Oxford Cambridge and RSA

# For issue on or after: 13 March 2020

## A Level Physics B (Advancing Physics)

**H557/02** Scientific literacy in physics

Advance Notice Article

**To prepare candidates for the examination taken on Monday 1 June 2020 – Afternoon**

**INSTRUCTIONS**
- Before the exam, read this article carefully and study the content of the learning outcomes for A Level Physics B (Advancing Physics).
- You can ask your teacher for advice and discuss this article with others in your class.
- You can investigate the topic of this article yourself using any resources available to you.
- Do **not** take this copy of the article or any notes into the exam.

**INFORMATION**
- In the exam you will answer questions on this article. The questions are worth 20–25 marks.
- A clean copy of this article will be given to you with the question paper.
- This document has **8** pages.

**ADVICE**
- In the exam you won't have time to read this article in full but you should refer to it in your answers.

## A date with the past

A number of flutes uncovered in an archaeological dig in China have been dated at around 9000 years old. The flutes, made from wing bones of large birds, are amongst the oldest playable musical instruments found. Although these ancient instruments look different from modern flutes or recorders, the physics that explains how the sounds are produced is the same for both new and very old instruments.

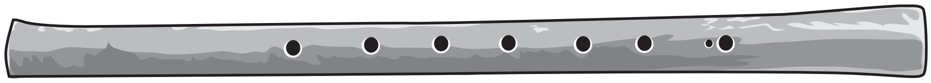
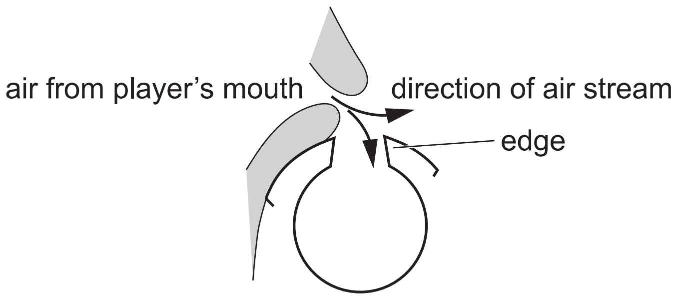


**Fig. 1** ancient Chinese flute

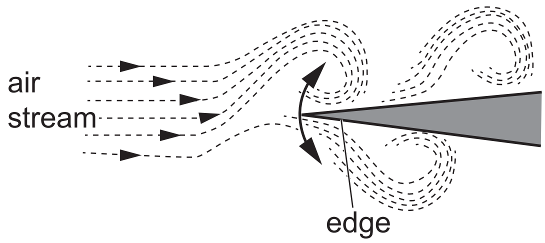
### Some physics of the flute

All flute-like instruments work on the same basic principles. The player directs a stream of air across an edge. This makes the edge oscillate as the air stream goes above and below the edge as shown in Fig. 2 and Fig. 3.




player forcing a stream of air across an edge

**Fig. 2**




oscillation of air stream over an edge

**Fig. 3**

The oscillation of the edge sends pressure waves down the tube which are reflected back up to the edge. The time taken for the wave to travel up and down the tube depends on the speed of the wave and the length of the tube. The edge will initially vibrate over a range of frequencies but after a very short time will vibrate with a frequency matching the frequency of the pressure wave in the tube. This happens because the vibration of the air in the tube will drive the same frequency vibration of the edge. This feedback mechanism produces a standing wave in the tube; this is the wave that determines the frequency of the note you hear. The speed of sound in air increases with temperature so the frequency of the note sounded by a flute will rise when the player's breath warms the air in the tube.

Flutes are **open pipes**. Waves in open pipes have an antinode near each end of the pipe (where one end is the bottom of the tube and the other is near the oscillating edge) as shown in Fig. 4a. If the flute player makes the edge oscillate at twice the frequency, a standing wave of half the wavelength is produced, as shown in Fig. 4b. Further higher frequency, shorter wavelength standing waves can also be produced. In fact, a number of such higher frequency waves are produced at the same time so the note we hear from the flute is produced by superposition of waves of different frequencies simultaneously. The air in open pipes oscillates at the 'first harmonic', $f_1$, and at integer multiples of $f_1$. The second harmonic has frequency $f_2 = 2\,f_1$ and so on.

