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SENIOR PHYSICS CHALLENGE

(Year 12)

Friday 8th MARCH 2024

This question paper must not be taken out of the exam room

Name: ______________________________

School: ______________________________

Total Mark /50

Time Allowed: **One hour**

- Attempt as many questions as you can.
- Write your answers on this question paper. **Draw diagrams**.
- Marks allocated for each question are shown in brackets on the right.
- **Calculators**: Any standard calculator may be used, but calculators must not have symbolic algebra capability. If they are programmable, then they must be cleared or used in "exam mode".
- You may use any public examination formula booklet.
- Scribbled or unclear working will not gain marks.

This paper is about problem solving and the skills needed. It is designed to be a challenge even for the top Y12 physicists in the country. If you find the questions hard, they are. Do not be put off. The only way to overcome them is to struggle through and learn from them. Good luck.

Important Constants

Constant	**Symbol**	**Value**
Speed of light in free space	c	$3.00 \times 10^{8}\,\mathrm{m\,s^{-1}}$
Elementary charge	e	$1.60 \times 10^{-19}\,\mathrm{C}$
Planck constant	h	$6.63 \times 10^{-34}\,\mathrm{J\,s}$
Mass of electron	m_e	$9.11 \times 10^{-31}\,\mathrm{kg}$
Mass of proton	m_p	$1.67 \times 10^{-27}\,\mathrm{kg}$
Acceleration of free fall at Earth's surface	g	$9.81\,\mathrm{m\,s^{-2}}$
Avogadro constant	N_A	$6.02 \times 10^{23}\,\mathrm{mol^{-1}}$
Radius of Earth	R_E	$6.37 \times 10^{6}\,\mathrm{m}$
Radius of Earth's orbit	R_0	$1.496 \times 10^{11}\,\mathrm{m}$

$$T_{(\mathrm{K})} = T_{(^\circ\mathrm{C})} + 273$$

$$\text{Volume of a sphere} = \frac{4}{3}\pi r^3$$

$$\text{Surface area of a sphere} = 4\pi r^2$$

$$v^2 = u^2 + 2as \qquad v = u + at$$

$$s = ut + \tfrac{1}{2}at^2 \qquad s = \tfrac{1}{2}(u+v)t$$

$$E = hf \qquad R = \frac{\rho \ell}{A}$$

$$P = Fv \qquad P = E/t$$

$$P = VI \qquad V = IR$$

$$v = f\lambda \qquad P = \rho g h$$

$$R = R_1 + R_2 \qquad \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$PV = \textit{const.} \qquad \frac{PV}{T} = \textit{const.}$$

Section A - Multiple Choice Questions 1-10 Circle the best answer.

1. Newton's Law of Universal Gravitation describes the gravitational force between two objects. This force is proportional to the product of their masses and inversely proportional to the square of the distance between them. The constant of proportionality is known as G, the universal gravitational constant.

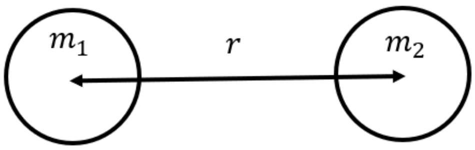

Figure 1

What are the units of G?

A. $\mathrm{kg^2\,m\,s^{-2}}$ B. $\mathrm{kg\,m\,s^{-2}}$ C. $\mathrm{kg^{-1}\,m^3\,s^{-2}}$ D. $\mathrm{kg\,m^2\,s^{-2}}$

[1]

2. The distance from Earth to the Moon is roughly 1 light second. Approximately how long would it take you to walk this distance?

Figure 2

A. 10 days B. 10 years C. 1000 years D. 10 000 years

[1]

3. A metric predecessor to the SI system of units is the cgs system, which is based on centimetres, grams and seconds, rather than metres, kilograms and seconds.
In the cgs system the unit of force is the dyne (from the Greek for power, or force).
It is defined as the force which accelerates a mass of $1\,\mathrm{g}$ at $1\,\mathrm{cm\,s^{-2}}$.
How many newtons is the equivalent of 50 dynes?

