryogenic methods. The first suggestion by Hess [37] was soon followed by the experimental demonstration [38]. Evaporative cooling has been reviewed in [10, 36].

The combination of laser cooling with magnetic trapping and evaporative cooling required further developments of the evaporation and magnetic trapping techniques. In particular, the need for optical access for many laser beams required the design of special magnetic traps or novel winding patterns for the coils. Furthermore, the evaporation process could be completely separated from the design of the magnetic trapping potential by removing atoms not through some saddle point of the trapping potential, but by using rf induced spinflips to transfer the atoms to non-trapped states. Since these developments constituted the major experimental advance in the realization of BEC, we review them in greater detail.

- Rf induced evaporative cooling
  In rf induced evaporation, an rf field selectively flips the spin of the most energetic atoms thus ejecting them from the trap and is exhaustively discussed in [10]. This technique was first proposed by Pritchard [39] and Walraven [40] and first demonstrated by our group when spatial truncation of magnetically trapped atoms was observed [41]. Increase in phase space density was reported by the MIT and Boulder groups at IQEC in May 1994 and at ICAP-14 [42, 43] and published after further progress had been achieved [44-46]. After that, the only missing step to BEC, the improvement of the magnetic trap, took less than a year.

- Traps for confining Bose-Einstein condensates

  The first observations of BEC were done in a spherical quadrupole trap which consisted of only two coils and had excellent optical access. Trap loss at the zero magnetic field point in the center of the trap was avoided by adding rotating magnetic fields [1] or a focused laser beam [3]. The Rice group used a permanent magnet trap [47].

  A more flexible trapping configuration which offers many advantages was introduced by the MIT group [48]. The cloverleaf design realized the so called Ioffe-Pritchard configuration [49] with DC electromagnets, which allowed variable anisotropy and strength of the trapping potentials. Several variants of this concept have been used successfully in subsequent BEC experiments [50-52]. The most recent advance in confinement of Bose condensates is all-optical confinement as discussed below [53].

Evaporative cooling turned out to work much better for alkali atoms than for hydrogen for which the technique was originally developed. This didn't come as a big surprise. Already in 1986, in a visionary paper, D. Pritchard correctly estimated the rate constants for elastic and inelastic collisions [54]. From these estimates one could easily predict that, in contrast to atomic hydrogen, the so-called good collisions (elastic collisions necessary for the evaporation process) would clearly dominate over the so-called bad collisions (inelastic two- and three-body collisions); therefore, evaporative cooling in alkalis would probably not be limited by intrinsic loss and heating processes. However, there was one paper which was much more pessimistic about inelastic processes [55]. People both at MIT and at Boulder probably didn't have full confidence in the more optimistic estimates and spent time to explore either theoretically [56] or experimentally [57] the possibility to confine atoms in the strong-field seeking hyperfine state. Trapping atoms in that state would eliminate inelastic two-body collisions which had limited progress toward BEC in atomic hydrogen. However, as estimated, these collisions turned out to be negligible for sodium and rubidium.

Since the early '90s there were focused programs both at Boulder an at MIT to combine laser cooling and evaporative cooling. The challenge was to simultaneously achieve effective laser cooling and trapping, which work best at low number densities (where optical absorption is negligible) and efficient evaporative cooling, which requires high densities. This shifted the emphasis of the optical techniques from attaining low temperatures and high phase-space density towards achieving high elastic collision rates in an ultra-high vacuum environment. The first major improvement towards this goal was the invention of the Dark SPOT trap in 1992 [24] which turned out to be crucial in the BEC work both at Boulder [1] and at MIT [3]. In the summer of 1992, with an elastic collision rate of 100/s in a Dark SPOT trap, it was clear that the achievement of evaporative cooling was mainly an engineering problem. The only requirement for evaporative cooling is a collisional rethermalization time much shorter than the lifetime of an atom in the trap.

We know now that the Dark SPOT trick and other tricks [58] were helpful, but not indispensable. This is best illustrated by the experiment at Rice which used only Doppler cooling (not even polarization gradient cooling or magneto-optical trapping) to load the magnetic trap [59] - techniques which had been developed in the '80s. The collision rate was very slow, but an excellent vacuum made a very slow evaporation process possible. So in hindsight, BEC did not require major innovations in cooling and trapping technology or major new ideas - it only required groups who were willing to take the risk of spending a few years and assembling state-of-the-art technology to combine laser and evaporative cooling. The major advances in cooling and trapping which were developed along the way created overkill and are responsible for the rapid developments in the field over the last years.