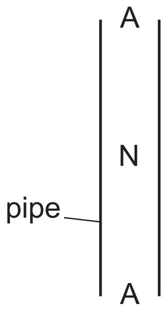



**Fig. 4a**
first harmonic

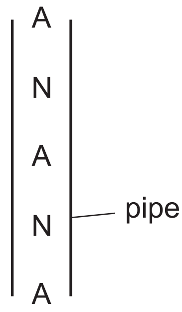



**Fig. 4b**
second harmonic

When a flute plays its lowest note, the frequency of the note you hear matches that of the first harmonic. The relative amplitude of the other harmonics in the note changes the shape of the waveform and gives the instrument its tone or *timbre*. This is why a flute producing a note of a given frequency sounds different from the same note produced on a different instrument; the first harmonic is the same frequency but the recipe of the higher harmonics on different instruments changes the superposition pattern of the waves. This is shown in Fig. 5a and b in which the second harmonic has a smaller amplitude than the first, producing the superposition shown.

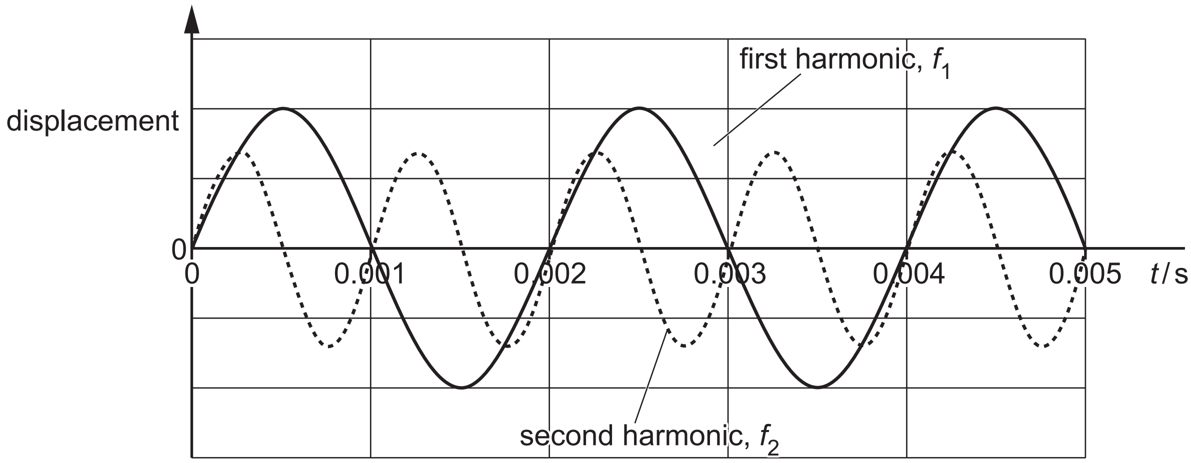



**Fig. 5a**

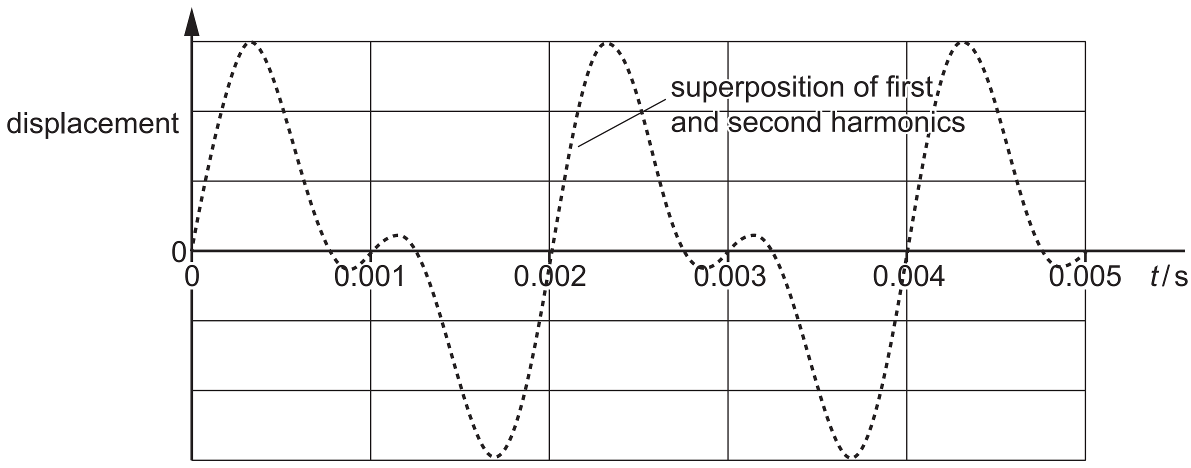



**Fig. 5b**

**Dating the instruments**

The age of the Chinese flutes was determined using ‘radiocarbon dating’. Nearly all carbon on Earth is $^{12}C$ but about 1.1% is $^{13}C$ and about $1 \times 10^{-10}$% is $^{14}C$. Carbon-14 nuclei are produced in the upper atmosphere when neutrons derived from cosmic rays interact with nitrogen nuclei as shown in the equation:

$${}^{14}_{7}N + {}^{1}_{0}n \longrightarrow {}^{14}_{6}C + {}^{1}_{1}p \, .$$

The $^{14}C$ nucleus undergoes beta decay into a $^{14}N$ nucleus. The half-life of the carbon-14 nuclide is around $5.70 \times 10^3$ years. For any sample of biological material, $R$ is the ratio of the number of $^{14}C$ nuclei to the number of $^{12}C$ nuclei, usually referred to as ‘the $^{14}C/^{12}C$ ratio’. In all living matter, this ratio $R = R_0$, which is constant, approximately the same as the ratio in air and has a value of about $1.4 \times 10^{-12}$. $R_0$ remains roughly constant because the decayed $^{14}C$ is continuously replaced with ‘new’ nuclei formed in the upper atmosphere.

