Answers to Coursebook questions – Chapter J5

1 **a** The difference in energy between the ground state and the first excited state is $\Delta E = \frac{13.6}{1} - \frac{13.6}{4} = 10.2\,\text{eV}$, an energy of order 10 eV or 1.6×10^{-18} J .
An electron in the ground state will be excited to the next state if this energy is offered to it. This energy can be provided by thermal motion.

b The average energy at temperature T is $\frac{3}{2}kT$ and so

$$\frac{3}{2}kT \approx 1.6 \times 10^{-18}\text{ J}$$

$$T \approx \frac{2 \times 1.6 \times 10^{-18}}{3 \times 1.38 \times 10^{-23}}$$

$$T \approx 8 \times 10^{4}\text{ K}$$

It is unlikely that at room temperatures there will be enough energy to force an electron in an excited state. The collisions will therefore be elastic.

2 **a** The numerical parts of this calculation are the same as in **Q1** with the same answer.

b The actual decoupling temperature is much lower, about 3000 K, because the formula we are using gives the average energy corresponding to the given temperature. It is possible to excite or ionize atoms at the lower temperatures because there are sufficient numbers of very energetic photons even at those low temperatures. (There is also a technical point that is beyond the syllabus: the average energy $\frac{3}{2}kT$ when applied to photons must be multiplied by 2 because there are two spin states for the photon, and this reduces the answer for the temperature by a factor of 2, which of course is still too large.)

3 **a** Decoupling refers to that epoch in the history of the universe when radiation could pass through matter (atoms of light elements) without exciting electrons in these atoms to higher energy states or ionizing them. At earlier times when the temperature was higher, photons would interact with the matter and would not travel through them – the radiation would be blocked.

b At 3000 K we have a peak wavelength of $\lambda = \frac{2.90 \times 10^{-3}}{3000} = 9.7 \times 10^{-7}\text{ m}$.

4 **a** Using $\frac{3}{2}kT$ or $3kT$ (see comment for **Q2**) as the average photon energy we get $\frac{3}{2}kT \approx \frac{3}{2} \times 1.38 \times 10^{-23} \times 3 \approx 6 \times 10^{-23}\text{ J} = 4 \times 10^{-4}\text{ eV}$
or $3kT \approx 3 \times 1.38 \times 10^{-23} \times 3 \approx 12 \times 10^{-23}\text{ J} = 8 \times 10^{-4}\text{ eV}$.

b The peak wavelength at 3 K is $\lambda = \frac{2.90 \times 10^{-3}}{3} = 9.7 \times 10^{-4}\text{ m}$.

The energy of such a photon is

$$E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{9.7 \times 10^{-4}} = 2 \times 10^{-22}\text{ J} = 1 \times 10^{-3}\text{ eV}$$

and is comparable to the estimates in (a).

c The energy is small but it is absorbed by a very large number of water molecules.

5 See **Q3**.

6 **a** This is shown in the answers on page 818 in *Physics for the IB Diploma*.

b With a rest energy of about 80 GeV, to produce two W bosons requires a photon energy of about 160 GeV. A photon would have this energy at a temperature T given by

$$\frac{3}{2}kT \approx 160\,\text{GeV} = 2.6 \times 10^{-8}\text{ J}$$

$$T \approx \frac{2 \times 2.6 \times 10^{-8}}{3 \times 1.38 \times 10^{-23}}$$

$$T \approx 1 \times 10^{15}\text{ K}$$

c The energy at temperature T used above is the average energy.
Even at lower energies there would be occasionally sufficient energy to produce the Ws not only at rest but also moving, i.e. with kinetic energy.

7 The matter would annihilate the antimatter into an enormous amount of radiation.

8 It is believed that in the very early universe there were almost equal numbers of particles and antiparticles, with a very slight excess of particles (one extra particle for every 10^{10} particle antiparticle pairs). At the high temperatures of the early universe two types of reactions took place: particles colliding with antiparticles and annihilating into radiation, and radiation materializing into particle–antiparticle pairs. As the temperature fell, it was no longer possible for the second reaction to take place since the radiation no longer had the energy to cause particle antiparticle pairs to be created out of the vacuum. The reverse process continued, however, resulting in the annihilation of particle antiparticle pairs. What was left is the matter we see today.

