8 Read the passage and answer the questions that follow.

## Laser cooling of atoms

Atoms in a gas are always in motion. The temperature of a gas is related to the average kinetic energy of its atoms—the faster they move, the higher the temperature. Physicists have found ways to slow atoms down using laser light, and in doing so, cool the atoms to extremely low temperatures. This process is called laser cooling, illustrated in Fig. 8.1.

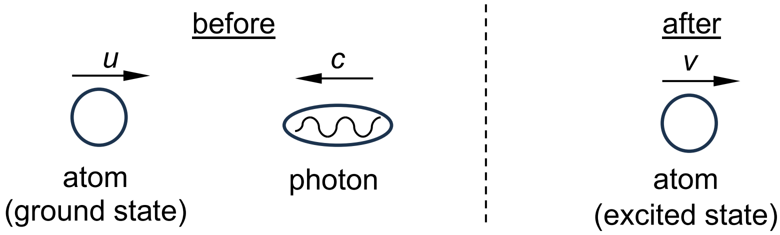


**Fig. 8.1**

Each photon has a small momentum. When the energy of the photon is just right, it can be absorbed by an atom, bringing it into an excited state. To slow an atom down, scientists shine light in the opposite direction that the atom is moving, so the atom absorbs photons, reducing its speed. Of course, after a short time, the atom will de-excite, emitting another photon – but this is in a random direction, rarely in the same direction as the first photon, and so generally the net effect is still that the atom's velocity in that axis is decreased.

Laser cooling experiments are often performed on rubidium (Rb) atoms. A simplified energy level diagram of the $^{87}$Rb atom is shown in Fig. 8.2, showing the ground state, the first two excited states (labelled A and B), and their energies.

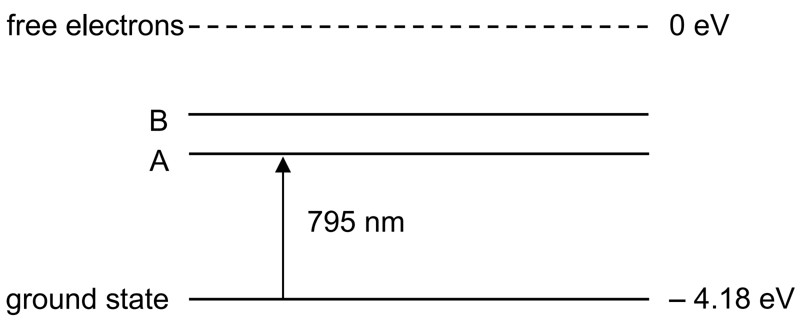


**Fig. 8.2 (not to scale)**

When an $^{87}$Rb atom absorbs a photon of wavelength 795 nm, it transitions from the ground state to state A.

Table 8 shows some data about rubidium-87 ($^{87}$Rb).

| | |
|---|---|
| atomic number | 37 |
| nucleon number | 87 |
| atomic mass | 86.9 u |
| melting point at 1 atm | 39.3 °C |
| boiling point at 1 atm | 688 °C |
| lifetime of state A | 27.6 ns |
| lifetime of state B | 26.2 ns |
| emission wavelength from state A | 795 nm |
| emission wavelength from state B | 780 nm |

**Table 8**

The setup of a laser cooling experiment is shown in Fig. 8.3 below.

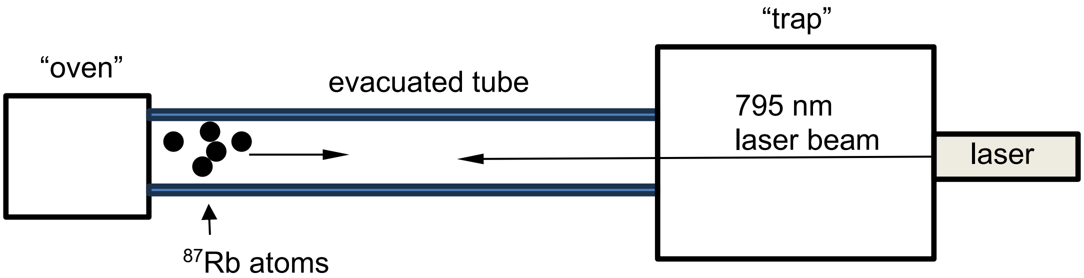


**Fig. 8.3**

A hot "oven" serves as a source of $^{87}$Rb atoms, which travel through the evacuated tube towards the "trap". A laser is directed in the opposite direction to the atoms' motion, slowing them down significantly. When they reach the "trap", they are slowed and cooled even further using other methods.

Laser cooling and other trapping methods have allowed physicists to make exciting discoveries, such as the first-ever creation of a Bose-Einstein Condensate in 1995 by Eric Cornell and Carl Wieman. A Bose-Einstein Condensate (BEC) is a new state of matter. In 1925, Bose and Einstein theorized that, as a consequence of wave-particle duality, at very low temperatures, the matter wave of atoms could have a wavelength $\lambda$ greater than the average separation $d$ between the atoms. When this happens, the matter waves of the individual atoms overlap to form a single wave, allowing the atoms to seemingly occupy the same space!

Of interest is the critical temperature $T_C$ at which a BEC is formed, which depends on several factors, including the separation $d$ between the atoms. This can be estimated using the relationship:

$$d \approx \frac{1}{\sqrt[3]{n}}$$

where $n$ is the number of particles per unit volume.

