Doing 'Cool Things' with Lasers!

The idea of laser cooling, which is featured on the cover of this issue of *Resonance*, starts from Einstein's seminal 1917 paper on the quantum theory of radiation in which he derived two new results: that atoms undergo stimulated emission, and that light of wavelength λ consists of photons carrying momentum h/λ, where h is Planck's constant. The idea of stimulated emission led to the development of lasers in the 1950s and revolutionised the field of spectroscopy. And the idea of photon momentum led to the concept of radiation pressure and light forces. When tunable lasers became available in the 1970s, scientists realised that lasers could be tuned near single atomic resonances where atoms scatter photons at a very large rate resulting in large radiation pressure forces. Using these ideas, two groups in 1975 independently proposed the use of near-resonant laser light to cool atoms or ions to very low temperatures. The proposal by Ted Hänsch and Arthur Schawlow was to cool neutral atoms using the Doppler effect, and the proposal by Dave Wineland and Hans Dehmelt was to cool trapped ions using motional sidebands (it was later realised that the sideband cooling technique for ions was equivalent to Doppler cooling for atoms). By 1980 laser cooling of ions was demonstrated by Wineland's group. In 1985, laser cooling of neutral sodium atoms to a temperature below 1 mK was demonstrated by Steven Chu and co-workers at AT&T Bell Labs using three pairs of orthogonal counter-propagating laser beams. This configuration of laser beams was termed 'optical molasses' to indicate the viscous effect of the laser light on the atomic motion.

Two major developments took place in the field of laser cooling of neutral atoms in the late 1980s. One was the idea by Pritchard's group that, by superposing an inhomogeneous magnetic field on the optical molasses configuration, the laser cooled atoms could be simultaneously *trapped.* The combination is now called a magneto-optic trap (MOT for short) and has become the workhorse in this field. It is the starting point for almost all laser cooling experiments. The second important development was the serendipitous discovery that, under the right conditions, laser cooling works much better than what is predicted by Doppler cooling theory. The temperatures attained are in the range of a few μK, about 10-100 times lower than what is achieved in Doppler molasses. This discovery led to the award of the 1997 Nobel Prize in Physics jointly to Steven Chu, Claude Cohen–Tannoudji and William Phillips.

Over the last decade, laser cooling of atoms and ions has developed into an important field of research. It has impacted research both in basic and applied physics. In basic physics, laser cooled ions have been used to study the foundations of quantum mechanics using entangled 'Schrödinger cat' states, to study quantum cryptography, and to build a rudimentary quantum computer using a chain of laser cooled ions where each ion acts as a quantum bit. Laser cooled atoms have been used to study long range molecule formation as ultra-cold atoms collide with each other. They have been used to build atom interferometers which are potentially sensitive to weak gravitational waves. Perhaps the most spectacular development in this field has been the observation of Bose–Einstein condensation in a dilute gas in 1995. Since then, alkali-atom condensates have been manipulated in many ways to strengthen our understanding of quantum mechanics. On the applied front, laser cooled ions have been proposed for future optical frequency standards or clocks. A clock based on a single trapped ion perhaps would be the ultimate in stability and reproducibility. Laser cooled Cs atoms have already been used to build a fountain clock which is 10 times better than existing atomic clocks. Cold atoms have also been manipulated by light beams for an emerging technology called 'atom lithography' where atoms are directly patterned on a silicon surface with nanometer resolution. This may be vital for future nano-fabrication goals.

In India, there has been a lot of interest in laser cooling and trapping in the last few years. Several conferences and workshops have been organised around the country. The importance of this field can be gauged from the fact that groups at the following institutions have initiated research in this area: Bhabha Atomic Research Centre (Mumbai), Centre for Advanced Technology (Indore), Indian Institute of Astrophysics (Bangalore), National Physical Laboratory (New Delhi), and Raman Research Institute (Bangalore), apart from our group at the Indian Institute of Science (Bangalore). BARC has a group working on ion traps (see the article by Pushpa Rao and others on page 22) and a group working on neutral atom traps. Our group has started work on three separate experiments. The first one is on laser cooling of rubidium (Rb) atoms with the goal of achieving Bose–Einstein condensation. The picture on the cover of this issue shows about 10^8 Rb atoms trapped in our MOT. The second experiment is on laser cooling of ytterbium (Yb). This has the goal of using cold atoms for precise measurements, which will tell us if physical laws violate time-reversal symmetry. The third experiment is on trapping of Yb^+, i.e. singly charged Yb ion, in a linear radio-frequency trap similar to the Paul trap described in the article by Pushpa Rao and others. The trapped ions will be laser cooled and then used for precision spectroscopic measurements, perhaps even to build a quantum computer!

Laser cooling has become accessible to many research groups because of the advent of tunable diode lasers. This has brought down the cost of setting up the laser system from about US$100,000 to less than $1000. For example, our Rb MOT uses commercial diode lasers that are commonly used in CD players and laser printers. The cost of a diode is only about $50. By building some electronics and optics around it, the laser can be made useful for laser cooling experiments with precise tunability. One disadvantage of diode lasers is that they are available only in the wavelength range of 620 nm (red) to 2000 nm (near infrared) and do not cover much of the visible or ultraviolet regions. But recent developments in the field of nonlinear optical crystals has allowed the diode laser output to be frequency doubled (or the wavelength to be halved). The figure on page 21 shows the blue output from a frequency doubler we have built in the laboratory. The input to the doubler is from a diode laser operating at 800 nm and the output is at 400 nm.

Laser cooling and trapping is an exciting field of research full of new possibilities. While the field has matured over the last decade, a lot of work remains to be done. To take one concrete example, the first observation of Bose–Einstein condensation was in 1995. Five years later, there are only about 20 working condensates around the world. And most of the results so far have only confirmed our understanding of quantum mechanics. The real advantage of a condensate is that all the atoms in the system behave coherently, or as one giant atom. This feature of the condensate has not really been used to full advantage in making measurements that are much more precise than possible with a thermal (incoherent) cloud of atoms. The field will really blossom when such experiments are devised.

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