OXFORD CAMBRIDGE AND RSA EXAMINATIONS

ADVANCED GCE

G495

PHYSICS B (ADVANCING PHYSICS)

Unit G495: Field and Particle Pictures

ADVANCE NOTICE

TUESDAY 21 JUNE 2011: Morning
DURATION: 2 hours

SUITABLE FOR VISUALLY IMPAIRED CANDIDATES

READ INSTRUCTIONS OVERLEAF

DC (AC/SW) 11MEP06325 47899

INSTRUCTIONS TO CANDIDATES

- Take the article away and read through it carefully. Spend some time looking up any technical terms or phrases you do not understand. You are not required to research further the particular topic described in the article.
- For the examination in June 2011 you will be given a fresh copy of this article, together with a question paper. You will not be able to take your original copy into the examination with you.
- The values of standard physical constants will be given in the Advancing Physics Data, Formulae and Relationships booklet. Any additional data required are given in the appropriate question.

INFORMATION FOR CANDIDATES

- Questions in Section C of paper G495 Field and Particle Pictures will refer to this Advance Notice material and may give additional data related to it.
- Section C will be worth about 40 marks.
- Sections A and B of paper G495 will not be based on the material in the Advance Notice.
- There will be 2 marks for quality of written communication (QWC) assessed in Section C.

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How the metre measures up

For as long as human beings have been measuring things, there has been a need for the standardisation of units, to enable agreement amongst and between communities. Very often, the chosen starting point for deciding on basic units has been the human body itself – for example, the heartbeat as a unit of time.

A very early example of a distance unit is the Egyptian *cubit*, which was first defined and used over 5000 years ago. It was based on the length of a human arm (from the elbow to extended finger tip). Such definitions, though useful, are unsatisfactory for accurate measurements for the simple reason that humans come in a variety of shapes and sizes, so one Egyptian's cubit is likely to be different from another's. The idea of a standard unit was necessary and a famous example of this is the English *yard*, still used today in the UK and North America. It was defined in 1120 by the English king Henry the First, as the exact length of his own arm. Since the king could not be transported to wherever a length of cloth needed to be measured, iron bars were made to the same length and stored around the country. From them, wooden rulers could be made for everyday use. Thus arose the custom of having a single primary standard (the king's arm), and secondary standards made from it. Some of the original, now rusty, iron bars still exist in museums.

A TRULY GLOBAL SOLUTION

It was not until the 17th century that the unit of distance known to us today as the *metre* began to emerge as the standard unit of length. As part of his attempt to create a language system in which

scholars could communicate more effectively, John Wilkins, the Secretary of the Royal Society in London, proposed a standard system of measurement based on units of ten, i.e. a decimal system. Two years later, in 1670, the French scientist and priest Gabriel Mouton proposed a similar system, but with more detail, in which it was suggested that the standard unit of length should be the *milliare*, defined as the distance covered by one minute of arc along a meridian on the surface of the Earth (see Fig. 1). This corresponds today to a distance known as a Nautical Mile.

