BPhO
British Physics Olympiad

SENIOR PHYSICS CHALLENGE

(Year 12)

4th MARCH 2022

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 cannot be programmable and must not have symbolic algebra capability.
- You may use any public examination formula booklet.
- Scribbled or unclear working will not gain marks.

This paper is about problem solving. It is designed to be a challenge 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	$1.496 \times 10^{11}\,\mathrm{m}$

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

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

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

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

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

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

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

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

$$v = f\lambda$$

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

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

Qus. 1-5 Circle the best answer.

1. Estimate the mass of the Earth.

   A. 10^{20} kg B. 10^{22} kg C. 10^{24} kg D. 10^{26} kg E. 10^{28} kg

[1]

2. A block of mass m remains stationary on a rough slope as shown in **Fig. 1**. Which of the following could be equal to the magnitude of the frictional force F_f on the block?

   A. $N\cos\theta_2$ B. $N\sin\theta_2$ C. $mg\cos\theta_2$ D. $mg\sin\theta_2$ E. $mg\sin\theta_3$

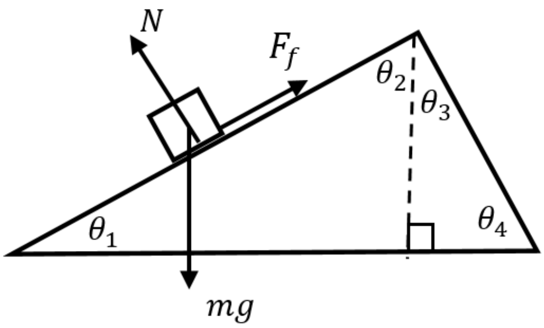

Figure 1

[1]

3. Energies in particle accelerators are measured in eV. What is the kinetic energy to an order of magnitude, in eV, of a snail of mass 1 g which crawls along at a rate of 1 cm in 10 s?

   A. 1 eV B. 1 keV C. 1 MeV D. 1 GeV E. 1 TeV

[1]

4. In a modern electric car, the most important reason the batteries are lithium ion rather than lead acid is

   A. lithium cells are easier to recycle

   B. lithium is much cheaper than lead

   C. lithium is less dense so the batteries are much lighter

   D. the energy density of the lithium battery is much greater

   E. lead batteries are full of dangerous acid

[1]

5. A source of high frequency sound from a sonar under the ocean surface sends a $60\,\mathrm{kHz}$ sound towards the surface. What is the wavelength of sound in the air above?
The speed of sound in air is $330\,\mathrm{m\,s^{-1}}$

A. $0.18\,\mathrm{m}$ B. $0.18\,\mathrm{mm}$ C. $5.5\,\mathrm{m}$ D. $5.5\,\mathrm{mm}$ E. $19.8\,\mathrm{m}$

[1]

6. (a) A small ball of mass m is attached to a point by a light string of length ℓ and hangs down under gravity, shown in **Fig. 2**. The point of attachment is accelerated to the right with a constant acceleration a, so that the string hangs at an angle θ to the vertical, with a tension T in the string.

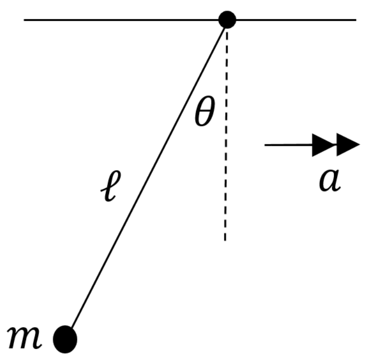

Figure 2: Ball on a light string which is accelerated to the right.

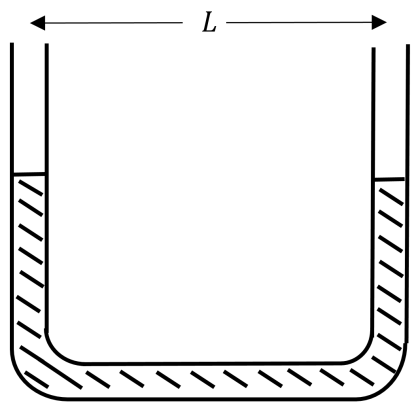

Figure 3: U-tube containing water.

i. Write expressions for the horizontal and vertical components of the force on the ball, in terms of m, g, T, a and θ.

[2]

ii. Obtain an expression for the angle of the string to the vertical, θ, in terms of a and g

[1]

(b) In the U-tube half filled with water of **Fig. 3**, the tube has a cross-sectional area A. The U-tube has a horizontal acceleration, a, to the right and in the plane of the U-tube. This will cause a height difference h in the levels of the water.

i. Sketch the U-tube with the water levels in the tube, showing the water surface on each side.

