BEC FAQ

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One of the most exciting developments in physics in the last two years has been the realization and study of Bose-Einstein condensation (BEC) in atomic gases. Writing a review article about this development, however, is likely to be an unrewarding task for two reasons. Firstly, the content of any such review is bound to be outdated even before it has come into print, being overtaken by the continuing rapid progress in the field. Secondly, quite a few reviews have already appeared recently, both for insiders and outsiders (see in particular Q. 10 below), so it becomes increasingly hard not to regurgitate what has already been written.

Instead of giving yet another review, I present here a list of frequently asked questions (FAQ) and answers. The purpose of this approach (inspired by similar FAQs that are common for computer software) is to point the reader to relevant resources (original papers, review articles, web sites) as efficiently as possible, and to give some additional information which one typically does NOT find elsewhere, while at the same time avoiding duplication as much as possible.

I will focus on the experiments, since these have clearly driven the field, even though substantial theoretical progress has also been made. My experience with BEC is largely based on a one-year postdoc period (May 1995-May 1996) I spent in the group of prof. Wolfgang Ketterle at MIT.

Contents

1 What is BEC?

Bose-Einstein condensation is one of the most surprising new features that arises in the theory of the ideal gas, when one moves from a classical description to a quantum-mechanical description. Specifically, BEC occurs when an ideal gas of bosons is cooled to such low temperatures that the quantum-mechanical de Broglie wavelength becomes comparable to the average interparticle spacing. At a well-defined temperature the number of particles in the quantum ground state suddenly increases dramatically. In fact, this number becomes *macroscopic*, i.e., it becomes a sizeable fraction of the total number of particles. Most textbooks on statistical mechanics discuss BEC in some detail. The most popular textbook in the BEC community seems to be Ref. [1]. In the thermodynamic limit (i.e., in the limit of infinite system size) BEC is a phase transition.

2 Who discovered BEC, and why is it called BEC?

Unlike what is suggested by the name "Bose-Einstein condensation", this phenomenon was not discovered (theoretically) by Bose at all, but by Albert Einstein alone, in 1924. An excellent account of the early history of this subject can be found in [2] (Chapter 23). In a nutshell: in 1924, Bose found a new derivation of Planck's black body radiation law (the "ideal gas law" for photons) [3]. This derivation contained a number of new ideas on how one could describe the particles that make up light. For instance, Bose treated the phase space cells as independent, not the particles, a dramatic deviation from classical concepts. Inspired by these ideas, Einstein applied the same reasoning to massive particles (where the total number of particles is conserved), in a series of three papers [4]. The second paper, written in 1924 and published in 1925, describes for the first time the "condensation" phenomenon. It might thus seem more appropriate to call it "Einstein condensation" and in fact some authors have used this name, see e.g. [5].

On the other hand, BEC is a direct consequence of Bose-Einstein statistics, the distribution law for integer-spin particles, and Bose contributed significantly to the elucidation of this law. Such particles are now called bosons (because it is more convenient than "bose-einsteinons", pronunciationwise?). As a result, Bose's name now seems to be used for almost all phenomena related to integer-spin particles: it has become common practice to speak of the "Bose gas", "Bose statistics" and "Bose condensation".

3 What are the theoretical ingredients for BEC?

The essential steps for arriving at Bose-Einstein condensation are as follows (see also Q. 4): consider a large collection of identical, indistinguishable particles. Distribute them over a large set of "states". Each state may contain any number of particles. It takes a certain energy to add a particle to a state, this energy may depend on the state, but not on the number of particles present in that state. Find the most probable distribution over the different possible energies, assuming that the particles are randomly distributed over the states (taking, e.g., constant average energy; this then defines the temperature). Out comes Bose-Einstein statistics. Now impose the constraint that the total number of particles is fixed. When the temperature is lowered to the point where only about one state per particle is available, Bose-Einstein condensation will result[1].

