Bose-Einstein Condensate from the Fridge

Ensembles of buffer-gas loaded magnetically trapped atoms can be evaporatively cooled all the way down to quantum degeneracy.

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Rejected by the *Philosophical Magazine*, S.N. Bose's paper on photon statistics landed famously, in June 1924, on the desk of A. Einstein, who had duly translated it and promptly passed it on for publication [1]. Led by the same dialectics that made him adopt his 1905 "heuristic viewpoint" about a gas of "light quanta" [2], Einstein recognized that Bose's "viewpoint" (Einstein's parlance in quotes) can, conversely, be applied to an ideal gas of atoms or molecules [3]. Such a dualistic approach was consistent with L. de Broglie's Thesis, of which Einstein had been likely aware at the time [5]. Bose's counting was non-Boltzmannian, as it implicitly – and fortuitously – entailed indistinguishability of the "molecules" of light or gas [6]. Combining Bose's counting with a constraint on the number of "molecules" (which is conserved) led Einstein to the following prediction [4]: "I maintain that [below a critical temperature] a number of molecules steadily growing with increasing density goes over in the [ground] quantum state (which has zero kinetic energy) while the remaining molecules distribute themselves according to their [chemical potential] ... A separation is effected; one part condenses, the rest remains as 'saturated ideal gas'." However, as F. London put it in 1938, "in the course of time the [condensation] of the Bose-Einstein gas has rather got the reputation of having only a purely imaginary existence" [7]. It took the effort of D. Kleppner and T. Greytak at MIT in Cambridge, Massachusetts, and their scientific progeny, direct and removed, in particular E. Cornell, R. Hulet, W. Ketterle, D. Pritchard, and C. Wiemann, to achieve eventually, in the 1990's, Bose-Einstein condensation (BEC) in the laboratory. The latest advance, described in the paper of Doret *et al.* [8], demonstrates that a BEC can be created from a buffer-gas cooled cloud of atoms, i.e., without resorting to atom-specific laser cooling, which so far has been the workhorse of cold-atom physics.

Although the paths taken toward BEC by various research groups have differed in the laser-cooling and trap-loading steps, they all had the subsequent step in common: *evaporative cooling* in the trap. The idea of evaporative cooling came to H. Hess in the mid-1980's when he was a postdoc in the MIT group [9]: he recognized that by lowering the depth of a trap holding a cloud of atoms in thermal equilibrium with one another will *both* reduce the cloud's temperature (the most energetic atoms will escape first) and increase the cloud's density (the atoms will be confined by a smaller volume) – at least as long as there are enough elastic collisions to maintain the thermal equilibrium (and not too many inelastic collisions to destroy the sample). Such a dual action is exactly what's needed in order to attain BEC (or quantum degeneracy in general), since in that regime the product of the number density, n, and the cube of the thermal de Broglie wavelength, $\Lambda = h/(2\pi mkT)^{1/2}$, has to be on the order of unity, $n\Lambda^3 \approx 1$ (h and k are, respectively, Planck's and Boltzmann's constants, m is the atomic mass, and T the absolute temperature) [10]. The MIT group was set on condensing atomic hydrogen, which features a unique property shared by no other atom: it can be thermalized to a few hundred millikelvin by a surface, albeit a very special one, namely that of liquid helium. Every other atom-surface pair has a much higher binding energy so that the atoms' vapor pressure is negligible – except, of course, for helium itself. Surface thermalization of hydrogen allowed loading of a magnetic trap and subsequent evaporative cooling à la Hess [11], which led later to a BEC of hydrogen [12].

Helium's vapor pressure is a uniquely useful property as well: it's high enough for helium to act as a buffer gas that can cool other species injected into it sympathetically, via elastic collisions. The technique of *buffer-gas cooling*, developed by the group of J. Doyle at Harvard University in 1994-98 [13], circumvents the limitation of the hydrogen surface thermalization technique by loading atoms (or molecules) into a trap *before* they can touch a surface, stick to it and get lost. The helium buffer gas can itself be cooled by a cryogenic device, such as a cryostat or a dilution refrigerator. Because buffer-gas cooling is largely independent of the energy levels and most other attributes of the cooled particles, it is *versatile*, applicable equally well to essentially any atoms *or* molecules. Under typical conditions, about 100 thermalization collisions are needed. In order to ensure thermalization along a path shorter than the dimensions of the cryogenic cell (i.e., about a cm), the buffer gas must have a sufficiently high density. Since gas density goes down with decreasing temperature (the gas gets frozen out), a certain minimum temperature exists below which the number density would be too low to enable thermalization (roughly 10^{16} atoms per cm^3). This minimum temperature is about 500 mK in the case of the bosonic isotope ^{4}He – quite cold, but not cold-enough to reach quantum degeneracy. Fortunately, buffer-gas cooling naturally combines with deep magnetic traps, as both require cryogenics. Magnetic traps, in turn, have large volumes, capable of confining clouds with a large number of atoms. Such clouds can be therefore substantially cooled by Hess's evaporation, before running out of atoms and thus elastic collisions instrumental for maintaining the requisite thermal equilibrium. Doret *et al.* demonstrate that variants of evaporative cooling can take an ensemble of buffer-gas loaded magnetically trapped atoms all the way down to the BEC regime.

