# 12 *Other states of matter*

## 12.1 *Bose-Einstein Condensate*

Bose-Einstein condensates (BECs) are the 'newest' state of matter, produced in 1995 in a Colorado laboratory. Their existence was first theorised and then predicted 70 years previously by Einstein - following on from the work of the Indian physicist Satyendra Nath Bose.

Quantum theory suggests that at sufficiently cold temperatures, the (de Broglie) wavelength of atoms will become greater than their interatomic spacing, so that (provided they are indistinguishable particles) it becomes impossible to differentiate between each atom.

$$T_c < \frac{h^2}{3mk_B} n^{2/3}$$

For a condensate of a few thousand atoms, $T \lesssim 100$ nK is required.

To produce a condensate, several key steps are taken. First by *laser cooling*, the Doppler effect is used (to great effect) so that only atoms approaching the laser will absorb a photon. Re-radiation is non directional such that the net momentum exchange opposes expansion, allowing cooling to the order of $10^{-5}$ K. The cold atoms are then held in place by a *magnetic potential* whose strength is reduced to allow some particles to evaporate thus cooling the remaining particles further. At $T_c$ a collapse to a single 'super atom' is seen.

Condensates have several unusual properties including, zero heat capacity, superfluidity, quantised vorticity, and coherence of matter. In the future, BECs could have applications in atom lasers, and quantum computing.

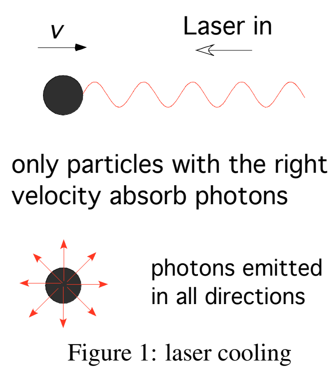


Figure 61: laser cooling

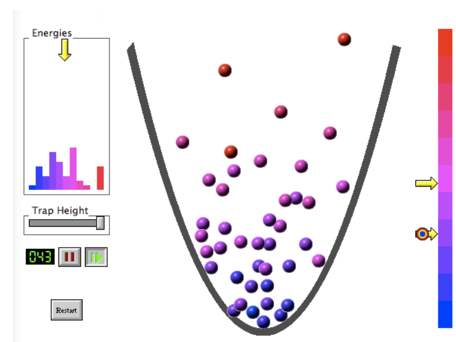


Figure 62: evaporative cooling

## 12.2 *Plasma*

Over 99% of the matter in our universe exists in the form of plasmas. A plasma can be described as **an ionised gas which exhibits collective behaviour**. Key aspects of a plasma are:

- 4th State of Matter, called plasma by Langmuir because of a perceived similarity to blood plasma.
- Comprised of collections of positive (usually ions) and negative (electrons) particles
- Plasmas are created by ionisation of atoms and so require extremely high temperatures
- Important for nuclear fusion
- Used in industrial processes (e.g. semi-conductor industry)

As plasmas consist of many moving charged particles (usually at low density), they interact with electric and magnetic fields and therefore exhibit *collective behaviour* along field lines.

1: Plasmas contain many charged particles so are a good conductor, they can also to some extent neutralise excessive charge. However finite thermal motion of electrons, means that neutralisation is not complete. There is an exponentially falling field of scale length Debye Length $\lambda_d$ (see fig **??**), where

$$\lambda_d = \left(\frac{\epsilon_0 k_B T}{ne^2}\right)^{1/2} \quad \text{(PS4)}$$

2: A large number of charged particles can act together through em forces to produce macroscopic effects, e.g. as well as sound waves, plasmas can support plasma waves, which are the oscillations of electron sheets around a median position with frequency $\omega_p$

$$\omega_p = \left(\frac{ne^2}{\epsilon_0 m}\right)^{1/2}$$

NB This oscillation frequency is not dependent on wavenumber (i.e. non dispersive waves).

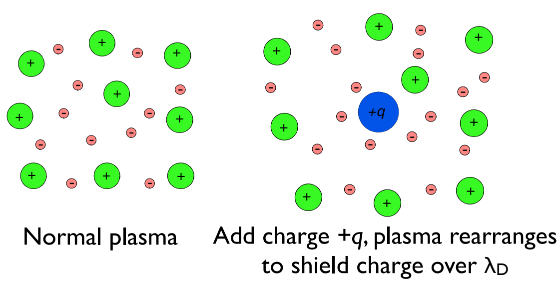


Figure 63: Debye shielding

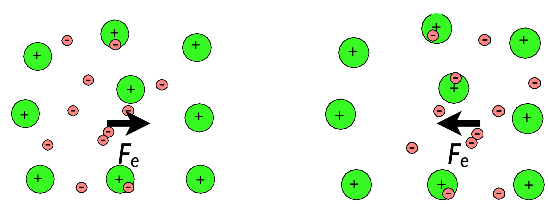


Figure 64: plasma wave

Plasmas are found in tokamak fusion reactors, inertial confinement experiments, lightning, flames, aurora, discharges, solar winds, stars, intergalactic plasma.