2.3 Atoms for BEC

The cast of characters would be incomplete without presenting the major actors, the atoms themselves. The only indispensable property for BEC is to pick a bosonic atom - and all stable atoms with the exception of beryllium have at least one bosonic isotope. The choice of an atom for a BEC experiment is mainly determined by the cooling and trapping techniques. Magnetic trapping requires atoms with a strong magnetic moment and therefore an unpaired electron. Laser cooling favors atoms with strong transitions in the visible or infrared region where commercial cw lasers are available.

BEC was realized with rubidium, lithium and sodium so far. Experiments on hydrogen, cesium, potassium and metastable helium are on their way. The collisional properties of theses atoms are discussed in [10].

2.4 Techniques to observe BEC

Prior to the BEC work most diagnostics on cold atoms were done by fluorescence. However, in fluorescence spectroscopy, one collects the scattered photons with a solid angle of typically only 1 %, whereas in absorption measurements, all absorbed (and subsequently scattered) photons are detected. Therefore, for sufficiently dense clouds, the signal-to-noise ratio for absorption methods is superior. Another advantage of absorption methods is that it gives directly absolute (column) densities whereas fluorescence requires additional calibration.

- Absorption imaging

  One of the earliest uses of absorption imaging for the diagnostics of cold atoms was the work on the Dark SPOT trap [24]. Absorption imaging was used to observe the ballistically expanding condensates released from the trap by a sudden switch-off [1, 3, 48]. It can also be used to directly image sufficiently large and not too dense samples of trapped atoms [45, 52]; however, dispersive methods (see below) are generally superior.

- Three-dimensional absorption imaging
  Absorption imaging is usually a two dimensional technique due to the line-of sight integration. However, it can be used in a tomographic way to achieve three-dimensional resolution: a thin light sheet selects atoms by optical pumping, and only these atoms absorb the probe light which propagates perpendicular to the light sheet [60].
- Dispersive imaging
  Alternatively, trapped atoms can be probed with photons which are coherently scattered in the forward direction. These photons are phase-shifted (dispersion) and scattered in an angular region that is determined by diffraction (for our experiments typically 10 mrad). Thus the recoil heating due to coherent scattering is small. The coherently scattered photons can be detected using spatial filtering methods (dark ground imaging [61], phase-contrast imaging [62]) or polarization methods [63]. At far detuning, the number of dispersively scattered photons exceeds the absorbed photons by a factor which is roughly the resonant optical thickness (typically 300 in our experiments). Therefore dispersive imaging gives superior signals for very dense clouds. This method was used to obtain non-destructive real-time movies of the dynamics of a condensate [13, 62].

2.5 Manipulation of Bose-Einstein condensates

Having achieved BEC, one would like to study the properties of condensates in different shapes and symmetries, and also explore their dynamic behavior. The extremely low temperature of the condensate and the high sticking probability of atoms on cold surfaces only allow non-contact manipulation of condensates using electromagnetic fields.

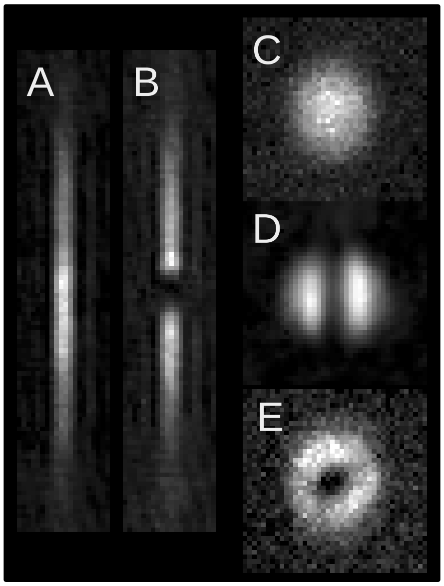

Fig. 1 Getting a Bose-Einstein condensate into shape! This figure shows the variety of condensate shapes which were realized with magnetic traps and far-off resonant blue-detuned laser beams. The elongated shapes (A-B) were obtained in a cloverleaf magnetic trap with maximum radial confinement. Spherical clouds (C-E), were realized by adiabatically decreasing the radial confinement. The light-shift potential of a focused, blue detuned laser repelled the atoms locally in the trap. Depending on the intensity and shape of the laser beam, this resulted either in two condensates with adjustable separation or in a condensate with a hole in the center, thus creating a toroidal (“donut”) shape. These *in-situ* images were taken using the non-destructive phase contrast imaging technique. The axial extension of the condensate in A was about 300 μm. The same scale has been used in all images.