The bosons that are condensed in the demonstration experiment are metastable helium atoms, He(2^3S) $\equiv$He*, which have been condensed previously by other means, see ref. [14] for a survey. They are produced from the nonmagnetic, ground-state buffer gas by a radio-frequency (RF) glow discharge (which excites about a 10^{-5} fraction of the He buffer-gas atoms present). Metastable helium is paramagnetic, with a dipole moment of 2 Bohr magnetons, and thus can be magnetically trapped; its radiative lifetime is about 7800 s [15]. The anti-Helmholtz magnetic trap used in the experiment has a depth of almost 5 K, capable of confining an initial population of about 10^{11} He* atoms, buffer-gas loaded at a temperature of about 500 mK, see Figure 1. After loading, the buffer gas is removed by a cryo-sorption pump, leaving behind a cloud of magnetically levitating He* atoms. The evaporative cooling step which follows reduces the cloud's temperature to the mK range. In order for the step to be successful, the ratio of the elastic to any inelastic collision cross sections that may convert a trappable state into an untrappable one must be large (exceeding about 100). This is apparently well satisfied for He*. If inelastic collisions are a Scylla of evaporative cooling, Majorana transitions are its Charybdis. Atoms (and molecules) can be namely also converted from trappable to untrappable states by adiabatic passage through regions of zero field strength. Therefore, in order to skirt Charybdis, the magnetic field of the trap must be non-zero everywhere. An anti-Helmholtz trap would not do, as its minimum is at zero field. In an Ioffe-Pritchard trap, the minimum is uplifted to a nonzero value by a magnetic field generated by an extra magnetic coil [16]. In the work of Doret *et al.*, the magnetic field of the anti-Helmholtz trap is reduced asymmetrically during the evaporative cooling step, which serves the additional purpose of moving the trapped cloud into an Ioffe-Pritchard trap, in which the He* cloud can be further evaporatively cooled down to the BEC regime, cf. Fig. 1. This is done not by reducing the depth of the Ioffe-Pritchard trap, but by slashing away the translationally hotter atoms by a fine-tuned resonant RF field (dubbed an RF knife). This last step leaves behind a BEC whose "separated" core consists of about 200 000 to 300 000 He* atoms, surrounded by a tenuous "saturated ideal gas." The BEC's lifetime is limited by Penning ionization arising from binary and even ternary collisions of He* atoms, each of which carries an electronic energy of about 20 eV, equivalent to a temperature of 230 000 K, i.e., roughly 40-times the surface temperature of the star that gives helium its name. The Penning ionization rates are, however, low enough to keep the huge electronic energy out of the game for a while, lending the He* BEC a lifetime of about a second.

The experiment of Doret *et al.* demonstrates that when it comes to creating quantum gases using evaporative cooling in a magnetic trap, the buffer-gas cooling technique is the most versatile one to deploy for the first cooling step. In particular, there are atoms predicted to have good collisional properties, such as atomic nitrogen, which are extremely difficult to laser cool. Such atoms may also serve as precursors of intriguing molecules that could be synthesized from the ultracold atoms, e.g., via magneto- or photo-association. The work marks the beginning of an era of plenty, when we can help ourselves to chemically diverse BEC's by reaching for the fridge.

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[1] Bose, S.N. *Z. Phys.***26**, 178 (1924).

[2] Einstein, A. *Ann. Phys.***17**, 132 (1905).

[3] Einstein, A. *Sitzungsberichte Preuss. Akad. Wiss.* p. 261 (1924).

[4] Einstein, A. *Sitzungsberichte Preuss. Akad. Wiss.* p. 3 (1925).

