Observation of Atoms Laser-Cooled Below the Doppler Limit

This 1989 paper [1] reported a breakthrough which led to a Nobel Prize for William D. Phillips—the first Nobel to be awarded to a NBS/NIST staff scientist. The experiment described in the paper demonstrated that light from a laser could be used to cool atoms to a much lower temperature than was previously thought possible. The fact that light carries momentum and can exert a force on objects was realized by James Clerk Maxwell in his theory of electromagnetism, developed in the 19th century. At the turn of the century, experiments by Lebedev [2] and Nichols and Hull [3] for the first time measured these forces in the laboratory. This concept of radiation pressure helped explain why comet tails point away from the sun and was important in understanding the stability of certain types of stars, but it had little laboratory relevance until the advent of the laser. In 1975, two groups proposed the counter-intuitive idea that radiation pressure from a laser could be used to *cool* atoms [4,5]. By carefully choosing the frequency of the laser, it appeared possible to cause the atoms to emit light at a slightly higher frequency (energy) than they absorbed, carrying away the thermal energy of the atom. This frequency difference derived from the Doppler shift due to the motion of the atoms. Doppler cooling was first demonstrated [6] with trapped ions in 1978 (at NBS by the Wineland group).

William Phillips joined the Electricity Division at NBS in 1978 to work on the gyromagnetic ratio of the proton and the SI ampere experiments, with the understanding that he could devote some of his time to developing laser cooling ideas for neutral atoms and atomic beams. He was joined in his efforts by a long-term visitor to NBS, Harold Metcalf from the State University of New York at Stony Brook. Several of the key achievements in neutral-atom laser cooling were produced by what would become the Laser Cooling Group. These included the demonstration of efficient ways of decelerating atomic beams with laser light: Zeeman cooling [7], in which the changing Doppler shift of a decelerating atomic beam is compensated by a spatially-varying magnetic field, and "chirped" cooling [8], where the Doppler shift is compensated by a changing laser frequency. These two methods are still the only methods used today to decelerate atomic beams. Another significant accomplishment of the Laser Cooling Group was the first trapping of neutral atoms with magnetic fields [9] in 1985. Magnetic trapping is now widely used in dozens of experiments studying Bose-Einstein condensation of dilute gases.

By the late 1980s a few groups around the world were investigating the properties of "optical molasses," the name given to a "sticky" configuration of laser beams that could cool and hold on to atoms for as long as a few seconds. The action of the light upon the atoms created a viscous environment for the atoms, hence the "molasses" appellation. A group at Bell Laboratories, headed by Steven Chu, had measured a temperature of 240 μK [10] for a sample of sodium optical molasses, in accord with the Doppler cooling theory that had been developed a few years earlier. The NBS group had made a number of measurements of the properties of a sodium molasses, such as the lifetime of the atoms in the molasses. Each measurement they made had disturbing discrepancies between the results and the Doppler theory. At the urging of one of the members of the team, Paul Lett, then a recently arrived postdoctoral fellow, they set out to measure the temperature of the atoms. This was something that they had shied away from earlier because its measurement was rather difficult and it had already been done at Bell Labs. They crafted a new, sensitive technique to measure the velocity distribution of the cold atoms, and thus extract the temperature. The time-of-flight technique they developed looked for fluorescence from atoms that traversed a probe laser beam after being released from the molasses. The duration of the pulse of fluorescence would be inversely proportional to the atomic velocity, which would allow the extraction of the temperature. For reasons of convenience, they placed the probe above the molasses (at 240 μK the atoms would have plenty of thermal velocity to overcome gravity to reach the probe). After a number of puzzling days with no signals, they moved the probe *under* the molasses and immediately saw a strong pulse of fluorescence (Fig. 1). To their great surprise, the temperature that they found was 40 μK (the atoms were so cold that gravity turned them around before they could reach the probe placed above the molasses). This result was six times lower than what the theory had predicted was the ultimate limit, the so-called Doppler limit, as well as contradicting the Bell Labs results [11]. To assure that some unknown feature of their new measurement technique was not deceiving them, they measured the temperature with three other methods, all of which were