- Magnetic fields
  Magnetic fields have been used to adiabatically expand the condensate ([1, 61, 62]). In our experiments, we have varied the aspect ratio between more than 20 and one (spherical trap, see Fig. 1). Modulation of the magnetic trapping field was employed to excite collective excitations [64-67]. A pulsed magnetic field gradient has been used to launch a Bose condensate into an atomic fountain [7, 8].
- Optical dipole forces
  Magnetic fields cannot be used for “microsurgery” on condensates, i.e. to apply small spatial perturbations. This can be done instead by using the dipole force of focused far-off-resonant laser beams. Our group used this method to excite special collective excitations [66] and propagating sound [61]. Optical dipole forces can also be used to create special trapping potentials (Fig. 1). We have created toroidal “donut” condensates (as part of our ongoing effort to see

persistent currents) and realized double well potentials with two separated condensates (which subsequently interfered [60]). Finally, infrared light has been used to achieve all-optical confinement of a condensate [53].

The combination of magnetic fields and far-off-resonant light is very versatile - the magnetic field provides the general confinement, blue light is used to add blips and red light to add dips to the trapping potential. So we have all the tools to shape, slice, kick, shake and stir condensates!

- Rf fields
  Radiofrequency radiation can be used to change the hyperfine state of trapped atoms. This was used to switch atoms from a trapped to an untrapped hyperfine state, thus realizing an output coupler for an atom laser [68]. Rf methods were also used to transfer condensates between trapped states, either in an optical trap [53] or in a magnetic trap using a two-photon rf transition [69].

3. EXPERIMENTS ON BEC DONE SO FAR

The first observations of BEC have led to intense worldwide research activities. Several hundred papers have already been published on BEC. However, only a small fraction of them (about 20 major papers) are experimental - experimental projects have a much longer lead time than theoretical studies! In the following paragraphs we summarize the status of the experimental work (neglecting the many important theoretical contributions to this field; see Ref. [70] for a comprehensive review). The following section will mention all experimental papers published so far even if there is some overlap with the previous section.

3.1 Observations of BEC

In the summer of 1995, the first observations of Bose-Einstein condensates in dilute atomic vapors were reported [1-3]. Each experiment used different atomic species, loading schemes and trap configurations - demonstrating that the achievement of BEC did not depend on any particular technique. A tabular comparison of the techniques and parameter of these experiments appeared in Refs. [5, 8]. A second wave of successful BEC experiments have recently been reported [51, 52, 71-73] - so we expect that the field will gain additional momentum!

3.2 Static properties

Several quantitative studies of equilibrium properties of a condensate were done using time-of-flight absorption imaging.

- Condensate fraction
  The condensate fraction was studied as a function of temperature, and good agreement with the predicted $1-(T/T_C)^3$ dependence was found [48, 74]. The transition temperature T_C agreed with the prediction for the ideal gas to within 5 % [74]. Shifts in T_c of similar magnitude are expected due to interactions and finite size effects, and their observation is now in reach.
- Mean-field energy
  The kinetic energy of expanding condensates released from the magnetic trap is equal to the sum of the kinetic and the interaction energies of the trapped condensate. Usually, the interaction energy dominates, and its dependence on the number of condensates atoms was studied [48]. Ref. [75] explored the transition between the kinetic energy and mean field energy dominated regimes .
- Specific heat
  Ref. [74] determined the specific heat of the trapped condensate from release energy measurements, and found evidence for a discontinuity at T_C.

3.3 Dynamic properties

- Collective excitations at zero temperature
  Collective excitations of liquid helium played a key role in determining its superfluid properties. It is now well understood that the phonon-nature of the low-lying excitations implies superfluidity up to a critical velocity which is given by the speed of sound. The first studies of collective excitations in Bose condensed atomic gases [64, 65] focused on the excitations of an (almost) pure condensate. They were studied by modulating the trapping potential and detecting shape oscillations using time-of-flight absorption imaging.
- Collective excitations at finite temperature
  The damping of collective modes and frequency shifts as a function of temperature were addressed in Refs. [66, 67]. Accounting for those finite-temperature effects is a challenge to many-body theory. The MIT experiment [66] used large condensates in the hydrodynamic limit and identified modes analogous to zero, first and second sound in liquid helium.

- Propagation of sound
  The propagation of density perturbations was studied with a time-resolved imaging technique [61]. The speed of sound was determined as a function of density and was found to be in good agreement with Bogoliubov theory.
- Formation of the condensate
  The growth of the condensate was observed after suddenly quenching a cold atom cloud below the BEC transition temperature [76]. The intrinsic dynamics of condensate growth was in agreement with a model assuming bosonic stimulation, i.e., (N+1) times enhancement of elastic scattering into the ground state containing N atoms.
- Decay of the condensate
  Refs. [53, 77] studied the decay of the condensate and explained it by three body recombination, which leads to molecule formation and loss of the atoms from the trap. Burt et al. [77] compared the rate coefficient to the one observed for a thermal cloud and found a factor of six suppression of collisions between condensate atoms due to higher-order correlations.

