Time, Einstein, and the Coldest Thing in the Universe

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Laser cooling of atoms has led to a new generation of atomic clocks that are essentially free of inaccuracy arising from motional effects such as the relativistic time dilation predicted by Einstein. Microkelvin atoms in atomic fountains now provide the world's most accurate timekeeping; clocks at LPTF in Paris and NIST in Boulder are accurate to a second in 20 million years. The performance of these clocks is, however, limited by earth's gravity. The atoms are in free-fall, and in the best of the clocks they stay for only about a second before falling out. This limited observation time limits the precision and accuracy of earthbound clocks. Clocks in the microgravity environment of earth orbit should be much better, but the microkelvin temperatures achieved with ordinary laser cooling are not low enough to fully exploit the advantage: the thermal velocity of even microkelvin atoms is large enough that a small cloud of atoms will spread too much during times much longer than a second.

While there are several ways to reach temperatures below the microkelvin limits of "ordinary" laser cooling, a particularly intriguing one is Bose-Einstein condensation (BEC). The phenomenon predicted by Einstein in the early part of the century was first achieved by evaporative cooling of a rubidium gas in 1995 at NIST in Boulder. In BEC, a large fraction of the atoms in a gas occupy the lowest possible quantum state of motion. Temperatures achieved are in the nanokelvin range, but for many purposes, a Bose-Einstein condensate can be thought of as being effectively at zero temperature.

A few clock generations hence, an orbiting Bose-Einstein condensate may well provide timekeeping several orders of magnitude more accurate than today's earthbound devices. Already, however, BEC has changed the landscape of atomic physics. The atoms in a BEC, being all in the same quantum state, have deBroglie wave coherence properties similar to the optical wave coherence properties of laser light.

In experiments at NIST in Gaithersburg we have exploited the coherence of BECs in a series of atom optics experiments where the atomic waves take the role played by light waves in conventional optics. Diffraction and Bragg reflection have become our standard tools for coherent manipulation of the condensates, allowing interferometric measurements of their properties.

Following the same path taken with optical lasers shortly after their invention, we demonstrate non-linear atom optics. Four wave mixing of deBroglie waves creates a new atom wave from the non-linear interaction of three other waves. Phase imprinting the condensate wavefunction produces a soliton that propagates in the atomic gas.

Bose-Einstein condensates so large that they are visible to the naked eye nevertheless represent a single, coherent, macroscopic quantum mechanical wavefunction. We have sufficient control over this macroscopic wavefunction that we can print letters onto its quantum phase, and reveal the message by interferometry.

Coherent atom waves are as different from ordinary atoms as lasers are from lightbulbs. Their applications might also be as interesting and as diverse.