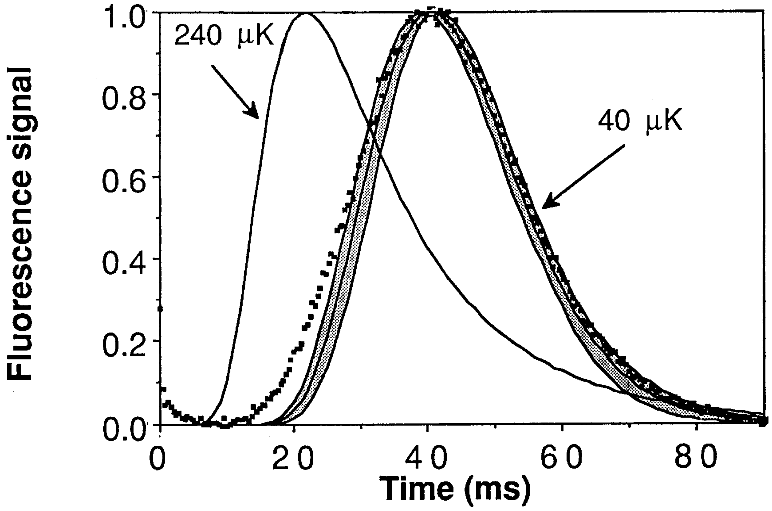

Fig. 1. Time-of-flight measurement of the temperature of optical molasses. The points show the experimental measurements of the time-of-flight distribution of atoms falling from an optical molasses through a probe laser beam situated 12 mm below. The solid lines show the predicted distribution curves for 40 μK and 240 μK (the predicted lower limit of Doppler cooling). The band around the 40 μK curve reflects the uncertainty in the measurement of the geometry of the molasses and probe.

in agreement—the temperature of optical molasses was much lower than anyone had thought possible. This was announced in *Physical Review Letters* and was rapidly confirmed in other laboratories around the world (including that of Chu, who had moved to Stanford). Almost as rapidly, a new theory of laser cooling was developed that explained these results [12]. Not only did it extend the simple theory by taking into account the detailed atomic structure of the atoms, but it also showed that there existed qualitatively different laser-cooling mechanisms that had not been anticipated. (Claude Cohen-Tannoudji shared the 1997 Nobel Prize in Physics with Phillips and Chu, in part for his development of the sub-Doppler laser-cooling theory.)

Spurred in part by the spectacularly low temperatures possible with these new cooling mechanisms, laser-cooling experiments blossomed around the world with more than 100 laboratories involved in such research by the late 1990s. These ultracold temperatures have had an impact in many areas of atomic physics, spawning whole new areas of research, such as ultracold collision physics and optical lattices. They were critical as the first step in the creation of the much sought after Bose-Einstein condensation of an atomic gas, achieved in 1995 at NIST/JILA [13]. The table-top aspect of laser-cooling experiments has spurred their introduction into many undergraduate laboratory courses, providing for many students the first exposure to modern laser technology and atomic physics.

The most significant societal impact of this discovery is in time-keeping, one of the traditional core responsibilities of NBS/NIST. The second is defined with respect to a microwave transition in the cesium atom, which fortuitously is an ideal atom to laser-cool. The sub-Doppler laser-cooling temperature for cesium (1 μK to 2 μK) can be *100 times* lower than the Doppler limit. Because such cold atoms move so slowly, they can be observed for a much longer time than was previously possible, dramatically increasing the precision and accuracy of a cesium frequency standard. Using an idea from 1954, well ahead of its time but now made possible with sub-Doppler laser cooling, the cesium atoms form an atomic fountain, undergoing a one meter high parabolic trajectory in the earth's gravitational field with a resulting hundred-fold increase in the observation time. This has led to an immediate improvement of the performance of frequency standards and, as of this writing, the definition of the second is in large part determined by laser-cooled cesium atomic clocks, including NIST's F-1 fountain standard which came on line in December 1999.

William Phillips joined the Electricity Division at NBS in 1978, and began his research in laser cooling soon thereafter, while continuing involvement in the Ampere experiment. Paul Lett, Richard Watts, Christoph Westbrook, and Phillip Gould were all postdoctoral fellows in the group in 1988 at the time of the publication of the sub-Doppler cooling paper. Lett has remained at NIST as a staff physicist in the Laser Cooling and Trapping Group; Watts was a staff physicist in the Photon Physics Group at NIST, but died in 1996; Westbrook left NIST in 1993 to become a staff physicist

Fig. 2. Current permanent staff members of the NIST Laser Cooling and Trapping Group, as photographed in Stockholm for the awarding of the 1997 Nobel Prize in Physics. From the left: Paul Lett, Steven Rolston (joined NBS in 1988), William Phillips, and Kristian Helmerson (joined NIST in 1991).

at l' Institut d'Optique, Orsay, France; Gould left NBS in 1988 to become a professor of Physics at the University of Connecticut. Harold Metcalf was a visiting scientist at NBS/NIST and is a professor of physics at the State University of New York at Stony Brook. The Laser Cooling and Trapping Group moved to the Atomic Physics Division in the Physics Laboratory at NIST in 1991. The group has continued to be an active, prolific group, with over 25 publications in premier journals such as *Physical Review Letters, Nature,* and *Science.* They are recognized world leaders in the areas of laser cooling, ultracold collision physics, optical lattices, and Bose-Einstein condensation. Phillips was recognized as a co-recipient of the 1997 Nobel Prize in Physics "for development of methods to cool and trap atoms with laser light" [14].

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