3.4 Coherence properties and atom laser

The first experiments on BEC characterized Bose condensates by the appearance of a cold and dense peak of ultracold atoms, either in images of expanding clouds or direct images of the trapped atoms. Recent experiments investigated the coherence properties of Bose-Einstein condensates, which are described by a macroscopic wavefunction.

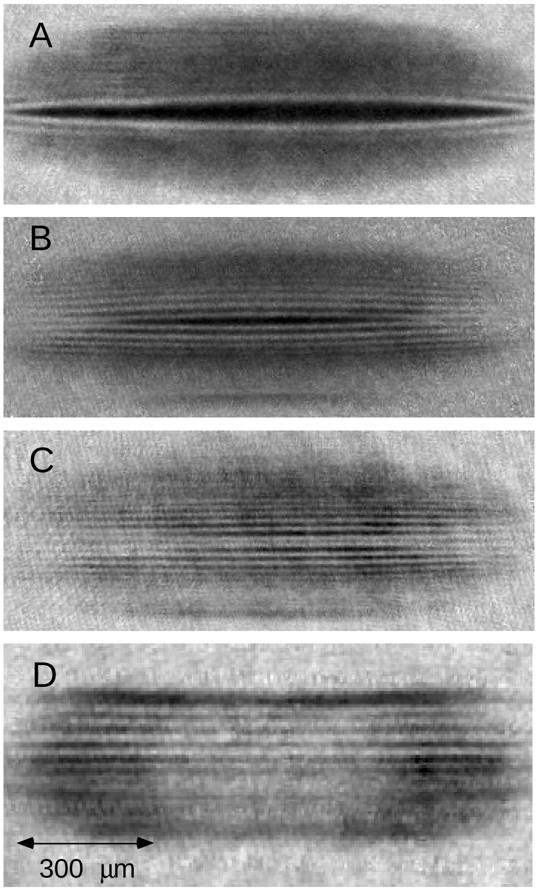

Fig. 2 Patterns of interference between two condensates. These figures are absorption images taken 40 ms after two condensates (similar to Fig. 1B) were released from the magnetic trap and overlapped during the ballistic expansion [60]. Figures A-C show the interference pattern of condensates with different initial separations. In C, the condensates were fully separated before release, whereas in A and B, they were not. In the case of an incomplete separation, a central fringe appears to which the other fringes are 'phase locked' [84]. Fig. D shows the interference of pulses of atoms coupled out from a double condensate such as in Fig. 1B. The hollow feature of this pattern is caused by repulsive interactions between the outcoupled atoms and those left behind in the trap. The fringe pattern in D confirmed that rf output coupling is a coherent process.

- Interference between two Bose condensates
  The observation of interference between two independent condensates provided the experimental proof that condensates are coherent and exhibit long-range correlations (Figs. 2 and 3) [60]. Interference between two spatially separated condensates is analogous to a double-slit experiment in optics used to determine first-order coherence.

- Higher order coherences
  Higher-order short range coherence can be inferred from the study of processes which depend on the square or the cube of the local density. Mean field energy measurements provided evidence for second-order coherence [78], and the suppression of three body collisions between condensate atoms revealed third-order coherence [77].
- Output coupler for an atom laser
  The realization of a simple outcoupling mechanism for trapped condensates, using rf-pulses [68], and the proof that the outcoupled pulses are coherent [60] (see Fig. 2D) demonstrated the potential of BEC to generate coherent atomic beams and realized a rudimentary pulsed atom laser.
- Bosonic stimulation in the formation of a condensate
  Our recent study of the formation of a condensate showed evidence for bosonic stimulation [76]. Bosonic stimulation in elastic scattering is the gain process of an atom laser based on evaporative cooling.

