

**ADVANCED GCE
PHYSICS B (ADVANCING PHYSICS)**

Advances in Physics

INSERT

FRIDAY 25 JANUARY 2008

2865/01

Morning

Time: 1 hour 30 minutes



INSTRUCTIONS TO CANDIDATES

- This insert contains the article required to answer the questions in Section A.

This document consists of **7** printed pages and **1** blank page.

Measuring Time

Sundials and Water Clocks

Since ancient Babylonian times, the year has been separated into recognisable intervals of months, weeks and days, even though the names and lengths of the months have changed. The fact that the Earth's orbital period – 365.24 days – is not a whole number of days has been known since very ancient times. Different methods have been adopted to keep the calendar tallying with the Earth's position in its orbit around the Sun. The Gregorian calendar, established by decree in 1592 by Pope Gregory XIII, set the current system by which one year in four has 366 days, with one exception: century years all have 365 days unless they are multiples of 400, which happened in both 1600 and 2000. This did take some time to be established across the world, and many countries became several days out of step with others in the intervening time.

The Romans divided the day in a recognisable way into 24 hours. Daylight hours were the ones that could be monitored, as they were measured with a sundial. The time shown by a sundial is complicated by the tilt and eccentric orbit of the Earth, so that this provides, at best, a rough indication of the time of day.

The water clock or clepsydra – the word means 'water thief', and it is still used in modern Greek for a wristwatch – provided the first attempt to use a physical change to measure time by the flow of water out of or into a container. The original function of these devices, like an egg-timer, was to measure short intervals. They were useful in making sure that speakers did not go on for too long in the Roman Senate!

The simple design, shown in Fig. 1, has an obvious drawback: the process being used to measure the flow of time is not constant. As water drains through the hole at the bottom of the water clock, the pressure forcing it out drops, reducing the rate of flow. As a consequence, the time markers on the inside of the clock have to get closer and closer together, unless the clock is built with a non-linear curved shape shown in Fig. 2.

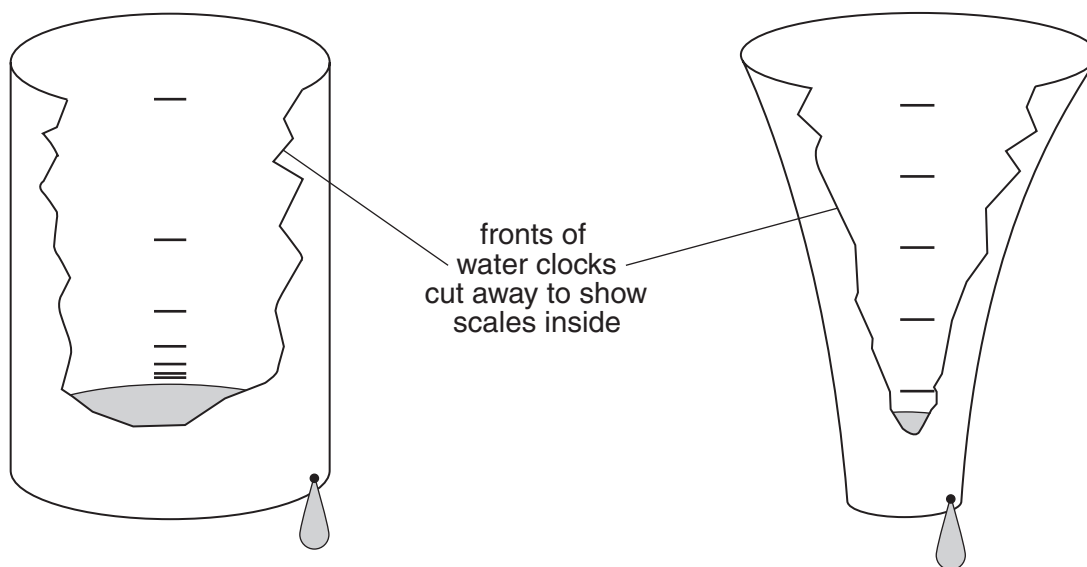


Fig. 1

Fig. 2

More elaborate mechanisms were developed which produced a constant flow of water into a vessel, with floats attached by chains and pulleys to an index outside the clock. A layer of oil on the surface can restrict evaporation, which is a considerable source of inaccuracy in the Mediterranean countries where clepsydras were developed.

30 Mechanical Clocks

Early mechanical clocks, such as the medieval clocks of Wells and Strasbourg Cathedrals, were based on a rotating bar called a foliot connected to a rod called a verge. Together with a toothed crown wheel, these provided the **escapement** of these clocks: a system by which the movement produced by the stored energy in a lifted weight in the clock is released in small, regular steps to move the clock hands.