The characteristics described above show that the occurrence of BEC in a gas relies on some of the most basic ingredients of modern physics. First, the wave-particle duality that is characteristic of quantum mechanics. The wave character is essential, because it quantizes the states, and limits their number to about one per h^3 of phase-space volume. The particle character is essential, because it limits the occupation of any state to an integer number. Second, some basics of statistical mechanics, namely the equal *a priori* probability of each possible distribution over the states, and the method of finding the most probable energy distribution. Third, some specific quantum aspects of many-particle systems, namely that identical particles are fundamentally indistinguishable, and the fact that for bosons the occupation of any state can be arbitrarily large.

Finally, it is perhaps useful to point out that for BEC to occur, it is essential that the total number of particles (or at least its average value) be kept fixed. This is the only reason that photons do not exhibit BEC: their total number is typically not conserved.

Equations

The precise condition for the critical temperature T_c where BEC occurs is

$$n\Lambda^3 = 2.612..., \tag{1}$$

where n is the number density, and Λ the thermal de Broglie wavelength, defined as

$$\Lambda = \frac{h}{\sqrt{2\pi m k_B T}}, \tag{2}$$

where h and k_B are Planck's and Boltzmann's constant respectively, and m is the mass of the particles. Note that this criterion has a simple physical interpretation: the macroscopic population of the ground state occurs once there is more than one particle per cubic thermal de Broglie wavelength. I.e., below T_c the de Broglie waves of the particles necessarily overlap. The value of 2.612... comes out of the quantitative analysis, it is given by Riemann's function $\zeta(3/2)$. See [1] for more details.

4 How can one understand the physics of BEC?

Saturation

BEC is very much like the behavior of a saturable gas: when, at a fixed temperature, more and more particles are added, the excited-state population saturates at some point (the precise criterion is given by Eq. (1)), and all additional particles end up in the ground state. Consequently, another (very useful) way to interpret Eq. (1), is that it gives the (saturated) excited-state density n at temperature T, once condensation has occurred. When the temperature is further lowered, the excited-state density decreases (see Eq. 2), and consequently the ground-state fraction increases (as $1 - (T/T_c)^{3/2}$). The latter formula is specific for particles confined in a box potential. When the trapping potential is harmonic (this is a good approximation for current atomic BEC experiments) the situation is slightly different: the effective volume that is accessible to the

[1] An addition condition here is that the density of states is not peaked around zero energy, this is the case for most real-life systems.

particles decreases when the temperature is decreased, leading to an increased number density. Since the excited-state density at the center of the trap is still limited by the same Eq. (1), the condensate fraction now increases more rapidly as the temperature is decreases (as $1-(T/T_c)^3$, for constant total number of particles).

Maximizing entropy

Note that the saturation is NOT due to interactions between the particles, but due to their statistical properties. The essential ingredient is that thermal equilibrium is a state of maximum randomness (entropy). In other words, the equilibrium distribution of the particles over the allowed energies will be such that the number of different ways in which the particles can be distributed over the states (given the energy distribution) is maximized. When the number of particles exceeds the number of (thermally accessible) states, the number of possible configurations decreases. In order to maintain a large randomness, it then becomes profitable to "stow-away" a considerable part of the particles in the lowest-energy state, so that the remaining particles have more energy at their disposal, and can distribute themselves more thinly over more accessible states. Thus, as counterintuitive as it may seem, the piling up of particles in the ground state is caused by the system seeking its most randomized distribution.

Stimulated scattering

One other way to describe BEC (which may be particularly appealing for people that are familiar with the way lasers work) is as follows. The quantity $n\Lambda^3$ in Eq. (1), often called the phase-space density, is a measure for the average number of particles that is in the ground state. When $n\Lambda^3 \ll 1$ the two in fact become identical. It is a generic property of bosons that the probability of a transition to a certain final state is enhanced when that state is already occupied. In fact, this enhancement equals $N+1$, where N is the occupancy of the final state. In a laser, this yields the familiar distinction between stimulated and spontaneous emission. The laser threshold signals the point where stimulated emission becomes dominant over spontaneous emission.