A. $5 \times 10^4\,\mathrm{N}$ B. $50\,\mathrm{N}$ C. $5 \times 10^{-2}\,\mathrm{N}$ D. $5 \times 10^{-4}\,\mathrm{N}$

[1]

4. An eccentric billionaire wraps a rope around Earth's equator. She then wishes to raise the rope above the ground by 1m along its entire length.
Approximately how much extra rope does she need to insert into the original rope?

Radius of Earth $\approx 6400\,\text{km}$

Figure 3

A. $1\,\text{m}$ B. $6\,\text{m}$ C. $310\,\text{m}$ D. $6400\,\text{m}$

[1]

5. A child on a toboggan (a sled, sledge, or sleigh) as illustrated in **Fig. 4**, slides down a smooth, snowy hill onto a flat surface. There, due to friction, she comes to a halt after sliding a horizontal distance D. The next time she does this her brother joins her on the toboggan, doubling the mass descending the slope.
On the flat surface, the frictional force is proportional to the weight on the toboggan (sled).

Figure 4

How far do they slide across the horizontal surface this time?

A. $D/2$ B. D C. $3D/2$ D. $2D$

[1]

6. The Lorentz factor, γ (Greek letter gamma), is derived from Dutch physicist Henrik Lorentz's work on electrodynamics. It appears in Einstein's Special Relativity equations in which length, time, mass, momentum and energy are described for objects moving relative to an observer. The equation for γ is commonly written as

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

where v is the velocity of the moving object and c is the speed of light.
Which of the following graphs represents γ as a function of v?