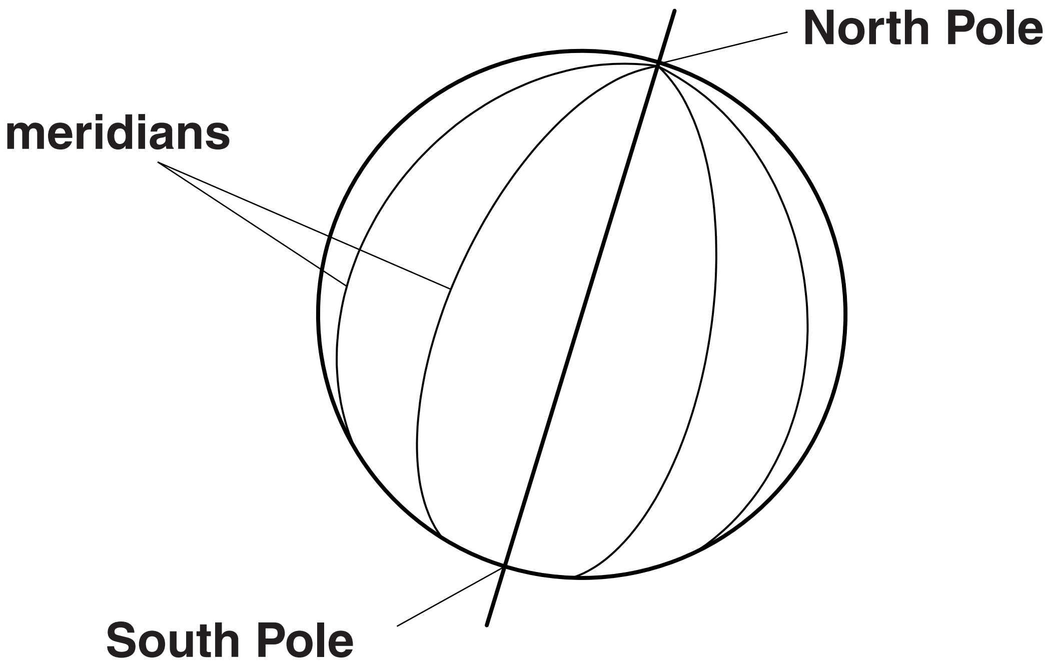

FIG. 1 A meridian is an imaginary circle drawn on the surface of the Earth, passing through both poles and meeting the Equator at right angles. It is a line of longitude.

In this system, a sub-division of the *milliare* was the *virga*, corresponding to 10^{-3} of a *milliare* and roughly equal to a unit already in use in Europe, the *toise*, a similarity which helped Mouton's system gain some acceptance. Mouton added that a pendulum could be used to assist standardization in different places. He stated that pendulum of length precisely 0.1 virga would "change direction 3959.2 times in exactly half an hour".

Mouton's proposal to base the unit of length on the dimensions of the Earth was discussed, adopted and refined for well over a hundred years, whilst all over the world many other basic units of length were still being used. During that time, the only other main contender for a universal definition was the pendulum approach. A pendulum with a period of two seconds (i.e. a half-period of exactly one second) was indeed preferred by many as a definition of the metric unit of length. It had several appealing advantages: it was simple, portable and the principle enabled a standard to be constructed anywhere. However, it was ultimately rejected as a method since it was itself dependant upon standardized time, the second, and sufficiently accurate and reliable clocks did not exist. Moreover, the period of a pendulum depends upon the gravitational field strength, which varies across the surface of the Earth.

STATING THE RULE

With international trade increasing dramatically, the need for standard units of measurement was becoming ever more crucial and so, in 1790, the French Academy of Sciences formally recommended that a meridian-based definition for unit length be adopted. Their recommendation was that the length of the meridian at sea level passing through Paris be measured and that the distance along it from the North Pole to the Equator be determined. One ten-millionth (10^{-7}) of that distance would be called a *metre* and this would form the basic unit for length.

This led in turn to the definitions of area and volume and also, using water as a standard substance, to the density of water, when 1 dm^3 of water was defined as having a mass of 1 kilogram. When an accurate determination of the meridian distance from the North Pole to the Equator was finally made in 1799, the so-called metric system was officially declared. This length became the standard metre and metal bars were produced against which others could be tested. In fact, the very first prototype was too short, as the calculation of the quarter-meridian did not take account of the Earth's rotation, which alters its shape, flattening the poles and causing a bulge at the Equator.

It was also important to produce a standard prototype from a suitable material. In 1874, a metre length made of a platinum-iridium alloy was produced. In 1889, the composition of the alloy was carefully defined. The new standard alloy consisted of 10% iridium, to within 0.0001 of a percent and the length of the bar was to be measured at exactly the melting point of ice.

Later still, in 1927, account was taken of other conditions. The metre was now defined as the distance between two particular marks on the upper surface of a platinum-iridium bar at 0 °C and standard atmospheric pressure, when supported by two cylinders of at least one centimetre diameter, positioned symmetrically on the same horizontal plane a set distance apart – see Fig. 2. It was important to define such details since the bar supported in this way would naturally bend and stretch under its own weight.