In a gas of atoms, the same phenomenon occurs when two atoms collide. Here stimulated scattering has the same role as stimulated emission in a laser. As long as the phase-space density is low, the state populations will be negligible compared to 1, and stimulated scattering will not play a role. But when the phase-space density is increased, stimulated scattering into the ground state (which always has the highest thermal population) will become important. This will lead to a self-accelerated build-up of ground-state population, in other words: Bose-Einstein condensation. This argument shows the qualitative similarity between the threshold behavior of a laser and Bose-Einstein condensation.

5 What are bosons?

A property of every particle is its spin, the intrinsic angular momentum. Quantum-mechanically, this spin is only allowed to have integer or half-integer values, and it turns out that these two cases have dramatically different properties. Particles with integer spin are called bosons, particles with half-integer spin (1/2, 3/2, 5/2, ...) are called fermions. The characteristic difference between them lies in the symmetry of the total (many-particle) wave function under the exchange of two identical particles. Since the particles are indistinguishable, the wave function after exchange must be identical to the initial wave function, except for a possible change in phase. For bosons, this phase shift is zero, for fermions it is π, i.e., the sign of the wave function reverses. A direct consequence of this is that no more than one fermion can be present in any particular state (otherwise the wave function is identical to its sign-reversed version, and thus identical to zero). This is Pauli's exclusion principle. For bosons there is no restriction on the number of particles per state. This difference is the source of the different behavior for ensembles of identical bosons (Bose-Einstein statistics) and fermions (Fermi-Dirac statistics).

As an aside, it may be noted here how several features of quantum mechanics come together when one considers composite particles (such as atoms). On the one hand the total spin of such a particle is composed of the individual spins of the composing particles. The final result for the total spin can vary (depending on the relative orientations of the individual spins). But a general rule is that angular-momentum summation rules imply that the composite always has integer spin when it contains an even number of fermions, and has half-integer spin when that number is odd.

On the other hand, we can consider a collection of identical composites, in a situation that the composites can not exchange their constituents, but can only be exchanged as whole entities. The exchange rules for the constituents now imply that the composites behaves as fermions under exchange when they contains an odd number of fermions (in total an odd number of sign changes) and as bosons when they contain an even number of fermions (even number of sign changes).

Thus the angular-momentum sum rules, taken together with the sign-change conventions for the fundamental particles, directly imply that composite particles also must behave as bosons when they have integer spin and as fermions when they have half-integer spin.

An example: sodium (^{23}Na) consists of 11 electrons, orbiting around a nucleus consisting of 11 protons and 12 neutrons. All these particles are fermions (spin 1/2). Since in total it contains an even number of fermions, ^{23}Na is a boson.

6 Where has BEC been observed so far?

First, it should be mentioned that the superfluid transition in liquid helium-4 can be characterized as BEC. It was London [6] who first pointed this out. However, the interactions between the helium atoms in the liquid are quite strong, considerably modifying the nature of the Bose condensate. For a long time, liquid helium remained the only system for which one could speak of BEC. In the nineties, BEC was demonstrated for excitons in semiconductors as well [7]. Here the interactions, although weak, are not yet very well understood; in addition the presence of the semiconductor host material complicates the analysis considerably. For an overview of the field of BEC before the realization of BEC in atomic gases, see [8].

In 1995, in a series of breakthrough experiments, BEC was observed in trapped atomic alkali gases, at JILA (June) [15] and MIT (September) [17] and evidence for BEC was obtained at Rice (July) [16]. in these systems the interactions are weak and well-understood, so that for the first time a detailed comparison to theory is possible. These groups have since then produced a considerable amount of new and exciting results (see Q. 10). Recently, at the CLEO/QELS conference (May 1997), the group of Heinzen (Austin, Texas) reported obtaining BEC as well (source: [9]).

7 What are the key experimental techniques?

Confinement (insulation) and cooling are the key requirements
In practice, BEC was achieved by combining laser slowing, cooling and trapping, magnetic trapping, evaporative cooling, and high-resolution imaging (both absorptive and dispersive). More information on these techniques is provided in almost all review articles (see Q. 10). Laser cooling has become quite a common technique (see also the other papers in this issue), for an overview, see [10, 11]. Evaporative cooling of magnetically trapped atomic gases was first developed for atomic hydrogen, at MIT and also in Amsterdam (see [12, 13] for an overview). The closest approach to BEC for atomic hydrogen to date (within an order of magnitude in phase-space density) is reported in [14].