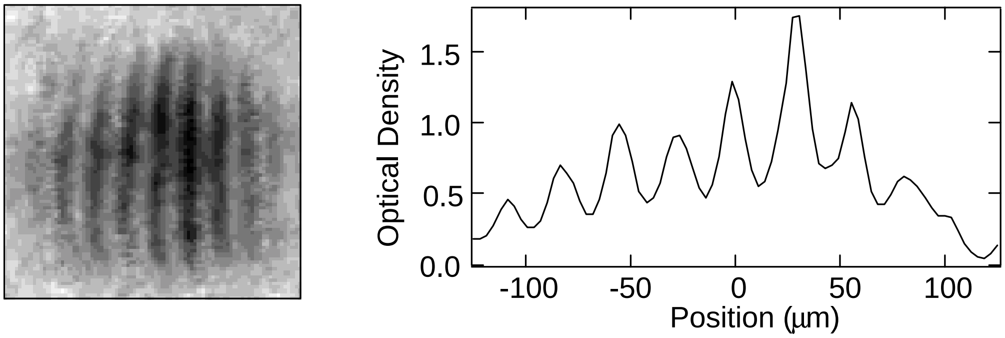

Fig. 3: Interference of two condensates. A cigar-shaped condensate was adiabatically expanded (Fig. 1C), split into two parts (Fig. 1D) and released. After 40 ms time-of-flight, the interference pattern was observed using absorption imaging. The smaller mean separation of the condensates resulted in larger fringe spacings and more complete overlap of the condensates in comparison to Fig. 2.

3.5 Further experiments

The field of BEC continues to advance rapidly due to the introduction of new experimental techniques. Each major step opens new vistas for exploration.

- Non-destructive imaging of Bose condensates
  Andrews et al. showed that dispersive light scattering can be used to observe the density distribution of a condensate without noticeable heating [62]. This concept is now used to take “movies” of up to 30 images of the same atomic cloud showing the real-time dynamics of condensates.
- Optical confinement of a Bose-Einstein condensate
  Sodium atoms were Bose condensed in a magnetic trap and then transferred into a red-detuned far-off-resonance trap provided by a single focused infrared laser beam. Much higher densities than in magnetic traps were achieved.
- Sympathetic cooling
  Sympathetic cooling of atoms in one hyperfine state by atoms in a different hyperfine state of rubidium [50] opens up intriguing possibilities of cooling atomic species into BEC for which direct cooling would be difficult or impossible.
- Production of multi-component condensates
  Myatt et al. discovered that two coexisting Bose condensates in different hyperfine states of rubidium are collisional stable due to an accidental suppression of spin relaxation [50]. A more general way of studying the dynamics of different spin states can be realized in an optical dipole trap [53]. It was shown that all three spin states (m=-1, 0, 1) of the F=1 ground state of sodium could be trapped in the purely optical trap.

4. CHALLENGES AHEAD

4.1 Engineering of quantum matter

More than two years have passed since the first observations of BEC in atomic gases. Many properties of this new form of quantum matter have been revealed and have stimulated theoretical work to describe trapped quantum degenerate gases.

However, there are many challenges ahead. One is to “engineer” a larger variety of degenerate quantum matter. Work to apply evaporative cooling not only to H [35], Na, Rb and Li, but also to K, Cs, He* and even to molecules [79] is progressing. The goal is to obtain Bose condensed samples with different interactions, and thus vary the strength of interactions from the non-interacting ideal gas limit close to the case where they become comparable to the thermal energy, i.e. the transition to a liquid. Of special interest are systems with negative scattering lengths (implying attractive interactions) and the study of the dynamics of the collapse. One intriguing possibility is to modify the strength of interactions by external magnetic [80, 81] or optical [82] fields (so-called Feshbach resonances). Multi-component condensates offer additional degrees of freedoms. And finally, another important goal is the observation of quantum degeneracy in a gas of fermions, and efforts with ^{6}Li and ^{40}K are under way.

4.2 Quantum transport

Bose-condensed gases are predicted to show superfluidity. Phenomena related to this are vortices, persistent currents and the existence of a critical velocity. We expect that many aspects of superfluidity in gases are different from liquids. Multi-component condensates might eventually lead to interpenetrating superfluids.

Another form of quantum transport would be tunneling between two Bose condensates [83]. The basic system of two condensates separated by a thin wall of light has been realized [60], but better control and probably thinner barriers are necessary to observe Josephson-type phenomena.

4.3 Atom laser

Our recent realization of a rudimentary atom laser was the first step towards generating and using coherent atomic beams. Goals for the future are the full characterization of the properties of atom lasers, improved control over the outcoupled pulses and the development of a (quasi-) cw scheme. Larger output power (bigger condensates) will facilitate the use of atom lasers in atom optics and other applications.