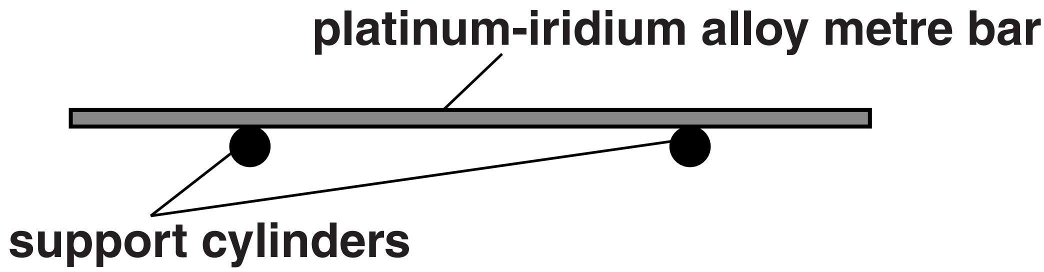

FIG. 2 Arrangement for supporting the 1927 standard metre bar

A NEW, ENLIGHTENED APPROACH

The definition based on the metre bar remained the acknowledged standard well into the twentieth century. However, continual cross-comparisons between standard bars showed that they changed lengths in unpredictable ways. Throughout that time, therefore, another approach was being developed and the basis of the definition of the standard for length shifted from being an artefact (the bar) to a physical property: the wavelength of light. This alternative definition became possible because of newly-developed optical instruments called interferometers. These devices enable precise values of wavelengths to be made from interference patterns.

One particular type was developed by the physicist Albert Michelson. A modern version of this is shown in Fig. 3, together with an explanation of how it works. As early as 1893, Michelson used it to measure the wavelengths of specific frequencies of light and thereafter advocated this as an improved method of defining distance. One particular measurement, that of the wavelength of the red line in the emission spectrum of the element cadmium, was made with particular accuracy and proposed as the basis for a new definition of the metre, though it was not adopted by the scientific community. Further support for the argument for a definition based on the interferometer came when Michelson's measurement was used to determine the value of the angström (10^{-10} m), thereafter accepted as the standard unit in the field of spectroscopy and atomic physics.

MICHELSON'S BEAM SPLITTER

The beam splitter directs half of the light from the laser toward a fixed mirror (OY) and directs the other half toward a moveable mirror whose position forwards and backwards (along OX) can be changed very precisely. The light that travels the path from the fixed mirror to the beam splitter is then recombined with the light reflected from the moveable mirror. These beams will have different optical path lengths and the path difference between them will result in a phase difference between them when they arrive at the detector. An observer can bring the light in and out of phase by adjusting the position of the moveable mirror. As the mirror is moved forwards or backwards along the direction of OX, the intensity of light at the detector will alternate between bright and dark. Moving the mirror a distance *d* changes the distance travelled by the beam of light reflecting off it by 2*d*. The optical path length can also be affected by changes in the refractive index of the medium through which the light passes.