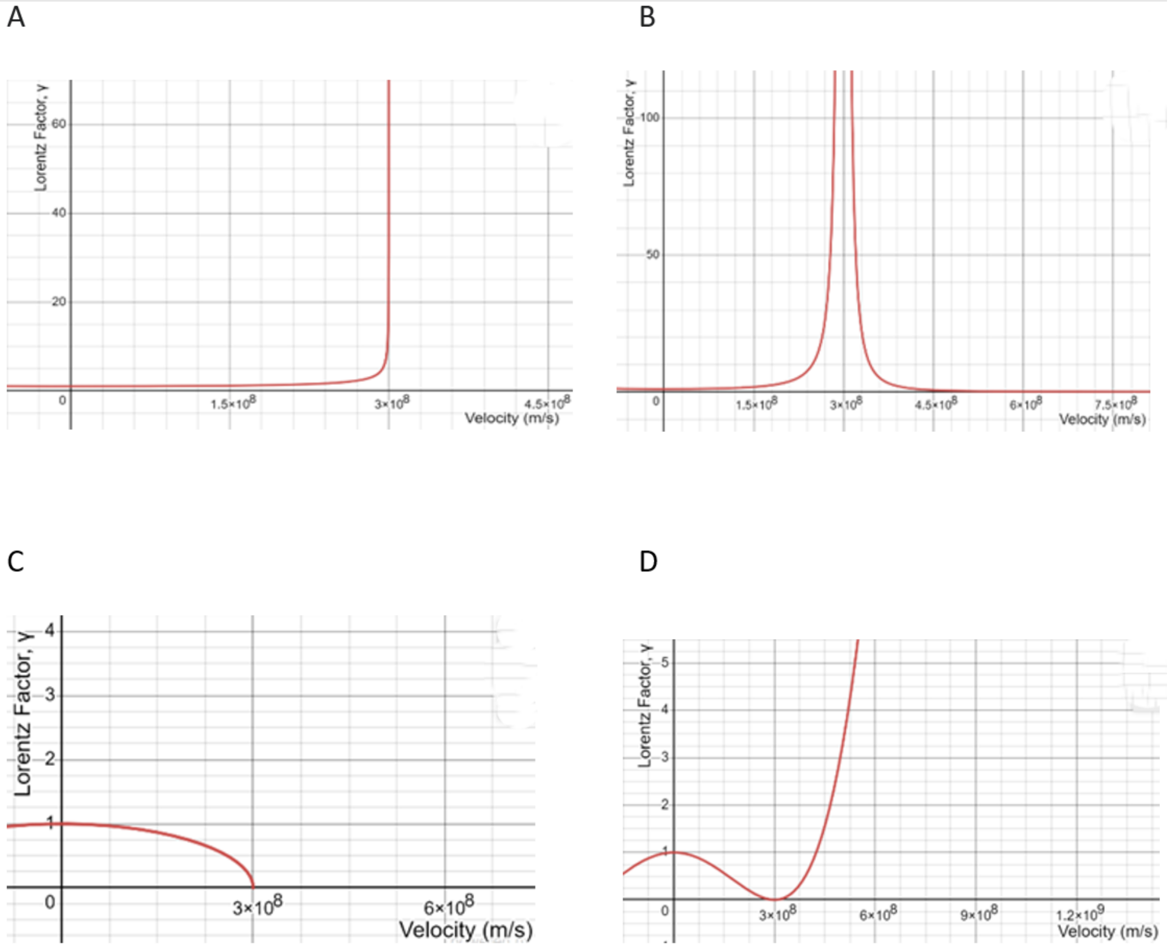

Figure 5

A. B. C. D.

[1]

7. A closed cylindrical glass jar is half full of dry sand. The sand grains have the same density but are of different sizes, ranging from $0.1\,\mathrm{mm}$ to $1\,\mathrm{mm}$ in diameter.

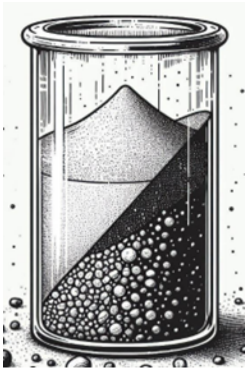

Figure 6

You shake the jar for a long time. Which of the following happens?

A. The smaller, lighter grains move to the bottom of the jar.

B. The larger, heavier grains move to the bottom of the jar.

C. They just move around randomly with no net effect.

D. It depends on the size of the jar.

[1]

8. Two walls face each other and are initially 12 metres apart. They are steadily brought together, each travelling at $0.30\,\mathrm{m\,s^{-1}}$. A fly trapped between the walls flies to and fro from wall to wall, moving at a right angle to their planes at a speed of $1.6\,\mathrm{m\,s^{-1}}$ until the walls meet. How far does the fly travel before the fly is squashed?

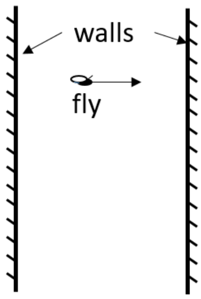

Figure 7

A. $8\,\mathrm{m}$ B. $16\,\mathrm{m}$ C. $32\,\mathrm{m}$ D. $64\,\mathrm{m}$

[1]

9. A cannon fires a shot directly upwards. The cannon ball reaches its highest point and then returns to the ground.
Taking into account air resistance, which of the following is true?

A. The time going up equals the time going down

B. The time going up is greater than the time going down

C. The time going up is less than the time coming down

D. Whether it's faster upwards or downwards depends on the initial speed of the cannon ball

[1]

10. The *spectral intensity*, I, of a star is the amount of energy per second falling normally on a unit area at a distance d from the star.
It is related to the power P of the star by the following equation:

$$I = \frac{P}{4\pi d^2}$$

A student moves her face towards a $60\,\mathrm{W}$ desk lamp until, at a distance of $0.2\,\mathrm{m}$, she feels the heat equivalent of a warm summer's day.

Figure 8

What is a reasonable estimate of the power of the Sun?

Distance from Earth to Sun $= 150$ million km.

A. $10^{19}\,\mathrm{W}$ B. $10^{22}\,\mathrm{W}$ C. $10^{25}\,\mathrm{W}$ D. $10^{28}\,\mathrm{W}$

[1]

[10 marks]

Section B - Longer Answer Questions

11. It is estimated that the average electric charge transported in a lightning strike is $20\,\mathrm{C}$, and the energy converted is 2.4×10^{10} J.

