Question 18 **(21 marks)**

Cooling with lasers

When we think of lasers, we think of extreme heat being generated. We imagine lasers cutting through metals. However, lasers can actually be used to cool things like monatomic low-density gases. They do this by lowering the average kinetic energy (KE) of the gas atoms.

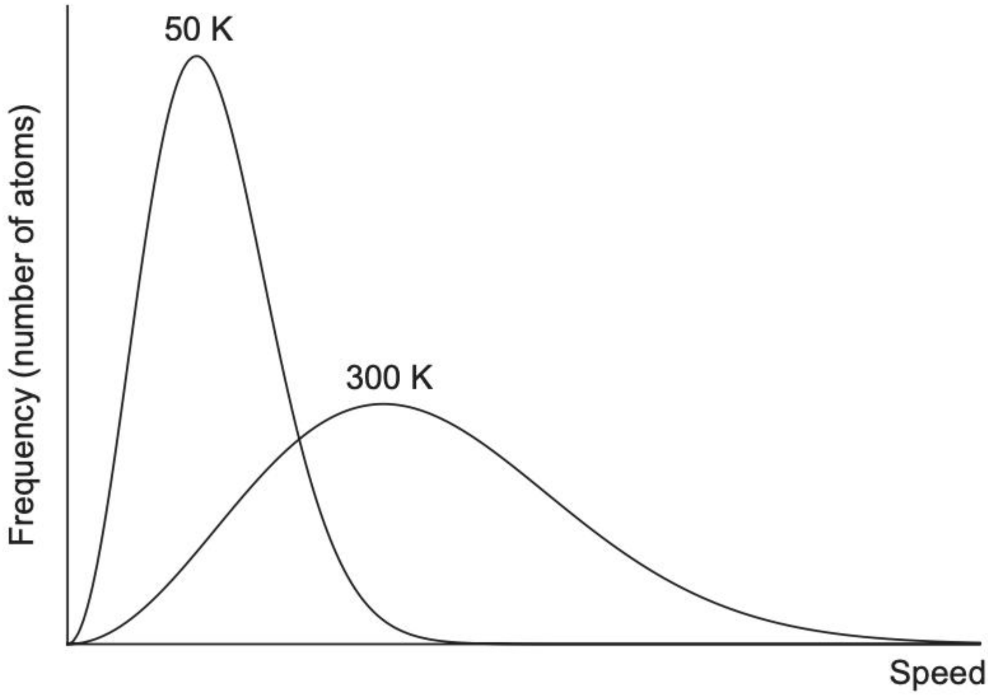

Figure 1: Number of atoms versus speed for a fixed sample of gas

In a sample of gas, the atoms are in constant random motion and possess a range of kinetic energies and speeds. Figure 1 above shows how the temperature of a sample of gas increases with the average KE of the atoms.

A laser produces photons that all have precisely the same energy. The frequency of the laser can be finely adjusted to suit the purpose. The number of photons produced can be altered by varying the power of the laser.

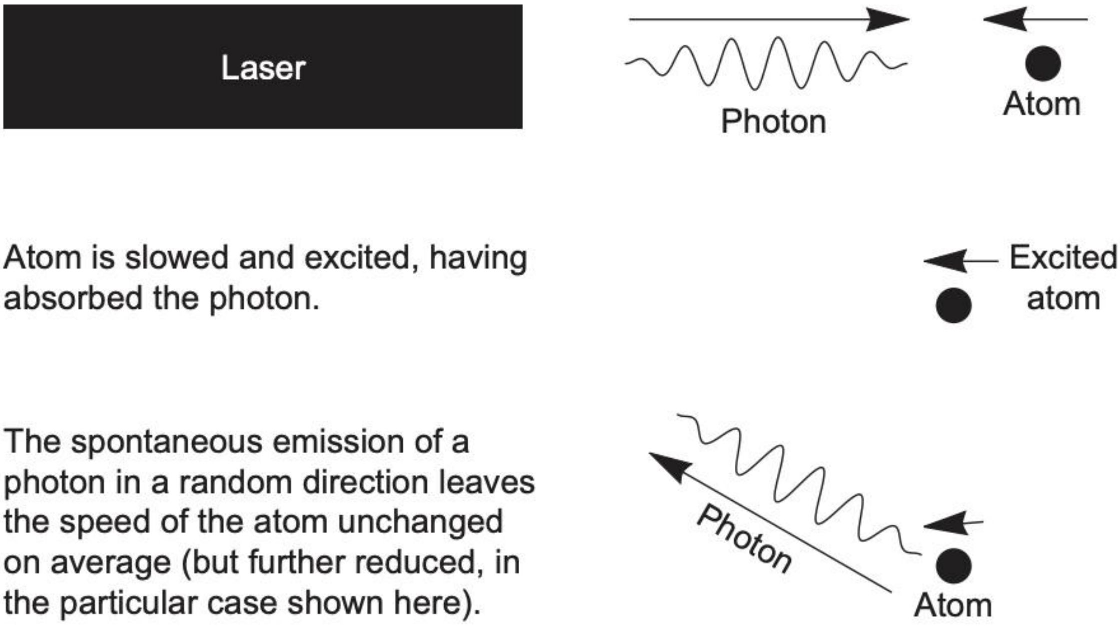

Figure 2: Front-on collisions between a laser photon and a gas atom

The laser is shone through the sample of gas. An atom of gas moving directly toward the source of the photons will have the light blue-shifted. Therefore, the frequency of the photon is increased. If the frequency of the light has been set just below the corresponding transition energy for the atom (the amount of energy required to promote an electron to a higher level), the photon will be absorbed along with its momentum. This slows the atom down. As the momentum of the atom is now reduced, so is its KE and, therefore, the temperature of the sample.

When the electron transitions back to its original level, it will emit the same frequency as the original photon. However, the direction in which the photon is emitted is random and, therefore, on average, has no effect on the atom's momentum and the temperature of the sample.

Further cooling can only be achieved if the photon energy is set closer to the atom's transition energy, but not equal to it. The average speed of the gas atoms and their transition energy must be known in order to set the frequency of the laser appropriately.

This process is used in modern quantum systems such as atomic clocks, which only work at temperatures close to absolute zero.

(a) (i) Calculate the momentum of a photon of frequency of 5.12×10^{16} Hz. (4 marks)

Answer: ______________ $kg\ m\ s^{-1}$

(ii) Calculate how many photons with the same frequency as in part (a)(i) on page 29 would be produced per second by a 10.0 W laser. (3 marks)

Answer: ______________________ s^{-1}

(b) An atom with a mass of 6.80×10^{-27} kg is travelling with a speed of 5.70×10^{2} m s^{-1} in the opposite direction to an incoming photon of the same wavelength as in part (a)(i) on page 29.

Calculate the percentage of speed it loses when it absorbs the incoming photon. (5 marks)

Answer: ______________________ %

(c) Explain the mechanism required for cooling to occur. (5 marks)

(d) The frequency of the laser is now set slightly higher than the corresponding transition energy of the gaseous atoms.

(i) What effect would this have on the temperature of the gaseous sample? Circle your answer. (1 mark)

A. Increase B. Decrease C. No effect

(ii) Explain your answer to part (d)(i). (3 marks)