Fig. 8.4 shows data from a laser cooling experiment when the temperature $T$ of the cloud of atoms is $T > T_C$, $T \approx T_C$, and $T < T_C$.

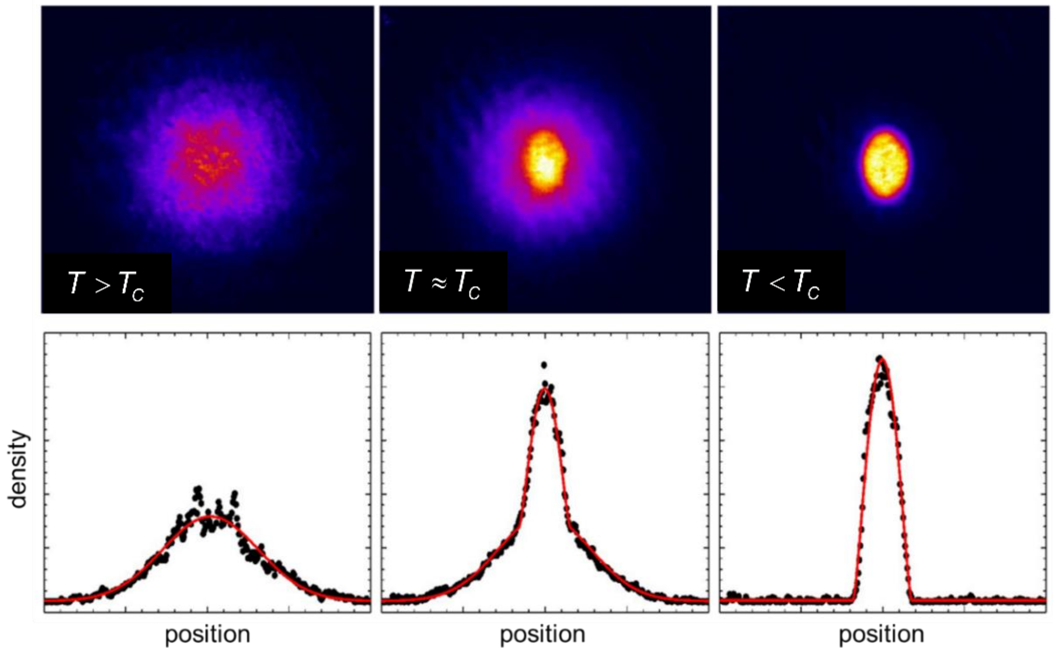


**Fig. 8.4**

**(a)** **(i)** With reference to Fig. 8.2, explain why rubidium-87 atoms ($^{87}Rb$) only absorb photons of certain frequencies.

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........................................................................................................................[2]

**(ii)** With reference to Fig. 8.2, determine the energy of state A in electron-volts.

energy = ........................... eV [3]

**(iii)** When an $^{87}Rb$ atom transitions from state A to the ground state, a photon is released. Suggest why this photon is difficult to observe with the naked eye.

........................................................................................................................

........................................................................................................................[1]

**(b)** A collection of $^{87}Rb$ atoms in the gaseous state emerge from the "oven" at a temperature of 1000 K.

Treating the $^{87}Rb$ atoms as an ideal gas, determine the average speed of an $^{87}Rb$ atom.

average speed = ........................... m s$^{-1}$ [2]

**(c)** Suggest what is meant by the “lifetime” of state A and state B in Table 8.

……………………………………………………………………………………………………………

……………………………………………………………………………………………………………[1]

**(d)** **(i)** Using the principle of conservation of linear momentum, determine the magnitude of the change in momentum of an $^{87}$Rb atom after it absorbs a photon from the laser, as in Fig. 8.1.

**Show your working clearly.**

change in momentum = ……………………… kg m $s^{-1}$ [3]

**(ii)** Explain why, when an excited $^{87}$Rb atom de-excites and emits a photon, the average change in momentum of the $^{87}$Rb atom over many such emissions is zero.

……………………………………………………………………………………………………………

……………………………………………………………………………………………………………[1]

**(iii)** Hence, using data from Table 8, determine the average force on the $^{87}$Rb atom through the entire process of absorbing and emitting a photon.

force = ……………………… N [2]

**(iv)** Give one reason why the $^{87}$Rb atoms could be cooled faster if the laser emitted photons that excite the atoms to state B instead of state A.

……………………………………………………………………………………………………………

……………………………………………………………………………………………………………[1]

**(e)** State how Fig. 8.4 shows that a Bose-Einstein Condensate forms when the temperature $T$ of the cloud of atoms is equal to or below the critical temperature $T_C$ .

.....................................................................................................................................

.....................................................................................................................................[1]

**(f)** The momentum of an $^{87}$Rb atom in the "trap" is given by:

$$p = \sqrt{3mkT}$$

where $m$ is the mass of an $^{87}$Rb atom, $T$ is the thermodynamic temperature of the collection of atoms, and $k$ is the Boltzmann constant.

Using the de Broglie relation, calculate the critical temperature $T_C$ at which a collection of $^{87}$Rb atoms forms a BEC in a "trap" where $n = 1.00 \times 10^{19}\ \text{m}^{-3}$.

$T_C$ = ............................ K [4]

[Total: 21 marks]