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6. REFERENCES

1. M.H. Anderson, J.R. Ensher, M.R. Matthews, C.E. Wieman, and E.A. Cornell, Science **269**, 198 (1995).
2. C.C. Bradley, C.A. Sackett, and R.G. Hulet, Phys. Rev. Lett. **78**, 985 (1997), see also: C.C. Bradley, C.A. Sackett, J.J. Tollet, and R.G. Hulet, Phys. Rev. Lett. **75**, 1687 (1995).
3. K.B. Davis, M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle, Phys. Rev. Lett. **75**, 3969 (1995).
4. K. Huang, in *Studies in Statistical Mechanics*, vol. II, edited by J. de Boer and G.E. Uhlenbeck (North-Holland, Amsterdam, 1964) p. 3.
5. W. Ketterle, M.R. Andrews, K.B. Davis, D.S. Durfee, D.M. Kurn, M.-O. Mewes, and N.J. van Druten, Physica Scripta **T66**, 31 (1996).
6. N.J. van Druten, C.G. Townsend, M.R. Andrews, D.S. Durfee, D.M. Kurn, M.-O. Mewes, and W. Ketterle, Czech. J. Phys. **46 (S6)**, 3077 (1996).
7. C.G. Townsend, N.J. van Druten, M.R. Andrews, D.S. Durfee, D.M. Kurn, M.-O. Mewes, and W. Ketterle, in *Ultracold Atoms and Bose-Einstein-Condensation, 1996*, edited by K. Burnett, OSA Trends in Optics and Photonics Series, Vol. 7 (Optical Society of America, Washington D.C., 1996) p. 2.
8. C.G. Townsend, N.J. van Druten, M.R. Andrews, D.S. Durfee, D.M. Kurn, M.-O. Mewes, and W. Ketterle, in *Atomic Physics 15*, Fifteenth International Conference on Atomic Physics, Amsterdam, August 1996 (World Scientific, Singapore, 1997) p. 192.
9. M.R. Andrews, D.S. Durfee, S. Inouye, D.M. Stamper-Kurn, H.-J. Miesner, and W. Ketterle, J. Low Temp. Phys. **110**, 153 (1998).

10. W. Ketterle and N.J. van Druten, in *Advances in Atomic, Molecular, and Optical Physics*, vol. 37, edited by B. Bederson and H. Walther (Academic Press, San Diego, 1996) p. 181.
11. W. Ketterle and M.-O. Mewes, LEOS Newsletter, IEEE, August 1996, pp. 18-21.
12. C.G. Townsend, W. Ketterle, and S. Stringari, Physics World, March 1997, pp. 29-34.
13. D.S. Durfee and W. Ketterle, Optics Express (1998), submitted.
14. W. Ketterle, in *McGraw-Hill 1999 Yearbook of Science & Technology*, companion volume to Encyclopedia of Science & Technology (McGraw-Hill), in press.
15. E. Arimondo, W.D. Phillips, and F. Strumia (editors), *Laser Manipulation of Atoms and Ions*, Proceedings of the International School of Physics “Enrico Fermi”, Course CXVIII (North-Holland, Amsterdam, 1992).
16. W.D. Phillips, J.V. Prodan, and H.J. Metcalf, J. Opt. Soc. Am. B **2**, 1751 (1985).
17. W.D. Phillips, in *Laser Manipulation of Atoms and Ions*, edited by E. Arimondo, W.D. Phillips, and F. Strumia, Proceedings of the International School of Physics “Enrico Fermi”, Course CXVIII (North-Holland, Amsterdam, 1992) p. 289.
18. J.V. Prodan, W.D. Phillips, and H. Metcalf, Phys. Rev. Lett. **49**, 1149 (1982).
19. M.A. Joffe, W. Ketterle, A. Martin, and D.E. Pritchard, J. Opt. Soc. Am. B **10**, 2257 (1993).
20. S. Chu, L. Hollberg, J.E. Bjorkholm, A. Cable, and A. Ashkin, Phys. Rev. Lett. **55**, 48 (1985).
21. S. Chu, in *Laser Manipulation of Atoms and Ions*, edited by E. Arimondo, W.D. Phillips, and F. Strumia, Proceedings of the International School of Physics “Enrico Fermi”, Course CXVIII (North-Holland, Amsterdam, 1992) p. 239.
22. E.L. Raab, M. Prentiss, A. Cable, S. Chu, and D.E. Pritchard, Phys. Rev. Lett. **59**, 2631 (1987).
23. D.E. Pritchard and W. Ketterle, in *Laser Manipulation of Atoms and Ions*, edited by E. Arimondo, W.D. Phillips, and F. Strumia, Proceedings of the International School of Physics “Enrico Fermi”, Course CXVIII (North-Holland, Amsterdam, 1992) p. 473.
24. W. Ketterle, K.B. Davis, M.A. Joffe, A. Martin, and D.E. Pritchard, Phys. Rev. Lett. **70**, 2253 (1993).
25. P.D. Lett, R.N. Watts, C.I. Westbrook, W.D. Phillips, P.L. Gould, and H.J. Metcalf, Phys. Rev. Lett. **61**, 169 (1988).
26. P.D. Lett, W.D. Phillips, S.L. Rolston, C.E. Tanner, R.N. Watts, and C.I. Westbrook, J. Opt. Soc. Am. B **6**, 2084 (1989).
27. A. Cable, M. Prentiss, and N.P. Bigelow, Optics Lett. **15**, 507 (1990).
28. C. Monroe, W. Swann, H. Robinson, and C. Wieman, Phys. Rev. Lett. **65**, 1571 (1990).
29. H.J. Lee, C.S. Adams, M. Kasevich, and S. Chu, Phys. Rev. Lett. **76**, 2658 (1996).
30. A.L. Migdall, J.V. Prodan, W.D. Phillips, T.H. Bergeman, and H.J. Metcalf, Phys. Rev. Lett. **54**, 2596 (1985).
31. V.S. Bagnato, G.P. Lafyatis, A.G. Martin, E.L. Raab, R.N. Ahmad-Bitar, and D.E. Pritchard, Phys. Rev. Lett. **58**, 2194 (1987).
32. H. Hess, G.P. Kochanski, J.M. Doyle, N. Masuhara, D. Kleppner, and T.J. Greytak, Phys. Rev. Lett. **59**, 672 (1987).
33. R. van Roijen, J.J. Berkhout, S. Jaakkola, and J.T.M. Walraven, Phys. Rev. Lett. **61**, 931 (1988).
34. T. Bergeman, G. Erez, and H. Metcalf, Phys. Rev. A **35**, 1535 (1987).
35. T.J. Greytak, in *Bose-Einstein Condensation*, edited by A. Griffin, D.W. Snoke, and S. Stringari (Cambridge University Press, Cambridge, 1995) p. 131.
36. J.T.M. Walraven, in *Quantum Dynamics of Simple Systems*, edited by G.L. Oppo, S.M. Barnett, E. Riis, and M. Wilkinson (Institute of Physics Publ., London, 1996) p. 315.
37. H.F. Hess, Phys. Rev. B **34**, 3476 (1986).
38. N. Masuhara, J.M. Doyle, J.C. Sandberg, D. Kleppner, T.J. Greytak, H.F. Hess, and G.P. Kochanski, Phys. Rev. Lett. **61**, 935 (1988).

