Researchers Can Now Vary the Atomic Interactions in a Bose–Einstein Condensate

Bose–Einstein condensates (BECs) were formed five years ago from rubidium-87 and sodium atoms, whose interactions are repulsive. BECs were also formed from lithium-7 atoms, which attract one another. (See the article by Wolfgang Ketterle in PHYSICS TODAY, December 1999, page 30.) Now researchers in Boulder, Colorado, have created a single condensate of rubidium-85 atoms, which can be taken continuously from the repulsive to the attractive regimes.[1] The experimenters can vary the strength of the interaction between the atoms in their condensate by a factor of 100 or more—and even flip its sign—by changing the external magnetic field. The ability to tune the interactions of a condensate opens the door to systematic explorations of atomic behavior in new regimes.

In a dramatic demonstration of this capability, the team forced a condensate into the attractive regime, where it collapsed in on itself: The condensate blew off some fraction of its mass, leaving a smaller condensate at the core, in a manner reminiscent of a supernova. This core was then brought back to the repulsive regime and reexpanded. Carl Wieman whimsically refers to the event as a "bose nova." (Wieman and Eric Cornell headed the experimental team, which also included Simon L. Cornish, Neil R. Claussen, and Jacob L. Roberts; all are affiliated with JILA, the National Institute of Standards and Technology, and the University of Colorado.) Randall Hulet and his group at Rice University had already seen the collapse of a condensate of attractive atoms,[2] but they do not have the ability to change the sign of the interaction.

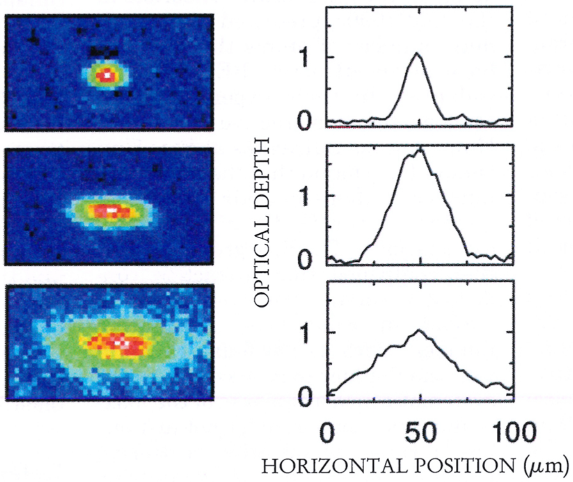
The scattering length

The interaction strength of condensates can be manipulated largely because it depends essentially on one parameter, a, the s-wave (zero angu-

> Like a couple in a love–hate relationship, atoms in a condensate can shift from attracting to repelling one another—just by the turn of an experimental knob.

lar momentum) scattering length between two atoms. When atoms repel, they behave much like a bunch of randomly moving hard spheres of radius a, bouncing elastically off one another. When atoms attract, they tend to pull together, and a is then negative.

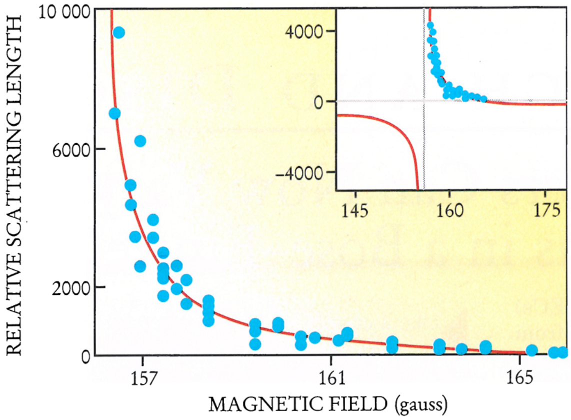
During an atomic collision, atoms can stick together for a short time and form a molecule. If the magnetic moment of the molecular state differs from that of the atoms, one can use a magnetic field to vary the energy difference between the atomic and molecular states. At a so-called Feshbach resonance, the energy of the molecular state matches the energy of the colliding atoms (which is essentially zero in a condensate), and the atoms can stick together for a long time. When the two atoms thus flirt with entering a molecular state, the scattering is greatly enhanced. As the magnetic field goes through this Feshbach resonance, a grows rapidly stronger, changes sign, and then weakens as the field is taken farther from resonance. (See the inset of the figure on page 18.) The use of Feshbach resonances to tune atomic interactions was suggested in 1992 by Boudewijn Verhaar, of the Eindhoven University of Technology in the Netherlands, and his colleagues.[3]



BEC GROWS with scattering length. False-color images in left-hand column show the condensate column density for magnetic fields of 162.5 G (top), 158.4 G (middle), and 156.4 G (bottom). Clearly the condensate expands as it nears the Feshbach resonance at 155 G, where the atoms become far more repulsive. Plots on right display the corresponding horizontal cross section. The number of atoms was varied to keep the optical depth constant. (Adapted from ref. 1.)

Although many atoms have Feshbach resonances, near which one can tune the interactions, such resonances have so far been seen only in a few atoms. That's because the resonances are only evident at very low temperatures, and they usually occur at inconveniently large magnetic fields. Two years ago, researchers at MIT were able to observe a Feshbach resonance in a sodium BEC by using optical rather than magnetic fields to trap the atoms.[4] They observed a tenfold variation of the scattering length, in agreement with theoretical predictions. However, heavy losses of atoms from the condensate near resonance prevented further experimentation. Other groups have since seen evidence of Feshbach resonances in cold atoms of ^{85}Rb and cesium, but not in condensates of those atoms.

