Laser Cooling: using light to cool down atoms

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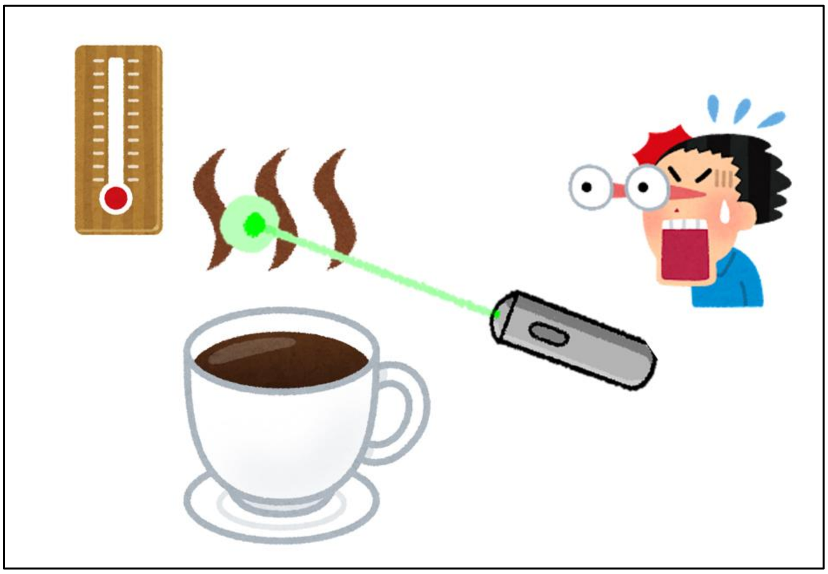

Starting with the invention of the light bulb by Edison in 1879, we humans have been utilizing the powerful tool named *light* in many ways. The most common way is using the light as a tool to brighten up our rooms like I am doing right now writing this script with a fluorescent light shining above my head. Other common ways would be, for example, solar power which converts light coming from the sun to usable energy, or laser processing which is utilized in factories to curve metal components using powerful light. Some people might also point out the underwater optical fibers which use light to instantly transport information across countries.

However, what is not commonly known is that, in the field of physics, light has also been a powerful tool to cool atoms to amazingly low temperatures. This technique is called laser cooling. In a typical laser cooling process, atoms reach a temperature of micro-Kelvins (0.000001 Kelvin! or -273 degrees Celsius), which is, as you can tell, very cold.

So, how is it possible to cool atoms using light? To answer this question, we need to first understand what it means to cool atoms. Or in other words, the difference between hot and cold atoms. The difference is the velocity of the composing atoms. When atoms are hot, or for example, when your coffee is hot, it means that the composing atoms, or the H_2O molecules in your coffee, are moving quite fast. While on the other hand, when atoms are cold, or when your coffee has gone cold, it means that the composing atoms, or the H_2O molecules in your coffee, are moving quite slow. In this sense, cooling atoms means slowing down the atoms.

An easy way to slow down something would be, to push it back to the opposite direction of its movement. If light can somehow push the atom, a countering light could slow down the atom's speed. Maybe surprisingly, light does have this ability. Although the light has no mass, it does contain momentum, which is the ability to push something. Since the momentum of light is quite small, a heavy object like we humans would literary be not pushed. This is why we do not feel getting pushed by the light of the sun, although we are, to a very small extent. However, for atoms, which only have a small mass, the momentum of light could give them a significant pushback. When an atom is absorbing propagating light moving towards them, it will constantly get pushed back. If we shine the atom from all directions, the atom would, roughly speaking, not be able to move in any directions resulting in a halt.

A bright reader might wonder that, if we shine the atom from all directions, though the countering light would slow down the atom's speed, the light that is chasing might accelerate it. This is true and there is an intriguing mechanism that avoids this.

Atoms only absorb light that has certain frequencies, or in other words colors, that they prefer. An unpreferable color would not be absorbed and light would just pass through the atom without pushing it. When encountering a light while moving, atoms feel that the light has different frequencies than what they will feel when stopping. This is well known as the Doppler effect. I believe many of us have experienced hearing the siren of the ambulance differently according to whether it is coming towards or heading away from us. Light and sound are both waves, so the same thing happens. Using this phenomenon, if we tune the frequency of the light so that it would be *unpreferable* for atoms running away, and *preferable* for atoms moving toward the light, we can selectively slow down the countering atoms while not accelerating atoms running away.

The slow atoms achieved by laser cooling can be trapped and precisely observed. This opens the door for many important applications.

One prominent example is the optical lattice clock. This is a very accurate clock invented by a Japanese physicist in 2003. It only has an uncertainty of 10^{-18} or 1 second per 30 billion years! Regarding the fact that our universe is only 13.8 billion years old, this is quite an accuracy. The key concept of this optical lattice clock is to trap cold atoms in designated locations and observe the unique frequency that the atom has. Needless to say, cold atoms used in this clock were only possible by the technique of laser cooling.

The high accuracy of this clock not only allows to measure the precise time but also allows for detecting slight gravity differences predicted by the general theory of relativity. It is said that detection of several centimeters on the earth's surface would be possible with the installation of the optical lattice clock. This would be a game-changer in our current Global Positioning System (GPS) and could also significantly enhance our current monitoring system of the earth’s crust, leading to better predictions of volcano activities or earthquakes.

In the context of atomic physics, laser cooling has been one of the key techniques in advancing the field. Cold atoms achieved by laser cooling allowed precision measurements of the atom’s characteristics. Experimental verification of quantum statistics, such as the realization of the Bose-Einstein Condensation, was made possible by laser cooling. It has also opened the possibility of controlling molecular interaction processes, using cold atoms and molecules.

Light in life, might only be something to brighten up our rooms, but in the field of physics, light has been a powerful tool to open the door for extremely cold atoms.