[3]

ii. The arms of the tube are a distance L apart, By considering the forces on a thin disc of water in the tube or otherwise, deduce an equation relating h to a, g and L.

[2]

7. In an experiment to measure the length of an oil molecule that has a hydrophilic end (one end of the long molecule sticks in a water surface), a drop of the oil of volume $0.1\,\mathrm{mm}^3$ is touched on to the surface of some water in a tank. The oil spreads out to give a circular patch of area $1000\,\mathrm{cm}^2$. What is the length of the oil molecule?

[2]

8. One end of a uniform beam, of weight W is placed on a smooth horizontal plane. The other end, to which a light string is attached, rests against another smooth plane inclined at an angle α to the horizontal. The string, passing over a frictionless pulley at the top of the inclined plane, hangs vertically, and supports a weight, P.

   Sketch a diagram of the beam and the planes, marking on it the forces acting on the beam and on P. (There is no calculation required.)

[4]

9. Gamma radiation such as that from a Co-60 source is a penetrating radiation which requires shielding for safety purposes. The radiation is reduced in intensity when it passes through a material by a factor

$$S = 2^{-\frac{x}{a}}$$

   where x is the distance travelled through the material and a is a constant which depends on the material and gamma ray energy.
   What thickness x of lead will reduce the intensity of the same gamma rays to $\frac{1}{8}^{\text{th}}$ that of concrete of thickness $y = 1.0\,\text{m}$?
   For gamma rays produced by cobalt-60:
   a_{lead} for lead is $12\,\text{mm}$
   a_{concrete} for concrete is $60\,\text{mm}$

[3]

10. (a) A battery is connected to a lamp, a moving coil ammeter (illustrated in **Fig. 4**) and a switch, all in series. The needle of the ammeter hits the end stop when the switch is first closed, but then returns to read the normal value for the particular lamp. A thermistor is then included in series in the circuit. The lamp again runs at almost normal brightness when the switch is closed, but the needle of the ammeter no longer hits the end stop. Explain why.

Figure 4

[3]

(b) A filament lamp has a resistance which we can assume is proportional to its temperature in kelvin. A $50\,\mathrm{W}$ bulb operates on $230\,\mathrm{V}$ at a temperature of $2250\,\mathrm{K}$. What is the resistance of the bulb at room temperature of $27\,^{\circ}\mathrm{C}$?

[3]

A circuit of two resistors R and R_C in series is connected to a supply as shown in **Fig. 5**. The potentials at three points are marked as $0\,\mathrm{V}, V_\mathrm{A}, V_\mathrm{B}$. The current I in the circuit depends upon the value of R_C.

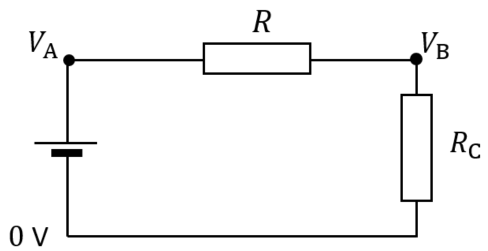

Figure 5

(c) i. Obtain a relation between $V_\mathrm{A}, V_\mathrm{B}, I$ and R.

ii. Sketch a graph of the current I ($y-$axis) against the potential V_{B} ($x-$axis). Mark on values where the line crosses each axis, and the gradient.

iii. R_{C} is now replaced by a filament light bulb. On your sketch graph above, add another line with an arrow that shows how I and V_{B} vary from the moment the bulb is switched on until its steady illumination.

[5]

(d) A relay is an electro-mechanical device in which a small current flowing through a coil magnetically operates a switch. A relay is illustrated in **Fig. 6**. With no current in the coil, the switch is open. In the circuit shown in **Fig. 7**, a small current flowing through the coil will close the switch and light the bulb.

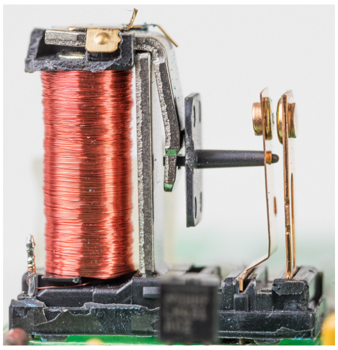

Figure 6

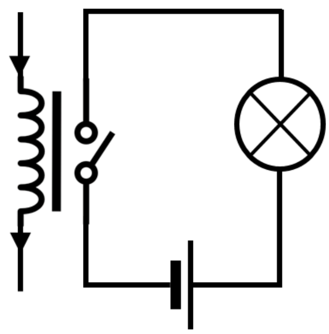

Figure 7

A potential divider circuit is made using a resistor, a cell and light dependent resistor (LDR). The resistor is in parallel with the coil.

i. In version A of the circuit, shown in **Fig. 8**, explain what would happen if light was shone on the LDR.