(a) (i). What is the potential difference between the cloud and the ground, at the moment of the lightning strike?

(ii). The air breaks down and becomes conducting when the the voltage across it exceeds $1.0 \times 10^{4}\,\mathrm{V\,cm^{-1}}$. What would be the maximum height of the charged thundercloud above the ground so that a lightning strike takes place?

[2]

(b) In a typical thunderstorm lightning flashes strike the ground at intervals of 2 minutes. Over the whole surface of the Earth the total current carried in this way between the atmosphere and the ground averages $1200\,\mathrm{A}$. Calculate the average number of thunderstorms taking place at any instant over the whole Earth.

[1]

(c) In order to determine whether these lightning strikes contribute much to the warming of the atmosphere, calculate the average heating power in a cubic metre of air due to these strikes if they all occurs in the lowest $1\,\mathrm{km}$ of the atmosphere.
Assume the Earth is a sphere of radius $6370\,\mathrm{km}$.

[1]

[4 marks]

12. Car tyres such as in **Fig. 9** come in a variety of sizes. One particular car uses tyres with a total external diameter, including the tread, of $621.5\,\mathrm{mm}$. When new, the tyres have a tread depth of $8.5\,\mathrm{mm}$.

Figure 9

When the tyres were installed, the car speedometer was calibrated to measure the correct speed by counting the rate of rotation of the wheel.
Some time later, the tyres are old and the tread has worn down to $1.6\,\mathrm{mm}$ depth.

(a) Explain whether the reading on the speedometer will now measure a too high, or a too low speed compared to the correct value.

[1]

(b) When the speedometer now shows $70\,\mathrm{mph}$, how fast is the car actually travelling?

[3]

[4 marks]

13. An electric toaster, illustrated in **Fig. 10**, draws a constant $1100\,\mathrm{W}$ of power.
Mains electricity is supplied at $230\,\mathrm{V}$.

When a toaster is turned on, the heating elements (the "red hot wires") very quickly get up to their operating temperature of $300\,°\mathrm{C}$, from room temperature of $20\,°\mathrm{C}$, in a time of 5.0 seconds.

Figure 10: Electric toaster

The elements are made of Nichrome, with a specific heat capacity of $450\,\mathrm{J\,kg^{-1}\,K^{-1}}$ and a density of $8.31\,\mathrm{g\,cm^{-3}}$.

(a) Calculate the mass of the heating elements.

[2]

(b) Calculate the resistance of the heating elements.

[2]

The elements are made of wire with a circular cross-section and a diameter of $1.0\,\mathrm{mm}$.

(c) Calculate the electrical resistivity of Nichrome.

[2]

(d) In reality, the power drawn by the toaster will not quite be constant. Explain what you would expect to happen to the power during those 5.0 seconds, and why.

[2]

[8 marks]

14. Imagine that you are an ancient architect, planning a pyramid. The pyramid illustrated in **Fig. 11** is to have a square base of side $40\,\mathrm{m}$, and be $40\,\mathrm{m}$ tall. It is solid, and made of blocks of rock of density $2500\,\mathrm{kg\,m}$.
You want to calculate the energy required to build the pyramid.

You know that the equation for the volume of a square-based pyramid is $\frac{1}{3}\times$ Base Area $\times$ Height.

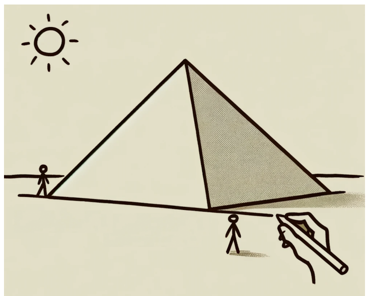

Figure 11: Square based pyramid

(a) Calculate the mass of the pyramid.

[2]

continued

The blocks all need to be lifted up to different heights, so to calculate the Work required is tricky. An estimate can be made by modelling the pyramid as a set of 14 large cubes.
9 of them are placed together in a 3×3 arrangement to form a square base. The next 4 cubes are placed on top of these to form a smaller square, and the last cube is placed on the very top, such that its top surface is $40\,\mathrm{m}$ above the ground.