Typically, the experiments with alkali atoms start with an atomic vapor with a phase-space density of 10^{-12} or lower. Laser cooling and trapping leads to a phase space density around 10^{-6}. The remaining six orders of magnitude are gained by evaporative cooling.

It is perhaps useful to point out here that alkali atoms are ideally suited for laser precooling because they have strong optical (or near-infrared) transitions (in contrast to atomic hydrogen, for which cryogenic precooling was used). The unpaired electron of alkali atoms (and of atomic hydrogen) also gives them a strong magnetic moment, allowing magnetic trapping. Several trapping configurations have been tried out for evaporative cooling (see Q. 8), but it seems the purely magnetostatic trap with a low bias field will become the standard. The latter traps have so far yielded the largest samples of atomic Bose-Einstein condensates (the cloverleaf and baseball traps mentioned below are examples of such traps). See also Q. 13.

8 What experiments have been done so far?

Over ten papers describing experiments on (evidence for) BEC in atomic gases have appeared. These are given in the reference list (in order of date of publication, Refs. [15]-[27]). A list per research group (including some as yet unpublished work that has been submitted):

JILA, Boulder (CO, USA), group of Eric Cornell and Carl Wieman, rubidium-87.
Group home page: [28].

TOP trap:
1. Observation of BEC [15].
2. Collective excitations of condensate [20].
3. Precise measurements of condensate fraction and internal energy [22].
4. Temperature-dependence of collective excitations [26].

Baseball trap:
5. Observation of BEC, with atoms in two different internal states, using sympathetic cooling [24].
6. Strong reduction of three-body recombination in a condensate [29].

Rice University, Houston (TX, USA) group of Randy Hulet, lithium-7.
Group home page: [30].

Permanent magnet trap.
1. Evidence for BEC [16].

2. Observation of BEC and limited condensate number, using polarization-contrast imaging [27].

MIT, Cambridge (MA, USA) group of Wolfgang Ketterle, sodium-23.
Group home page: [31].

Optically plugged spherical-quadrupole trap:
1. Observation of BEC [17].

Cloverleaf trap:
2. Observation of BEC, including determination of condensate fraction and condensate internal energy [19].
3. Nondestructive, dispersive ("dark-ground") imaging of BEC [18].
4. Collective excitations of condensate [21].
5. Radio-frequency output coupler for BEC [23].
6. Interference between two condensates [25].
7. Speed of sound in a condensate, using phase-contrast imaging [32].

9 What is the importance of the scattering length?

Interparticle interactions are very important when considering BEC experiments. Elastic collisions are essential for thermalization and evaporative cooling. Magnetically trapped atomic gases are sufficiently dilute that binary collisions dominate (only for the highest densities do three-body processes play a role). In addition, the temperatures are so low that only s-wave collisions are important (i.e., when the two collision partners have nonzero mutual orbital angular momentum, they can not come close enough to interact, due to the centrifugal barrier). These elastic s-wave collisions can be characterized by a single number, the s-wave scattering length, denoted by a. In many ways, the atoms act as hard spheres with radius a. For instance, the elastic collision cross section is $\sigma = 8\pi a^2$. The value of the scattering length depends very sensitively on details of the interatomic potential (the exact position of the last bound state is very important), see, e.g. [33]. Inelastic binary collisions are usually negligible for alkalis. One of the intrinsic problems of atomic hydrogen is its small scattering length, making inelastic binary collisions relatively important (see, e.g. [34]).

The sign of the scattering length becomes all-important when one considers the stability of a Bose-Einstein condensate. When $a < 0$, the net effect of collisions is an attractive interaction between the particles. When $a > 0$, the interaction is repulsive. Quantitatively, the interaction energy (within a mean-field description) is $4\pi\hbar^2 an/m$, where n is the density. An attractive interaction will tend to make a trapped condensate unstable (the attraction leads to compression, enhancing the density, leading to further compression and so on), in contrast to repulsive interactions (see Q. 12). Relevant references can be found in [27].