Atmospheric $^{14}C$ reacts with oxygen to form carbon dioxide which is taken up by plants through photosynthesis and then enters the food chain. When an organism dies it will no longer absorb $^{14}C$ so its $^{14}C/^{12}C$ ratio will fall over time. This means that by determining the ratio of $^{14}C/^{12}C$ (or $^{14}C/^{13}C$), the age of the organism or artefact made from once-living material (such as a flute made from a bird bone) can be found. The age of the material (the time since death, $t$) is given by the equation $t = -\dfrac{1}{\lambda}\ln\left(\dfrac{R_t}{R_0}\right)$ where $R_t$ is the ratio of $^{14}C/^{12}C$ in the specimen to be dated and $\lambda$ is the decay constant of the carbon-14 nuclide.

**Changes in the ratio**

The carbon-14 originally present in the organic matter that makes up fossil fuels is now present in vanishingly small amounts. This means that the proportion of carbon-14 in the atmosphere since the growth of burning of fossil fuels has reduced. A similar effect is found near volcanoes where plants photosynthesise carbon dioxide produced from ancient carbon, reducing the $^{14}C/^{12}C$ ratio in the still-living plants. Material from the sea also has a different $^{14}C/^{12}C$ ratio from organic material from the land because deep sea water, which has a lower $^{14}C/^{12}C$ ratio than the atmosphere, gradually mixes with surface water. Although $^{14}C$ is more likely to dissolve in the ocean than $^{12}C$, the effect of the water mixing means that a living fish, which should have a radiocarbon age of 0, can appear to have a radiocarbon age of 400 years as the oceanic and atmospheric $^{14}C/^{12}C$ ratios are different.

Finally, the atmospheric testing of nuclear bombs in the 1960s increased the number of neutrons in the atmosphere which again changed the proportion of $^{14}C/^{12}C$. All these effects have to be taken into account when estimating ages using radiocarbon dating.

One way to calibrate the ages found through radiocarbon dating is by comparing radiocarbon ages with ages found by counting tree rings. Each year a tree will add a new ring to its trunk as it grows. The carbon in the new ring will have the atmospheric $^{14}C/^{12}C$ ratio at the time of growing, but as soon as it stops growing the ratio will decrease. The rings near the centre of the tree trunk will have lower ratios than the outer rings. The age of the tree can be found by simply counting the rings and compared to the age determined by radiocarbon dating.