39. D.E. Pritchard, K. Helmerson, and A.G. Martin, in *Atomic Physics 11*, edited by S. Haroche, J.C. Gay, and G. Grynberg (World Scientific, Singapore, 1989) p. 179.
40. T.W. Hijmans, O.J. Luiten, I.D. Setija, and J.T.M. Walraven, J. Opt. Soc. Am. B **6**, 2235 (1989).
41. W. Ketterle, K.B. Davis, M.A. Joffe, A. Martin, and D.E. Pritchard, invited oral presentation at OSA Annual Meeting, Toronto, Canada, October 3-8, 1993.
42. K.B. Davis, M.O. Mewes, M.A. Joffe, and W. Ketterle, in *Fourteenth International Conference on Atomic Physics*, Boulder, Colorado, 1994, Book of Abstracts, 1-M3.
43. W. Petrich, M.H. Anderson, J.R. Ensher, and E.A. Cornell, in *Fourteenth International Conference on Atomic Physics*, Boulder, Colorado, 1994, Book of Abstracts, 1M-7.
44. C.S. Adams, H.J. Lee, N. Davidson, M. Kasevich, and S. Chu, Phys. Rev. Lett. **74**, 3577 (1995).
45. K.B. Davis, M.-O. Mewes, M.A. Joffe, M.R. Andrews, and W. Ketterle, Phys. Rev. Lett. **74**, 5202 (1995).
46. W. Petrich, M.H. Anderson, J.R. Ensher, and E.A. Cornell, Phys. Rev. Lett. **74**, 3352 (1995).
47. J.J. Tollet, C.C. Bradley, C.A. Sackett, and R.G. Hulet, Phys. Rev. A **51**, R22 (1995).
48. M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.M. Kurn, D.S. Durfee, and W. Ketterle, Phys. Rev. Lett. **77**, 416 (1996).
49. D.E. Pritchard, Phys. Rev. Lett. **51**, 1336 (1983).
50. C.J. Myatt, E.A. Burt, R.W. Ghrist, E.A. Cornell, and C.E. Wieman, Phys. Rev. Lett. **78**, 586 (1997).
51. U. Ernst, A. Marte, F. Schreck, J. Schuster, and G. Rempe, Europhys. Lett. **41**, 1 (1998).
52. L.V. Hau, B.D. Busch, C. Liu, Z. Dutton, M.M. Burns, and J.A. Golovchenko (1998), preprint.
53. D.M. Stamper-Kurn, M.R. Andrews, A. Chikkatur, S. Inouye, H.-J. Miesner, J. Stenger, and W. Ketterle, Phys. Rev. Lett. (1998), in press.
54. D.E. Pritchard, in *Electronic and Atomic Collisions*, edited by D.C. Lorents, W.E. Meyerhof, and J.R. Peterson (Elsevier, 1986) p. 593.
55. J. Vigué, Phys. Rev. A **34**, 4476 (1986).
56. W. Ketterle and D.E. Pritchard, Appl. Phys. B **54**, 403 (1992).
57. E.A. Cornell, C. Monroe, and C.E. Wieman, Phys. Rev. Lett. **67**, 2439 (1991).
58. W. Petrich, M.H. Anderson, J.R. Ensher, and E.A. Cornell, J. Opt. Soc. Am. B **11**, 1332 (1994).
59. C.C. Bradley, C.A. Sackett, J.J. Tollet, and R.G. Hulet, Phys. Rev. Lett. **75**, 1687 (1995).
60. M.R. Andrews, C.G. Townsend, H.-J. Miesner, D.S. Durfee, D.M. Kurn, and W. Ketterle, Science **275**, 637 (1997).
61. M.R. Andrews, D.M. Kurn, H.-J. Miesner, D.S. Durfee, C.G. Townsend, S. Inouye, and W. Ketterle, Phys. Rev. Lett. **79**, 553 (1997).
62. M.R. Andrews, M.-O. Mewes, N.J. van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle, Science **273**, 84 (1996).
63. C.A. Sackett, C.C. Bradley, M. Welling, and R.G. Hulet, Brazilian Journal of Physics **27**, 154 (1997).
64. D.S. Jin, J.R. Ensher, M.R. Matthews, C.E. Wieman, and E.A. Cornell, Phys. Rev. Lett. **77**, 420 (1996).
65. M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.M. Kurn, D.S. Durfee, C.G. Townsend, and W. Ketterle, Phys. Rev. Lett. **77**, 988 (1996).
66. D. Stamper-Kurn, H.-J. Miesner, S. Inouye, M.R. Andrews, and W. Ketterle, Phys. Rev. Lett. (1998), submitted.
67. D.S. Jin, M.R. Matthews, J.R. Ensher, C.E. Wieman, and E.A. Cornell, Phys. Rev. Lett. **78**, 764 (1997).
68. M.-O. Mewes, M.R. Andrews, D.M. Kurn, D.S. Durfee, C.G. Townsend, and W. Ketterle, Phys. Rev. Lett. **78**, 582 (1997).
69. E. Cornell, personal communication.