BEC is a feature of the ideal gas, i.e., the interactions should be small. In practice, the condensation behavior closely resembles that of BEC in an ideal gas when the interaction energy is much smaller than the thermal energy. This condition is fulfilled in all current atomic BEC experiments. Within the condensate interactions will become important as soon as the interaction energy is larger than the zero-point energy. Typically, this requires $\approx 10^3$ condensed atoms.

10 Where can I find more information?

- Review articles
  A very recent, informal review of atomic BEC can be found in [35]. More technical details, a lot of references, and some addition data, can be found in the earlier reviews [36, 37, 38] by the MIT group and [39] by the JILA group. More informal accounts by the JILA group include [40, 41]. Another early review is [42].

- News stories
  BEC has had ample press coverage. Some of the background stories in scientific magazines include [43, 44]. Science stretched their definition of a molecule to declare BEC "Molecule of the Year 1995" [45], and Time Magazine put BEC at number two in their Top 10 of the best science in 1995. BEC papers have received quite high citation scores, see e.g. [46]. Some of the excitement of Spring 1994, when evaporative cooling was first demonstrated for alkali atoms, can be found in [47]. Another recommended reading is [48].

- Evaporative cooling
  Two extensive reviews have appeared. [34] gives an overview of theoretical methods and ideas, experimental techniques, and a summary of the experiments done until 1996. [13] gives a detailed description of the theory of evaporative cooling, geared towards atomic hydrogen. The latter is mainly based on [49].

- Atomic hydrogen
  An excellent review of the atomic hydrogen work is [12]. A more popular account is [50]. Some of the most recent work can be found in [51] (MIT) and [52] (UvA).

- Books
  A broad overview of the state of the art in the field of BEC, one year prior to the realization of BEC in atomic gases, can be found in Ref. [8]. A book on statistical mechanics describing BEC in detail is [1].

- Websites
  The homepages of the groups that have observed BEC are given in Q. 8. A regularly updated list of electronically available preprints and reprints is maintained at Georgia Southern University: [53]. More general up to date information is also maintained there, see the BEC homepage [9]. Another source of preprints is the Los Alamos preprint server: [54]. BEC manuscripts appear there in either the "condensed matter" or the "quantum physics" section. More relevant links for atom trapping and cooling can be found in, e.g. [55, 56].

- Miscellaneous
  An overview of the field of laser cooling and trapping can be found in [10, 11]. [57] contains a recent reference list on atom trapping.

11 What is an atom laser?

A pragmatic definition could be: an atom laser is a device similar to a laser, with the photons replaced by atoms. There seems to be no consensus on a more precise definition, and perhaps this is only natural, since various different definitions of what constitutes a photon laser are also around (think for instance of the differences between pulsed and continuous lasers). This fuzziness, however, should not distract from the fact that the key characteristics are clear, namely that it is a bright, coherent source.

There is a close analogy between the BEC transition and laser threshold, as indicated above (Q. 4). Some of the standard ingredients of a laser have now been demonstrated for Bose-Einstein condensed atoms, such as coherence [25] and a pulsed output coupler [23]. Following the above pragmatic definition, this constitutes the realization of a pulsed atom laser. A discussion of some of the relevant issues can be found in [58]. Building a continuous-wave atom laser will require considerable extension of current experimental possibilities. A number of schemes to produce a (continuous) atom laser *without* relying on BEC have also been presented in the literature, e.g. [59] (more references can be found in [25]).

12 What is the situation with BEC in lithium?

Unlike the experiments at JILA and MIT, the BEC experiment at Rice university involves atoms with a negative scattering length. For the parameters of that experiment this implies theoretically that the condensate can not contain more than about 1500 atoms, otherwise the interaction energy becomes sufficiently large to overcome the zero-point energy, and the condensate collapses (see also Q. 9). The initial results [16], showed convincingly that conditions close to BEC were obtained, but only indirect evidence for the condensation phenomenon itself was obtained. The paper suggested that the condensate contained significantly more than 1500 atoms. This led to considerable discussion and speculation (see, e.g. [44]). Recently, however, the same group has employed a much improved detection method, and found that the condensate number in their experiment does not exceed 1500, in agreement with theory [27].