**Counting carbon-14**

Radiocarbon dating depends on establishing the ratio of $^{14}C/^{12}C$ in the specimen. Early measurements used the 'direct counting' method in which the activity of a known mass of carbon is measured to determine the $^{14}C/^{12}C$ ratio. This method can't be used for samples older than a few half-lives because the count rate becomes so low. Most radiocarbon dating now uses the process of accelerator mass spectrometry, first developed in the 1970s.

The carbon sample to be tested is turned into graphite. Negative carbon ions from the graphite and ionised molecules of similar mass (such as $^{12}CH_2^{\,2-}$ and $^{13}CH^-$ ) are selected by the first deflecting magnet. These pass through a 'tandem accelerator'. The ions accelerate through a p.d. of a few MV before passing through a 'stripper' that removes electrons from the ions, making them positive ($C^+$, $C^{2+}$, $C^{3+}$ or $C^{4+}$). This process also breaks up any accelerated polyatomic ions such as $^{13}CH^-$ . Positive ions of $^{12}C$, $^{13}C$ and $^{14}C$ are accelerated through a second potential difference of the same magnitude as the first. The second deflection magnet can be tuned to select for each isotope of carbon, allowing the $^{14}C/^{12}C$ ratio of the sample to be found by determining the numbers of each isotope that pass through the accelerator.

Fig. 6 shows a simplified schematic diagram of the process.

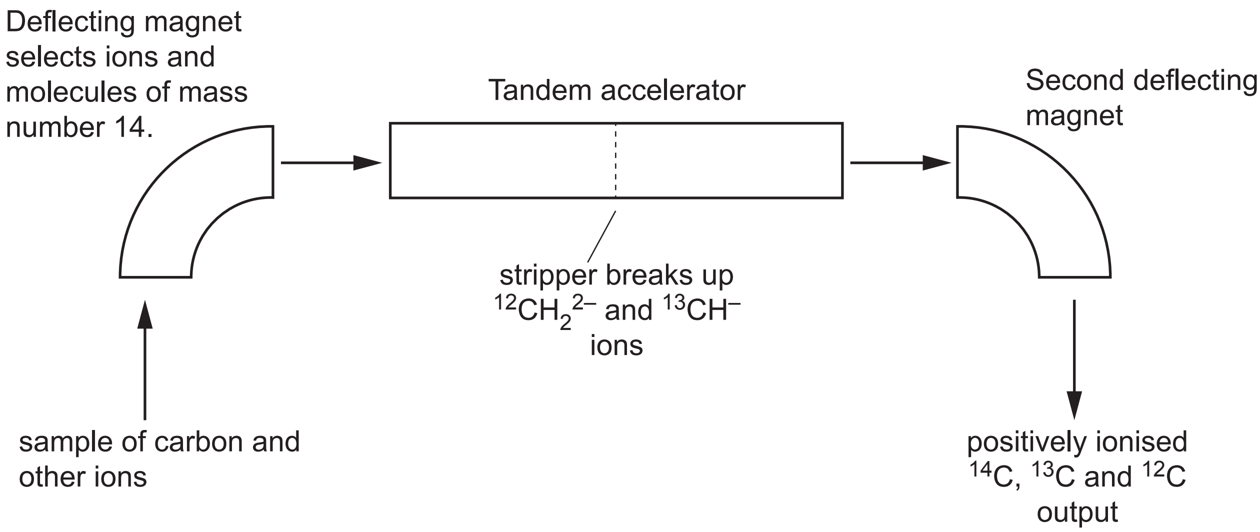



**Fig. 6**

The deflecting magnets produce a uniform magnetic field at right angles to the path of the ions. The interaction of the moving ions and the field results in a centripetal force on the ions which are deflected in a circular arc of radius $r$ given by the equation $r = \frac{p}{Bq}$ where $p$ is the momentum of the ion, $B$ is the magnetic flux density and $q$ is the charge on the ion.

Accelerator mass spectrometry helps archaeologists find the age of objects from a few milligrams of material, allowing the age of artefacts to be measured without damaging them. The ancient Chinese flutes are still playable after they have been dated, their eerie but recognisable sound giving a direct link to a long-vanished culture.

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