70. A.S. Parkins and D.F. Walls (1997), preprint.
71. D.-J. Han, R. Wynar, P. Courteille, and D. Heinzen, talk at CLEO/QELS, Baltimore, May 18-23, 1997.
72. M. Kasevich, talk at the IV. Workshop on Optics and Interferometry with Atoms, St. John's College, Oxford, July 21-23, 1997.
73. T. Esslinger, I. Bloch, and T.W. Hänsch, private communication and http://www.quantum.physik.uni-muenchen.de.
74. J.R. Ensher, D.S. Jin, M.R. Matthews, C.E. Wieman, and E.A. Cornell, Phys. Rev. Lett. **77**, 4984 (1996).
75. M. Holland, D.S. Jin, M.L. Chiofalo, and J. Cooper, Phys. Rev. Lett. **78**, 3801 (1997).
76. H.-J. Miesner, D.M. Stamper-Kurn, M.R. Andrews, D.S. Durfee, S. Inouye, and W. Ketterle, Science **279**, 1005 (1998).
77. E.A. Burt, R.W. Ghrist, C.J. Myatt, M.J. Holland, E.A. Cornell, and C.E. Wieman, Phys. Rev. Lett. **79**, 337 (1997).
78. W. Ketterle and H.-J. Miesner, Phys. Rev. A **56**, 3291 (1997).
79. J. Kim, B. Friedrich, D.P. Katz, D. Patterson, J.D. Weinstein, R. DeCarvalho, and J.M. Doyle, Phys. Rev. Lett. **78**, 3665 (1997).
80. E. Tiesinga, B.J. Verhaar, and H.T.C. Stoof, Phys. Rev. A **47**, 4114 (1993).
81. A.J. Moerdijk, B.J. Verhaar, and A. Axelsson, Phys. Rev. A **51**, 4852 (1995).
82. P.O. Fedichev, Y. Kagan, G.V. Shlyapnikov, and J.T.M. Walraven (1997), preprint.
83. F. Dalfovo, L. Pitaevskii, and S. Stringari, Phys. Rev. A **54**, 4213 (1996).
84. A. Röhrl, M. Naraschewski, A. Schenzle, and H. Wallis, Phys. Rev. Lett. **78**, 4143 (1997).