[2]

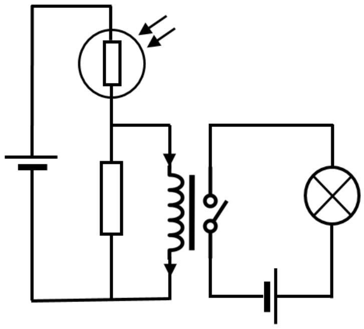

Figure 8: Potential divider arrangement connected to a relay. Version A.

ii. In version B of the circuit, the LDR and resistor are interchanged. The bulb is now placed physically over the LDR, and the light bulb starts flashing on and off. The light of the bulb affects the LDR which switches the relay. A very simple estimate can be made of the flashing rate by calculating the time taken for the filament to heat up, and assuming it cools down instantaneously.

The bulb is $24\,\mathrm{W}, 12\,\mathrm{V}$ with a filament length of $12\,\mathrm{cm}$. The temperature rise is from $300\,\mathrm{K}$ to $2300\,\mathrm{K}$ and the specific heat capacity of tungsten is $134\,\mathrm{J\,kg^{-1}\,K^{-1}}$. The density of tungsten is $19\,300\,\mathrm{kg\,m^{-3}}$ and the resistivity can be taken as $66 \times 10^{-8}\,\Omega\,\mathrm{m}$.
Calculate the time taken for the filament to heat up to estimate the flashing frequency. Ignore any heat loss.
Show intermediate steps in your calculation.

[4]

11. A linear electron accelerator consists of a series of hollow copper (drift) tubes of increasing lengths $\ell_1, \ell_2, \ell_3, \ldots$ along the beam and with a fixed small separation d between each tube. The tubes are connected to a high voltage, constant radio frequency AC supply where the peak voltage of the AC is V_0. Adjacent tubes are connected so that they will always have opposite polarities, as shown in **Fig. 9**. When an electron of charge e and mass m_e is passing through the inside of a tube, its two ends are at the same potential and so the electron feels no force and is not accelerated. So it "drifts" through the tube. It passes through a large potential difference between the tubes and, if the charged particle's motion is in sync with the AC supply, when it leaves a tube the polarities have been reversed and the charge is accelerated into the next drift tube. A schematic diagram is shown in **Fig. 10**

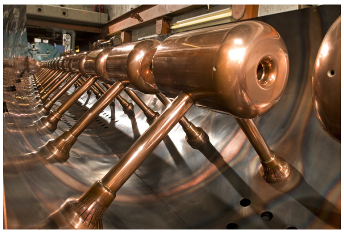

Figure 9

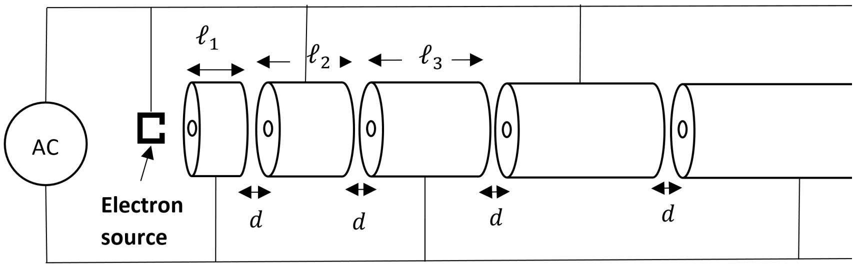

Figure 10

(a) i. Preliminary: a resistor has a potential difference of $5\,\mathrm{V}$ across it and a single electron flows through it. What is the thermal energy generated?

ii. To generate $2\,\mathrm{W}$, how many electrons flow through in a second?

[2]

(b) i. Sketch a graph of the AC voltage against time for two cycles of the AC.

ii. What is the maximum potential difference between adjacent tubes connected to the AC supply as shown?

iii. The frequency of the AC is f. State in terms of f, the shortest time T that the electron should take drifting through a tube in order that it experiences this maximum potential between tubes.

[3]

(c) i. The electrons leave the electron source in bunches starting with zero velocity, and are accelerated towards the first drift tube by the AC potential difference. In terms of e, V_0 and m_e, what is the maximum speed v_1 that the electron bunch can enter the first tube?

ii. Using your drift time from (b) iii and the speed from (c) i, obtain an expression for the length of the first drift tube, ℓ_1 in terms of e, V_0, m_e and f.

[3]

(d) i. The electron emerges from the end of the first tube with the same speed as it entered. What would be the speed of the electron as it leaves the second drift tube?

ii. What are the lengths of the drift tubes, ℓ_2, ℓ_3 in terms of the length of ℓ_1?

[3]

END OF PAPER

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