LASER COOLING

Chilling dense atomic gases

Laser-based Doppler cooling is a popular method for reducing the temperature of atoms, but it is limited to dilute gases. Now, researchers in Germany have demonstrated a laser scheme for cooling a highly dense gas mixture.

Mansoor Sheik-Bahae and Denis Seletskiy

For many years, the idea of using laser light to cool matter has attracted the attention of physicists seeking to construct refrigerators based on optical processes. In a recent Letter in Nature, Ulrich Vogl and Martin Weitz from the University of Bonn in Germany reported the first experimental demonstration of cooling based on the concept of collisional redistribution of radiation in a dense gas mixture. This cooling scheme was initially proposed by Berman and Stenholm in the 1970s in a paper describing the phenomenological theory of collisionally aided fluorescence. However, until now optical cooling in a moderately dense gas had not been demonstrated. The Bonn group has achieved a temperature drop of nearly 70 K in a gaseous mixture of Rb and Ar atoms, from a starting temperature of 620 K and with a density nearly ten billion times higher than that used with Doppler cooling. To put their observation in perspective, it is instructive to briefly review the history of the laser cooling of matter.

Soon after the birth of quantum mechanics and three decades before the invention of the laser, the German physicist Peter Pringsheim envisaged the cooling of matter using light. This idea immediately faced much scepticism because it seemed so counter-intuitive. The concept is simple: the absorption of incident photons with energy $h\nu$ is followed by the emission of luminescent photons with a higher energy $h\nu_0$, thus removing energy (and therefore heat) from the absorbing material. This worried scientists, as it was in conflict with Stokes’s law of fluorescence, which states that the emission wavelength is always longer than the excitation wavelength. But what worried Pringsheim’s critics the most was the apparent violation of the most sacred law in physics. The famous Russian physicist Lev Landau came to the rescue by assigning an entropy to light. In doing so, he showed that optical cooling is physically plausible because the resulting random fluorescence has a higher entropy than the incident coherent light. However, although the principle was reconciled with physical laws, no serious attempt to cool matter using light took place until the 1960s, when the laser appeared. The concept of slowing down atoms by exploiting their Doppler-shifted absorption resonance was suggested by Hänsch and Schawlow in 1975. Doppler cooling of dilute gases by counter-propagating laser beams was then demonstrated, leading to atom trapping and cooling to temperatures near absolute zero. This spawned a new and exciting era of physics that culminated in the observation of the Bose–Einstein condensate in 1995.

Scientists have also been interested in cooling much denser media than those allowed by Doppler broadening in gases. After all, Pringsheim’s idea involved the removal of vibrational energy (phonons) in a solid. Epstein and co-workers at Los Alamos National Laboratory achieved the first laser cooling of a solid in 1995. Ultrapure ytterbium-doped glass was cooled by a tenth of a degree using a laser tuned to a frequency just below the mean fluorescence frequency. The field of optical refrigeration has progressed significantly since that time, and cooling to nearly cryogenic temperatures was recently achieved with a ytterbium-doped crystal.

The new results reported by Vogl and Weitz are important because they represent the first laser cooling of a dense gaseous medium by reducing the kinetic energy of the constituent atoms. In contrast, previous methods achieved cooling by reducing molecular vibrations. Vogl and Weitz demonstrate cooling of a gaseous mixture of Rb and Ar at a pressure of 230 bars — nearly seven orders of magnitude higher than that typically used for the Doppler cooling of gases. The idea is elegant and simple: when the Rb and Ar atoms collide, the energy levels of the Rb atom are modified as a result of the Coulomb interaction (Fig. 1), and the resonant energy of the Rb ‘D-line’ (the 5p–5s transition) changes as a function of $R$, the separation between the atoms.

Vogl and Weitz exploit this fact by illuminating the gas with an incident laser beam of photon energy $h\nu$, which is tuned to the D-line resonance for small $R$. This means that when the Rb and Ar atoms enter close proximity and ‘collide’, the laser light resonates with the D-line and the photons are absorbed by the Rb atom, which is then excited to the 5p state. To escape the potential well in the 5p excited state, the Rb atom absorbs additional energy $6E \sim k_B T$ (where $k_B$ is the Boltzmann constant and $T$ is the temperature of the gas) from the kinetic energy reservoir, thus slowing down and cooling the atom. As is the case for all laser cooling processes, the cycle is not complete until the atom sheds the excess energy through anti-Stokes luminescence, emitting a photon of energy $h\nu_0 > h\nu$.