[5] Pais, A. *Subtle is the Lord*, Oxford University press, New York, 1982, p. 437.

[6] Darrigol, O. *Historical Studies in the Physical and Biological Sciences* **16**, 197 (1986).

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

[8] Doret, S.C., Connolly, C.B., Ketterle, W., Doyle, J.M. *Phys. Rev. Lett.* **XX**, xxxx (2009).

[9] Hess, H.F. *Phys. Rev.* **B 34**, 3476 (1986).

[10] Ketterle, W. in *Les Prix Nobel 2001*, The Nobel Foundation, Stockholm, 2002, pp. 118-154; *ChemPhysChem* **3**, 736 (2002); *Rev. Mod. Phys.* **74**, 1131 (2002).

[11] Masuhara, N., Doyle, J. M., Sandberg, J. C., Kleppner, D., Greytak, T. J., Hess, H. F., Kochanski, G. P. *Phys. Rev. Lett.* **61**, 935 (1988).

[12] Fried, D.G, Killian, T.C., Willmann, L., Landhuis, D., Moss, S.C., Kleppner, D., Greytak, T.J. *Phys. Rev. Lett.* **81**, 3811 (1998).

[13] Campbell, W., Doyle, J.M. in *Cold Molecules: Theory, Experiment, Applications*, Krems, R.V., Stwalley, W.C., Friedrich, B. (Eds.), CRC/Taylor and Francis, Boca Raton, 2009, pp. 473-508.

[14] Hulet, H. *Nature* **411**, 425 (2001).

[15] Hodgman, S.S., Dall, R.G., Byron, L.J., Baldwin, K.G.H., Buckman, S.J., Truscott, A.G. *Phys. Rev. Lett.* **103**, 053002 (2009).

[16] Esslinger, T., Bloch, I., Hansch, T.W. *Phys. Rev.* **A 58**, R2664 (1998).

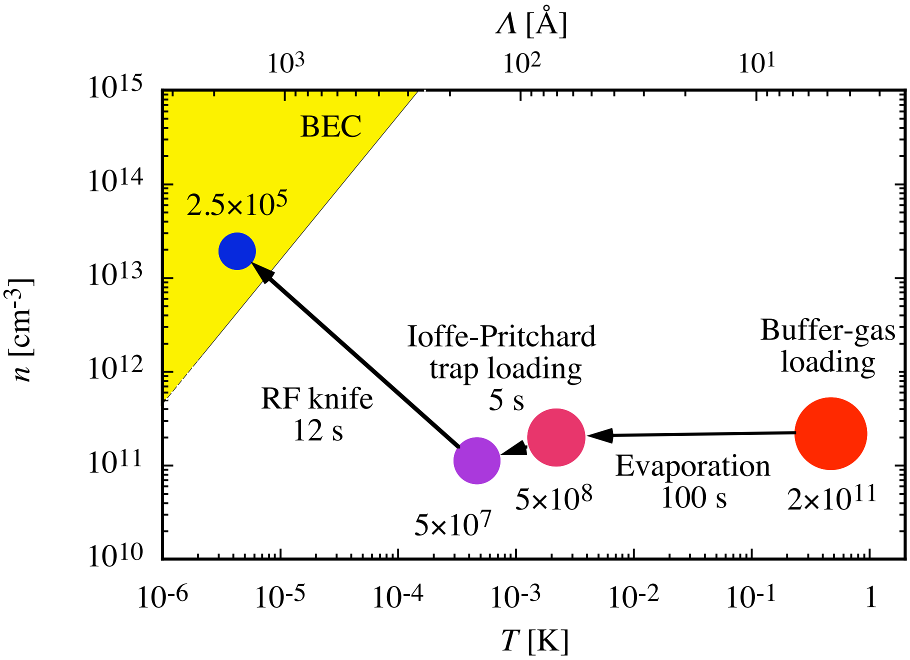

FIG. 1: Key steps on the pathway across the density (n) versus absolute temperature (T, lower abscissa) plane toward the Bose-Einstein condensate (BEC) of gaseous He(2^3S) ≡He*. The path's milestones are marked by color-coded circles (red corresponds to cold, blue to ultracold) whose area reflects the logarithm of the number of the trapped He* atoms. Also shown are the times chosen to take the steps. Yellow shading marks the region of quantum degeneracy where the de Broglie wavelength, Λ, of He* (upper abscissa) exceeds the mutual separation of the (bosonic) atoms, and thereby fosters the formation of a BEC. See text.