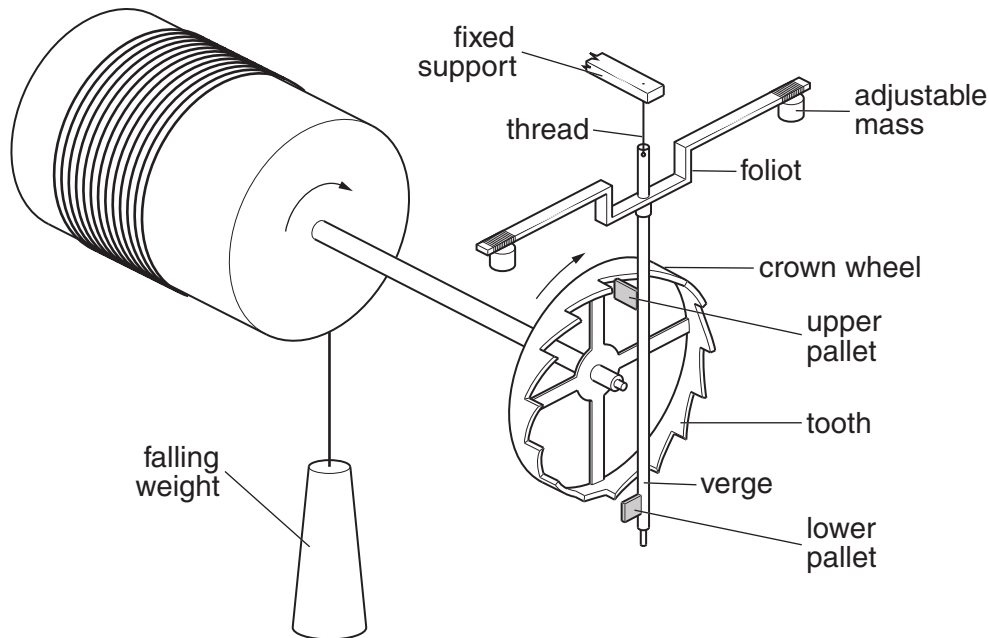


Fig. 3

The falling weight driving the clock rotates the crown wheel in the direction shown in Fig. 3. As the crown wheel rotates, it is stopped, released and then stopped again as one of the teeth strikes the upper or lower pallet of the verge. Each collision with one of the pallets reverses the direction of rotation of the verge and foliot. Movement of the verge allows the crown wheel to turn one tooth further. The time of oscillation of the system can be adjusted by moving the masses on the foliot.

Pendulum clocks were first designed by Galileo. There is a story that he noticed that the lamps in Pisa Cathedral swung on their long ropes with regular periods which depended on the length of the rope. Within a decade of Galileo's observation, the Dutch scientist Christiaan Huygens had devised a practical working pendulum clock. He needed to overcome a problem with pendulum oscillations: when the amplitude is large, the period ceases to be independent of amplitude, so only small amplitude oscillations, less than 5° , are allowed. This is difficult with an escapement which needs the verge and pallets to turn through a large angle. Huygens devised an ingenious way of dealing with this, by keeping the pendulum swing small while gears allowed the rotating verge to move through a greater angle. Pendulum clocks remained the best timekeepers for three centuries.

Piezoelectricity and Digital Watches

A new development in the technology of time-keeping followed the discovery of piezoelectricity by Pierre Curie, before he transferred his interest to radioactivity. Applying a mechanical stress to certain crystals produces an electrical potential difference in the direction of the strain. The reverse is also true: applying an electric field to those same crystals produces strain in the direction of the electric field. This is the fundamental principle used in quartz oscillators, which form an essential part of electronic clocks, including those in computers.

60 A quartz oscillator is a small resonant slab of quartz with conducting surfaces, as shown in Fig. 4.

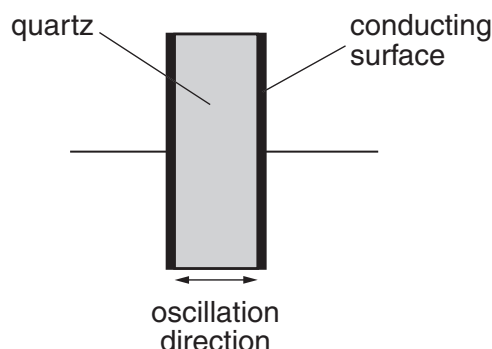


Fig. 4

65 When the circuit containing a quartz crystal is switched on, random electrical signals in the circuit will cause the crystal to change in shape in the direction shown in Fig. 4. Random electrical signals contain a range of frequencies, and a frequency which matches the natural frequency of the crystal will cause it to resonate. The electrical output rapidly becomes dominated by this frequency, and the system produces a very steady frequency. This frequency, which may be the fundamental frequency of the crystal or else a harmonic, provides a useful standard wherever a stable signal with a very precise frequency is needed, such as in a computer or a digital watch.