It is important to note that cooling is not possible if fluorescence occurs while the excited Rb atom is inside the collision-induced potential well and has not yet absorbed additional thermal energy. The collision time is, however, many orders of magnitude shorter than the spontaneous-emission lifetime of the D-line. A similar situation exists for the optical refrigeration of solids, where the
electron–phonon interaction rate must exceed the spontaneous-emission rate. In all laser cooling systems, the cooling efficiency reduces as the temperature decreases. This results from the depletion of thermal energy in the reservoir, which provides the vibrational or translational energy needed to enable the anti-Stokes fluorescence. Furthermore, as the system cools and/or the density increases, the mean fluorescence energy red-shifts because the mean interatomic separation between the atoms reduces. Consequently, this narrows the spectral regime in which cooling can occur at a reasonable pump absorption (laser power). The Vogl and Weitz experiment maintains high cooling efficiency by heating the gas mixture to an initial temperature of 620 K, thus allowing an ample amount of fast Rb atoms to participate in the cooling. This results in net cooling by almost 70 K at a significant cooling power of around 90 mW — four to five orders of magnitude larger than Doppler cooling.

These results, however, do not indicate the lowest attainable temperature of this method. In their 1978 paper, Berman and Stenholm described a set of constraints, such as the gas mixture and wavelength, that will eventually limit such a technique. It will be interesting to put these constraints to the test and investigate any fundamental limitations involved. For example, it is worth investigating the effects of photo-association at low temperatures, and of multiple collisions due to the high densities involved. Aside from the diminishing efficiency at low temperatures, it will be essential to understand whether the only limitation in achievable temperature is set by the parasitic absorption from unwanted impurities in the gas mixture. This absorption is the key limiting factor in solid-state laser cooling, but one hopes that gaseous media are less prone to such contamination.

The pioneering research of Vogl and Weitz has proved the validity and potential of this new laser cooling approach. The road ahead will certainly be challenging and exciting; many other gas mixtures are being investigated under various conditions, with the aim of attaining much lower cooling temperatures.

References

TERAHERTZ TECHNOLOGY

An ultrafast amplifier

The integration of an optically pumped switch in a quantum cascade laser device yields a semiconductor terahertz amplifier that promises to extend the capabilities of time-domain spectroscopy.

Alessandro Tredicucci and Aldo Di Carlo

Terahertz (THz) photonics is attracting ever-growing attention in applications that deal with chemical recognition and detection. Areas of interest include security and customs control, non-destructive testing in the pharmaceutical industry and biomolecular diagnostics and communications. Since its development in the 1980s, the workhorse of THz spectroscopy has been the coherent time-domain technique, in which picosecond pulses of THz radiation are used to investigate a sample. These pulses are typically generated using short (~100 fs) visible-wavelength laser pulses to generate electric charges in a photoconductive material, which are then accelerated (and thus emit THz radiation) by two antenna-like electrodes. The THz pulse shape is reconstructed in both amplitude and phase using the same visible-wavelength laser pulses as a time gate for the detection. Spectroscopic information is recovered by creating a Fourier transform of the temporal profile of the THz pulse, yielding a broadband signal that typically spans from a few hundred gigahertz to a few THz. Despite the low average THz powers typically used — generally in the nanowatt range — this coherent detection scheme still allows for spectroscopy with high signal-to-noise ratios of up to 70 dB. In many cases, however, its applications are being hampered by the low power delivered by existing THz sources, making the development of a convenient and practical THz amplifier highly desirable.

One potential candidate is presented on page 715 of this issue by Jukam et al., who demonstrate that a cleverly modified quantum cascade laser can amplify the intensity of these ultrafast THz pulses to achieve gains of over 20 dB. This result is likely to open up new prospects for THz time-domain spectroscopy, particularly in fields where strong signal attenuation is currently the limiting factor. For example, in stand-off detection and sensing, atmospheric absorption due to water vapour is restricting distances to around ten metres.

A THz-emitting semiconductor injection laser based on the quantum cascade (QC) scheme was first reported in 2002. Such lasers rely on electronic transitions between sub-bands in the conduction band of a carefully engineered heterostructure, an alternating-layer sequence of two different semiconductor compounds.

The laser transition energy (and thus the operation wavelength) therefore does not depend on the particular semiconductor material used, but instead is mostly determined by the thickness of the layers. This concept can in principle also be used to create a gain medium to amplify THz waves.

When designing any kind of optical amplifier, an important issue is to eliminate the presence of any optical cavities that could establish a feedback process, for two reasons: first, to prevent the device from reaching a lasing condition, which limits the gain to its threshold value for self-oscillation and therefore limits the achievable amplification; and second, to minimize resonant enhancement at specific frequencies to avoid unwanted ripples in the gain spectrum.

In the case of a THz QC amplifier, preventing the device from reaching a lasing condition is particularly relevant because the net material gain achievable is small and...