9 **a** The available energy is $2 \times 270 = 540\,\text{GeV}$.

b This corresponds to a temperature of:

$$\frac{3}{2}kT \approx 540\,\text{GeV} = 8.6 \times 10^{-8}\text{ J}$$

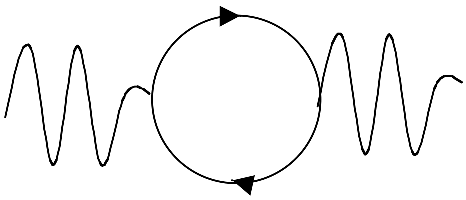
$$T \approx \frac{2 \times 8.6 \times 10^{-8}}{3 \times 1.38 \times 10^{-23}}$$

$$T \approx 4 \times 10^{15}\text{ K}$$

The universe was about 10^{-12} s old at this temperature.

c The energy available during these collisions corresponds to a very high temperature, comparable to the temperatures of the early universe. In this way, the conditions prevailing during the collisions are similar to the conditions of the early universe.

10 Calculations in particle physics come up with infinite answers when Feynman diagrams involving loops are calculated, such as, for example, a photon materializing into an electron–positron pair that subsequently annihilates to produce the photon again:



It has been possible to remove these infinities and obtain finite, physically meaningful answers by a process called renormalization. This same method fails completely when applied to gravitation.

11 It is believed that at the very early universe the energies available were so enormous that one can no longer use a classical theory of gravity, as quantum effects would become important for gravitation as well. The energy, distance scale and the time at which this happens are taken to be the Planck scale for energy, distance and time. These numbers are formed from the basic constants of physics and are:

$$E \approx \sqrt{\frac{hc^5}{G}} \approx 10^{19}\text{ GeV}$$

$$L \approx \sqrt{\frac{hG}{c^3}} \approx 10^{-35}\text{ m}$$

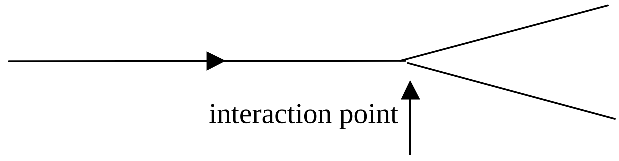
$$t \approx \sqrt{\frac{hG}{c^5}} \approx 10^{-43}\text{ s}$$

12 String theories differ in that the basic ingredients are one-dimensional objects called strings rather than point particles. Another difference is that they are formulated in many dimensions and not just the 4 dimensions of ordinary particle physics.

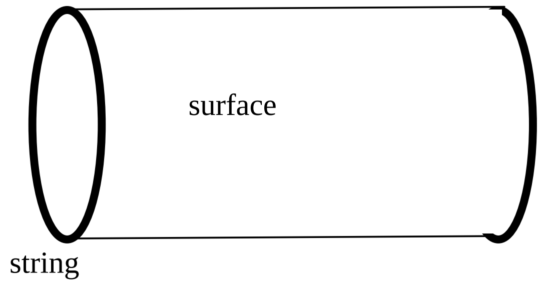
13 The main reason is that they can perhaps provide a quantum theory of gravitation – something that has eluded physicists for decades – as well as for unified theory of interactions.

The problem seems to be that interactions in particle physics take place at a point, and this is what creates the infinities. A point particle traces out a line as time passes:

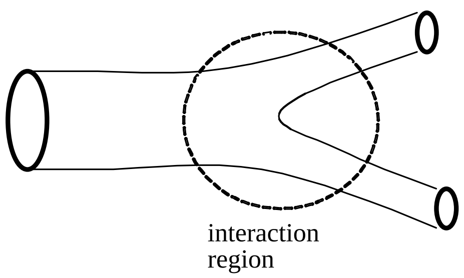
and an interaction takes place at a point:



A closed string, on the other hand, traces out a two-dimensional surface as time passes:



and interactions are not at a point:



14 The extra dimensions are believed to curl up and form a closed space, they do not extend indefinitely as the usual space dimensions we are familiar with.
The size of the closed space formed by these extra dimensions is expected to be microscopically small – we would be unaware of them at ordinary energies.