(b) Assume that the 14 the cubes have the same total mass as the original pyramid and the bottom 9 cubes rest on the ground. Calculate

(i). the size and the mass of each cube in this model,

(ii). the final heights of their centres of mass,

(iii). the total work done required to lift the higher cubes into place.

[4]

(c) If a very long wooden plank was leaned against one face of the model cube pyramid from the ground straight to the top, what would be the angle of the plank with respect to the horizontal?

[1]

(d) If you wanted to build this model pyramid in a year, how many labourers would it take?
Assume a manual labourer has a useful energy output of around 800 kcal/day, where 1 kcal $= 4.18 \times 10^3$ J.

[1]

[8 marks]

15. Two forces, P and Q, acting respectively, (i) horizontally, and (ii) along the slope, of a frictionless, inclined plane at angle θ to the horizontal, can each, in turn, be individually used to support a block of weight W on the slope.

(a) On the two separate force diagrams for P and Q below, sketch and label the forces that hold the block in place.

Figure 12

[2]

(b) Resolve the forces in each diagram in suitable directions so that you obtain equations for P and also for Q in terms of W and θ.

[1]

(c) Show how you could eliminate θ to obtain $W = \dfrac{PQ}{(P^2 - Q^2)^{\frac{1}{2}}}$.

[1]

[4 marks]

16. A lion, with eyes $80\,\mathrm{cm}$ above the ground, sees the sun set at $8\,\mathrm{pm}$.
A giraffe stands with its eyes at $3.5\,\mathrm{m}$ above the ground.

(Radius of Earth = $6370\,\mathrm{km}$)

Figure 13

(a) (i). Sketch a diagram from a side-view, of an arc of the Earth and the line to the horizon as seen from an eye located on the Earth's surface and an eye located at a small height h above the surface.

(ii). Hence obtain an expression for the an approximate distance to the horizon d, as seen by an eye at height h.
Determine an expression for the angle θ subtended at the centre of the Earth by this distance.

[4]

(b) Calculate the difference in angles corresponding to the different heights of the giraffe's and the lion's eyes.

[2]

(c) Hence calculate the time at which the giraffe sees the Sun set.

[2]

[8 marks]

17. Imagine that after finishing this competition paper, you drink a mug of tea. You can estimate how many molecules of the water in your mug were previously drunk by Julius Caesar when he was alive.
Assume that the water molecules that went through him in his lifetime have been circulated through the oceans and in rain and are thoroughly mixed with water in our present day.

Figure 14: Earth

List of variables needed:

- The Radius of the Earth (in m) is R_{E}.
- The average depth of the Earth's oceans (in m) is d.
- The fraction of the Earth's surface covered by ocean is f_{ocean}.
- The density of water (in $\mathrm{kg\,m^{-3}}$) is ρ.
- The molar mass (mass of one mole of water in grams) is $M_{\text{water}} = \dfrac{M_{\text{water}}}{10^3}$ in kg.
- The internal volume of a mug (in m^3) is V_{mug}.
- The volume of water a human drinks in a day (in m^3) is V_{day}.
- Caesar's lifetime (in days) is t.
- The Avogadro Number is . (This is the number of molecules of a substance in 1 mole of that substance.)

(a) Form an equation, using the list of variables above, which you could use to calculate how many molecules of the water in your mug were previously drunk by Julius Caesar when he was alive.

Explain your steps clearly, stating what you're calculating at each stage. Make use of the units to help you.
Marks will be awarded for a clear process and explanation of your equation, as well as the equation itself.
As a suggestion, you might obtain expressions for

(i). the number of molecules consumed by Caesar in his lifetime
(ii). the number of molecules in the oceans
(iii). the number of molecules in a mug.

[3]

(b) Write down an overall expression for the number of molecules drunk by Caesar that you might find in your own mug.

(An approximate result seems to be about 10^8 molecules.) [1]

[4 marks]

END OF PAPER