Molecular and Atomic Clocks

70 The first suggestions for clocks based on oscillations at this very small scale were those involving the rate of radioactive decay, but the randomness associated with radioactive decay limits its precision unless the activity of the sample is unreasonably large. The first practical molecular clock used a resonant system in which an ammonia molecule (NH_3) flipped between two possible states as shown in Fig. 5.

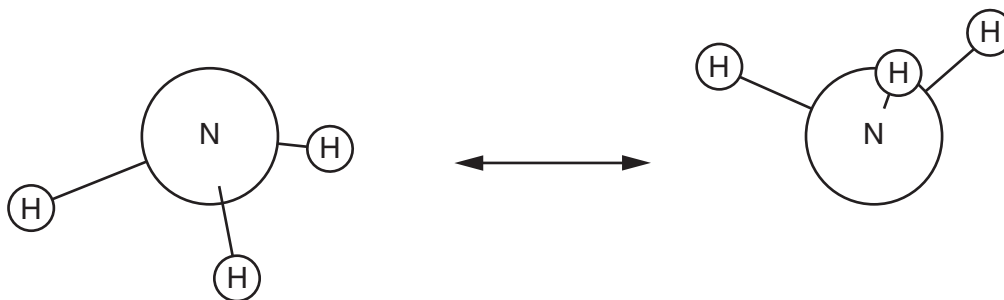


Fig. 5

75 The movement is rather like an umbrella turning inside-out. The three hydrogen atoms have two stable arrangements, above and below the nitrogen atom. When the molecule flips between these two arrangements, it does so extremely rapidly. Although an accuracy of one part in 10^7 , roughly a second per year, can be obtained with an ammonia vapour clock, even greater precision can be obtained using atomic beams.

80 Atomic beam clocks rely on an energy level change in the atoms. The atoms chosen were those of the alkali metal caesium, named after the colour of the principal line in its spectrum – *caesius* in Latin means 'sky-blue'. The frequency of this spectral line, about 6×10^{14} Hz, is associated with an energy level change of 2.73 eV, but the frequency standard in the atomic clock is very much smaller, about 9 GHz. This very much smaller energy level change is due to a quantum interaction between the nucleus and the inner electrons, and one particular caesium nucleus
85 proved particularly suitable: caesium-133.

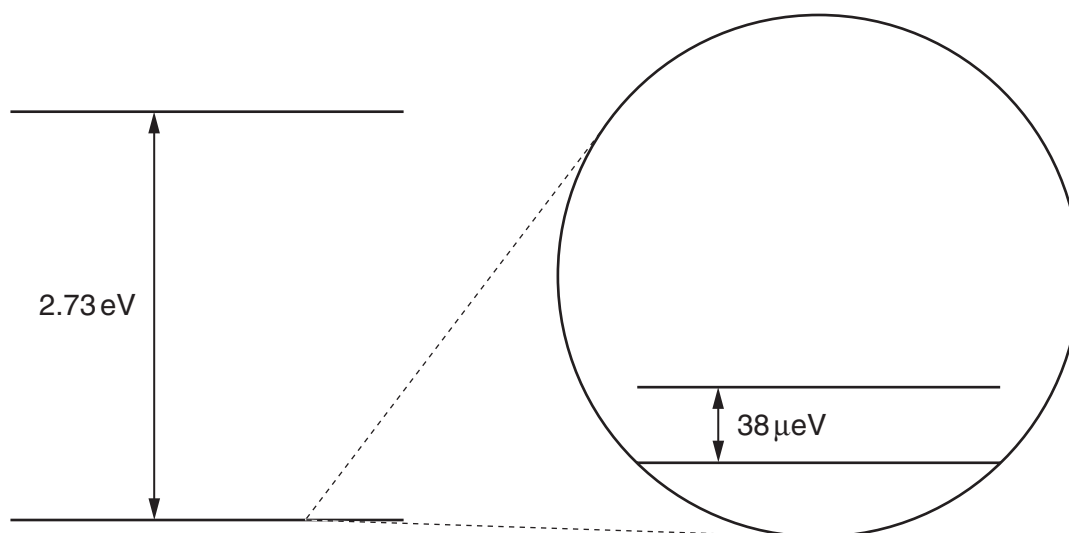


Fig. 6

As Fig. 6 suggests, the small energy level change responsible for the 9GHz radiation cannot easily be shown on the same energy level diagram as the transition causing the blue colour in the spectrum of caesium.