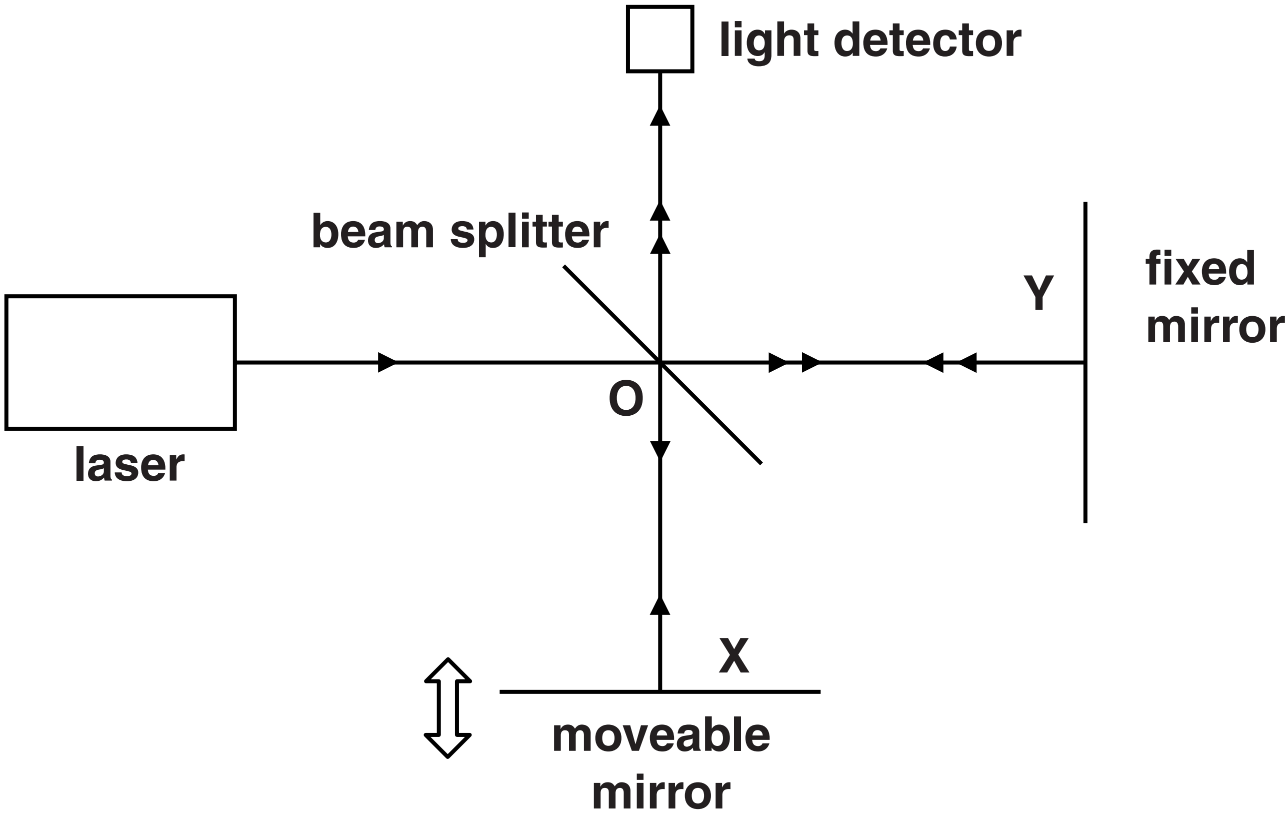

FIG. 3 Schematic diagram of a modern version of a Michelson interferometer and (in text box) an explanation of how it works

Eventually, in 1960, at the 11th General Conference on Weights and Measures (CGPM), a new definition of the metre was adopted. It was defined in terms of the interferometer measurement, in a vacuum, of the wavelength of the light emitted due to an electron transition between two particular energy levels within a krypton-86 atom. Thus, one metre became precisely 1 650 763.73 wavelengths of the red-orange line in the krypton-86 spectrum and the metre was now something that could be universally reproduced and was no longer based on an artefact that could erode or be damaged.

THE LASER POINTS THE WAY

For the next twenty years, improvements to the value defined in this way were made by the production of increasingly accurate interferometers. However, although this new definition of the metre has a precision of nine significant figures, there were some problems using interferometry to measure distances to this precision. One problem is that atomic spectral lines are not completely monochromatic. A solution appeared in the shape of newly-developed highly-stabilised lasers producing monochromatic light. Another factor, though, was to influence the definition: the re-defining of the standard unit of time (the second) in terms of the frequency of a particular emission from a caesium-133 atom. This made the second an absolute quantity, i.e. independent of other physical variables. In view of these advances, in 1983, the 17th CGPM redefined the metre as

"The distance travelled by light in a vacuum during a time interval of 1/299 792 458 seconds".
In effect, this defined the speed of light to be EXACTLY $2.99792458 \times 10^{8}\,\mathrm{m\,s^{-1}}$.

In order to use this definition of the metre in practical ways of measuring distances, the International Office of Weights and Measures (BIPM) has recommended using one of the following methods:

1. **Measure the time taken, *t*, for light to travel the required distance, *L*, and use $L = ct$.**
2. **Measure the frequency, *f*, of a stabilised laser in terms of the caesium time standard and find the wavelength from $\lambda = c/f$.**
3. **From a list of standard wavelengths issued by BIPM, use a suitable line which is known to a stated accuracy.**

Methods 2 and 3 use interferometry, with method 2 being used when the highest possible accuracy is required. Method 3 would be used routinely for calibration purposes using 'off the shelf' lasers.

The metre can now be replicated to a high degree of accuracy across the world. The metre has been changed from being an empirical standard to being an absolute one. Clearly, when defining the standard unit of distance over the centuries, scientists have gone to great lengths to get it right.

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