13 Why is it difficult to create a Bose-condensed atomic gas?

It seems that reaching the initial conditions for efficient evaporative cooling is the most difficult part, experimentally[2]. Once this has been achieved, it is important to have a stable atom trap in which efficient evaporation can be maintained. Building such a trap is mainly a engineering task, for which several solutions have now been presented in the literature (see Q. 8).

The problem with the initial conditions is that laser cooling and evaporative cooling are somewhat mutually exclusive: laser cooling and trapping work best at low densities (optically thin samples), where problems with rescattered light can be avoided. Evaporative cooling works best at high densities, since it requires elastic collisions. Consequently, BEC experiments required a substantial amount of new techniques to be developed for laser-cooled atoms. Some of the steps typically needed are (i) "dark" cooling that is suited for high-density samples (ii) transfer

[2]The discussion here focuses on alkali atoms. For atomic hydrogen, see, e.g., [12].

of laser-cooled atoms into a magnetic trap and (iii) adiabatic compression of the magnetic trap, to further increase the density.

For evaporative cooling to work efficiently, one needs a large ratio of "good" (elastic) to "bad" (inelastic, decay) collisions (see also Q. 9). Typically, this requires a vacuum pressure that is better than 10^{-10} mbar, to ensure a sufficiently low rate of (bad) background-gas collisions. Another requirement is a sufficiently tightly confining trap, to increase the density and hence the elastic collision rate. The most successful approach to this end has been to use high-current ($\approx$ 300 A) dc electromagnets. These combine a stable trapping potential with the possibility of rapid ($\approx$ 0.1 ms) switching times.

Having a large ($> 10^9$) number of atoms at the initial stages of evaporative cooling is highly beneficial. Firstly, this increases the density and hence the elastic collision rate. Secondly, to gain the necessary six orders of magnitude in phase-space density, evaporative cooling typically loses three orders of magnitude in the number of atoms. So a large initial number is needed if one wants a Bose-Einstein condensate of substantial size (current state of the art: condensates of up to 5×10^6 atoms [19]). Combining such a large initial number of atoms with a low background pressure has only been obtained so far by separating the atom source from the final trapping region (either by using a Zeeman slower (Rice, MIT, Austin), or by using a double MOT (JILA)).

Although most of the above techniques are not difficult to master in principle, most of them were not routinely available in the laser-cooling and -trapping community. A telling sign here is that until very recently no other lab was able to reach BEC after it was reported by three groups in 1995. These groups (in particular JILA and MIT) had been working towards this goal for several years before 1995 (typically with a dedicated group of $\geq$ 3 people).

References

[1] K. Huang, *Statistical Mechanics*, 2nd ed. (Wiley, New York, 1987).

[2] A. Pais, *Subtle is the Lord...* (Oxford University Press, Oxford, 1982).

[3] Bose, Z. Phys. **26**, 178 (1924).

[4] A. Einstein, Sitz. Preuss. Akad. Wiss. 1924, p. 261; 1925, p. 3; 1925, p. 18.

[5] W. E. Lamb, Jr. and A. Nordsieck, Phys. Rev. **59**, 677 (1941).

[6] F. London, Nature **141**, 643 (1938).

[7] Jia Ling Lin and J. P. Wolfe, Phys. Rev. Lett. **71**, 1222 (1993).

[8] *Bose-Einstein Condensation*, edited by A. Griffin, D. W. Snoke, and S. Stringari (Cambridge University Press, Cambridge, 1995).

[9] http://amo.phy.gasou.edu/bec.html.

[10] Special issue on optical cooling and trapping, J. Opt. Soc. Am. B **6**, 2018 (1989).

[11] *Laser manipulation of Atoms and Ions*, edited by E. Arimondo, W. D. Phillips, and F. Strumia (North-Holland, Amsterdam, 1992).