90 In the atomic clock, caesium is vaporised in an oven. Atoms escape at high speed through a hole in the oven and pass between electromagnets which separate the beam into two beams, corresponding to the two energy levels separated by $38\mu\text{eV}$ shown in Fig. 6. Atoms in the lower energy state pass into a cavity where they are irradiated with microwaves of the appropriate frequency to be absorbed. The frequency of the microwaves is adjusted until the maximum absorption occurs. Digital electronic circuits are then used to divide the frequency of the oscillator
95 producing the microwaves step by step until a frequency of exactly 5MHz is produced. This maintains the oscillation of a quartz crystal at 5MHz, which is the output of the atomic clock. More electronic circuits divide the frequency further to give a 1 Hz digital signal which counts seconds.

100 A caesium atomic clock is so stable and precise that since 1967 it has been used to define the second: this is the duration of 9 192 631 770 cycles of microwave radiation absorbed or emitted by the transition of caesium-133 atoms in their ground state shown above. This definition was chosen to agree with the astronomical second, $\frac{1}{86\,400}$ of the length of an average day in 1820.

The caesium clock second is the most accurate definition of a unit that mankind has yet achieved, as caesium clocks measure frequency with an accuracy of between 2 and 3 parts in 10^{14} . This
105 corresponds to a time measurement accurate to almost one second in ten million years.

The Global Positioning System and Leap Seconds

The astonishing precision of atomic clocks allows them to be used for measurements of position by timing radio signals in the Global Positioning System (GPS). A series of 24 satellites, on three separate orbits of radius of 2.4×10^7 m, circles the Earth twice a day (Fig. 7).

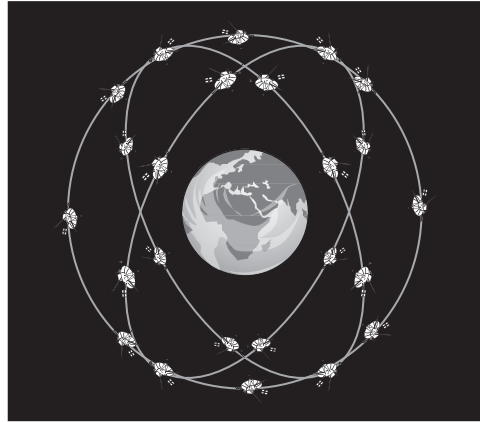


Fig. 7

- 110 The orbits are arranged so that at least four satellites are always in direct line-of-sight to any point on the Earth. This is the minimum number required for accurate location of a receiver on the surface of the Earth. The satellites all contain caesium atomic clocks, and transmit signals to Earth. The GPS receiver also has a clock, and it compares the time delay between its clock and the ones on the satellites, enabling it to work out the distance from each one. The satellites are
- 115 not stationary, so a GPS receiver also contains data tables which allow it to predict accurately the position of each satellite at any one time. The GPS receiver also continuously updates and corrects its own quartz clock, based on the accurate time signals from the satellites, and also updates its satellite data tables.

- One problem which arises in this system is that the length of a day on Earth is not constant,
- 120 but is gradually lengthening. This happens as a result of tidal friction forces acting on the Earth. Gravitational interactions with the Moon and the Sun raise tides in the Earth's oceans, and produce similar although smaller distortions in the shape of the solid Earth. These distortions produce heat and reduce the rotational kinetic energy of the Earth.

- Although the slowing of the Earth's rotation is not great, it has meant that the Earth's own daily
- 125 clock is running slower and slower. When the Earth was itself the basic timekeeper, this was of no consequence, but the atomic clock gives a different standard. Due to tidal friction, the Earth's rotation has been slowing at an average rate of 1.4ms per century. Well over a century has passed since the year on which the definition of the second was based, so a day is now about 2.5ms longer than 86400 seconds on the caesium clock. This corresponds to about a second
- 130 every year. This difference is corrected in a similar way to that in which the calendar allows for the extra quarter of a day in the year. An extra second, called a leap second, is added to the last minute of the last day in December or June. If you had been listening to the radio time signal at midnight of 31st December 2005, you would have heard the time signal consist of seven 'pips' instead of six.

- 135 Although these occasional leap seconds make no difference to our daily lives, and few people are aware that they occur, they prove to be a real inconvenience to the GPS. Whenever a leap second is introduced, all atomic clocks must be updated to allow for it. As a consequence, there is a move among scientists associated with GPS to abandon the procedure of adding leap seconds. They are not unopposed in this: other scientists, principally astronomers, have no wish to sever
- 140 the link between the measurement of time and the position of the Earth in space.

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