The Boulder experimenters used ^{85}Rb atoms, which have a Feshbach resonance at low enough magnetic fields to allow magnetic trapping of the atoms. They reduced the losses that can occur near a Feshbach resonance, in part by working at much lower condensate densities than in the MIT experiment. Luckily, the



SCATTERING LENGTH versus magnetic field near a Feshbach resonance at 155 G. Data points indicate the scattering length determined from the size of the condensate. Smooth curve is the theoretical expectation. The scattering length is given relative to the Bohr radius. Inset shows the full extent of the Feshbach resonance. (Adapted from ref. 1.)

researchers were also able to find a narrow window in the magnetic field just above the Feshbach resonance, where losses are lower than they would be even far from resonance. Still, the experimental team had to overcome a number of technical challenges before they could evaporatively cool the atoms to low enough temperatures to form a condensate. As the researchers caution in their paper, ^{85}Rb "is plagued with pitfalls for the unwary evaporator." They finally found a path to evaporative cooling by starting the cooling at a magnetic field far above resonance and then moving closer in. The team can now produce long-lasting condensates containing up to 10 000 atoms.

For the hyperfine ground state of ^{85}Rb used in this experiment, the Feshbach resonance occurs at a magnetic field of 155 G. The Boulder group ranged the magnetic field over values just above this (from 156 to 166 G) and imaged the shape of the condensate for each step in field strength. The closer the condensate comes to the Feshbach resonance, the larger it becomes thanks to the increased repulsion, as illustrated in the figure on the previous page. The researchers made quantitative measurements of the density distributions and from them deduced the value of the scattering length a. The values of a thus derived from experiment are plotted as a function of magnetic field in the figure above. Superposed on the data points is a smooth curve, which represents the theoretically expected variation of the scattering length with magnetic field.

When the Boulder researchers increased the magnetic field above 166.8 G, they entered the regime where a is expected to be negative. That's where they observed the bose nova explosion. In that event, Wieman estimates, some 20–40% of the atoms in the original condensate were ejected at high enough energies to escape the trap; another 10–20% were thrown out of the condensate but still oscillated within the trap. Left behind at the core was a smaller condensate.

Dramatics aside, the ability to exert some control over the onset of collapse opens new possibilities for exploring the dynamics of such implosions. In the region of negative scattering lengths, the attractive interaction makes a condensate unstable against collapse. However, as the size of a cloud shrinks, Heisenberg's uncertainty principle requires its momentum uncertainty and therefore its kinetic energy to increase. This energy increase prevents the collapse for a sufficiently small number of atoms in the condensate. Theorists in the mid-1990s predicted the maximum number of atoms that one can have in an attractive BEC before it collapses. In their experiments on condensates of attractive ^{7}Li atoms, Hulet and his colleagues at Rice University have found that the maximum number of atoms in their condensate is consistent with these theoretical expectations.[5] The Rice group has further confirmed that attractive condensates collapse by observing the spread in condensate occupation number.[2] With its newfound capabilities, the Boulder team has now begun systematic measurements of the maximum condensate size for not just one but a range of negative scattering lengths. The group is also studying the angular and energy distributions of the ejected material.

The challenge for theorists

To date, most measurements of the properties of BECs have been made in a regime of weak interactions, where the atomic collisions are described well by a mean field theory. The assumption has been that all collisions involve only two atoms. But near a Feshbach resonance, the atoms effectively get larger, and three-body interactions become more likely. Theorists are anxious to study what modifications will be required of their models in this new regime. Henk Stoof of the University of Utrecht in the Netherlands is interested in the impact of the larger scattering length on the oscillation modes of a condensate: Up to now, the oscillations have been studied in a regime where there are few elastic collisions between atoms in each cycle as the gas cloud expands and contracts; but the Boulder experiment allows one to study a cloud in the hydrodynamic (strong scattering) regime, where many elastic collisions occur during one cycle.

Even before the Boulder experiment, theorists had been doing simulations of how condensates collapse. Their models can now be challenged with new data. Stoof notes that many of the atoms ejected by the Boulder implosion still have low enough energies to be trapped; he thinks that the low energy can be explained in terms of elastic collisions between condensate atoms (inelastic collisions should impart higher energies). Keith Burnett of Oxford told us that "the ability to tune a mesoscopic system into collapse was one of the dreams driven by the first achievements of BEC. . . .This collapse of an unstable ground state (or vacuum) of a quantum field will have many features that we theorists would like to investigate." He rattled off a list of questions such as the role of quantum fluctuations in the dynamics, the relation of the "thermal" cloud present before the implosion to the collapsing core, and the part played by other thermal atoms produced in two- and three-body collisions. Reflecting the fun the theorists are having in this new playground, Burnett remarked, "What a blast!"

BARBARA GOSS LEVI

References

1. S. L. Cornish, N. R. Claussen, J. L. Roberts, E. A. Cornell, C. E. Wieman, to appear in Phys. Rev. Lett.
2. C. A. Sackett, J. M. Gerton, M. Welling, R. G. Hulet, Phys. Rev. Lett. **82**, 876 (1999).
3. See, for example, E. Tiesinga, A. J. Moerdijk, B. J. Verhaar, H. T. C. Stoof, Phys. Rev. A **46**, R1167 (1992).
4. S. Inouye, M. R. Andrews, J. Stenger, H.-J. Miesner, D. M. Stamper-Kurn, W. Ketterle, Nature **392**, 151 (1998).
5. C. C. Bradley, C. A. Sackett, R. G. Hulet, Phys. Rev. Lett. **78**, 985 (1997).