[12] T. J. Greytak, in Ref. [8], pp. 131–159.

[13] 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, Bristol, 1996).

[14] J. M. Doyle *et al.*, Phys. Rev. Lett. **67**, 603 (1991).

[15] M. H. Anderson *et al.*, Science **269**, 198 (1995).

[16] C. C. Bradley, C. A. Sackett, J. J. Tollett, and R. G. Hulet, Phys. Rev. Lett. **75**, 1687 (1995).

[17] K. B. Davis *et al.*, Phys. Rev. Lett. **75**, 3969 (1995).

[18] M. R. Andrews *et al.*, Science **273**, 84 (1996).

[19] M.-O. Mewes *et al.*, Phys. Rev. Lett. **77**, 416 (1996).

[20] D. S. Jin *et al.*, Phys. Rev. Lett. **77**, 420 (1996).

[21] M.-O. Mewes *et al.*, Phys. Rev. Lett. **77**, 988 (1996).

[22] J. R. Ensher *et al.*, Phys. Rev. Lett. **77**, 4984 (1996).

[23] M.-O. Mewes *et al.*, Phys. Rev. Lett. **78**, 582 (1997).

[24] C. J. Myatt *et al.*, Phys. Rev. Lett. **78**, 586 (1997).

[25] M. R. Andrews *et al.*, Science **275**, 637 (1997).

[26] D. S. Jin *et al.*, Phys. Rev. Lett. **78**, 764 (1997).

[27] C. C. Bradley, C. A. Sackett, and R. G. Hulet, Phys. Rev. Lett. **78**, 985 (1997).

[28] http://bec.colorado.edu.

[29] E. A. Burt *et al.*, submitted to Phys. Rev. Lett., May 1997.

[30] http://atomcool.rice.edu.

[31] http://bink.mit.edu/dallin/nat.html.

[32] M. R. Andrews *et al.*, submitted to Phys. Rev. Lett., March 1997.

[33] B. J. Verhaar, in *Atomic Physics 14*, edited by D. J. Wineland, C. E. Wieman, and S. J. Smith (AIP, New York, 1995), pp. 258–275.

[34] W. Ketterle and N. J. van Druten, in *Advances in Atomic, Molecular and Optical Physics*, edited by B. Bederson and H. Walther (Academic, San Diego, 1996), Vol. 37, pp. 181–236.

[35] C. Townsend, W. Ketterle, and S. Stringari, Physics World March 1997, p. 29.

[36] W. Ketterle *et al.*, Phys. Scr. **T66**, 31 (1996).

[37] N. J. van Druten *et al.*, Czech J. Phys. **46, Suppl. S6**, 3077 (1996).

[38] C. G. Townsend *et al.*, in *Trends in Optics and Photonics, Vol. 7, Ultracold Atoms and Bose-Einstein Condensation*, edited by K. Burnett (OSA, Washington DC, 1997), pp. 2–13. Will also appear in *Atomic Physics 15*, edited by H. B. van Linden van den Heuvell, J. T. M. Walraven, and M. W. Reynolds (World Scientific, Singapore, in press).

[39] D. S. Jin *et al.*, Czech J. Phys. **46, Suppl S6**, 3070 (1996).

[40] E. Cornell, J. Res. Nat. Inst. Stand. Technol. **101**, 419 (1996).

[41] C. E. Wieman *et al.*, in *Atomic Physics 15*, edited by H. B. van Linden van den Heuvell, J. T. M. Walraven, and M. W. Reynolds (World Scientific, Singapore, in press).

[42] K. Burnett, Contemp. Phys. **37**, 1 (1996).

[43] K. Burnett, Science **269**, 182 (1995); Physics World, October 1996, p. 18. G. P. Collins, Physics Today, August 1996, p. 18. B. Goss Levi, Physics Today, March 1997, p. 17. G. Taubes, Science **272**, 1587 (1996).

[44] G. P. Collins, Physics Today, March 1996, p. 18.

[45] F. E. Bloom, Science **270**, 1901 (1995).

[46] http://www.isinet.com/whatshot/htpr9721.html.