BPhO
British Physics Olympiad

SENIOR PHYSICS CHALLENGE

(AS CHALLENGE PAPER)

6th MARCH 2020

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	$1.496 \times 10^{11}\,\mathrm{m}$

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

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

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

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

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

$$E = hf$$

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

$$v = f\lambda \qquad V = IR$$

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

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

Qus. 1-5 Circle the best answer.

1. Estimate the mass of a soap bubble with a film thickness of 300 nm and a radius of 10 cm. The density of water is 1000 kg m^{-3}.

A. 4×10^{-2} kg B. 4×10^{-4} kg C. 4×10^{-5} kg D. 4×10^{-6} kg E. 4×10^{-7} kg

[1]

2. Which combination of vectors in **Fig. 1** could represent the resolved components of the vector V?

A. **A** B. **B** C. **C** D. **D** E. **E**

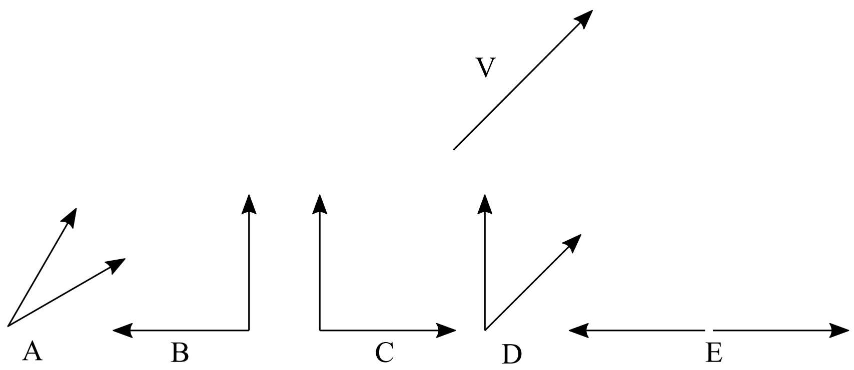


Figure 1

[1]

3. Protons in the CERN LHC orbit the 27 km circumference ring at almost the speed of light. If they were not held up by a magnetic field, through what height would they fall during one orbit?

A. 4×10^{-14} m B. 4×10^{-8} m C. 8×10^{-8} m D. 9×10^{-4} m E. 4×10^{-2} m

[1]

4. A long rope is held by two students, one at each end, and they begin shaking the rope to send waves along it. As they change the frequency, they sometimes see the waves cancelling out and sometimes adding together, to produce a wave that appears to remain almost stationary. The physics principle used to explain these observed effects is

A. refraction B. destructive interference C. constructive interference D. diffraction E. superposition

[1]

5. **Fig. 2** shows a uniform shelf of mass 4 kg supported at one end by a string, and by a hinge with no friction, fixed to a wall at P. If the string is held at an angle of $40°$ to the vertical and the shelf is horizontal, what is the tension in the string?

A. $62\,\mathrm{N}$ B. $40\,\mathrm{N}$ C. $31\,\mathrm{N}$ D. $26\,\mathrm{N}$ E. $20\,\mathrm{N}$

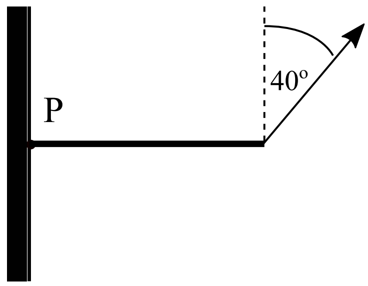


Figure 2

[1]

6. A jet aircraft travelling at Mach 3 (three times the speed of sound) in a horizontal path at a height of $15\,\mathrm{km}$ passes directly over an observer on the ground. Calculate the distance between the plane and the observer when they first hear the sound.

[4]

7. **Fig. 3** shows a point P moving in a circle of radius $4\,\mathrm{m}$ at a constant speed. It completes one rotation in $2.0\,\mathrm{s}$.

   What is its average velocity, giving the magnitude and compass direction (or draw an arrow),

(a) from A through one rotation back to A,

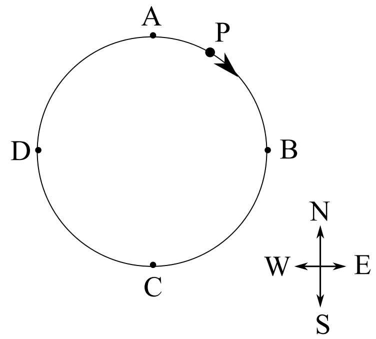


Figure 3

(b) between A and C, and

(c) between A and B?

[5]

8. Two massive cannon balls are fired from the same point at the same instant, and at the same angle θ to the horizontal, but with different velocities, v_1 and v_2 with $v_1 > v_2$. The horizontal motion of each ball is constant, whilst the vertical motions are subject to gravity, g. Ignore air resistance.

   (a) Sketch the paths of the two cannonballs to just beyond their maximum heights.

(b) Write down the equations of motion for the horizontal (x) and vertical (y) positions of each ball, in terms of time of flight, t, v_1 or v_2, θ and g. Use the notation x_1, y_1 and x_2, y_2 for the faster and slower balls respectively. (N.B. The balls go up and g is down.)

(c) Find the direction of the straight line joining the cannonballs at any time t after firing. Hint: this is similar to finding the gradient of a graph from points (x_1, y_1) and (x_2, y_2).

[6]

9. A vertical length ℓ of rope of mass m and cross-sectional area A is gradually lowered into water whilst holding the top end of the rope. When $\frac{1}{4}$ of the rope is submerged in water the tension at the top end of the rope is reduced to $\frac{5}{6}$ of the initial tension. What is the ratio of the density of the rope, ρ_r, to the density of water, ρ_w?
Hints: find the tension at the top of the rope when not in the water, in terms of g, A, ℓ, ρ_r. Then find the tension when a length d is in the water, now involving ρ_r and ρ_w.

[5]

10. To study the structure of crystals, materials scientists and biologists need to use X-rays with a wavelength approximately equal to the size of an atom. X-ray photons are produced when an electron, accelerated by a DC voltage, strikes a metal surface. In some instances, all of the kinetic energy of the electron can be used to create a single photon. Use the information given below to calculate the following quantities.

For sodium:	density	$\rho_m = 0.971 \times 10^3\,\mathrm{kg\,m^{-3}}$
	molar mass	$M = 23.0\,\mathrm{g\,mol^{-1}}$

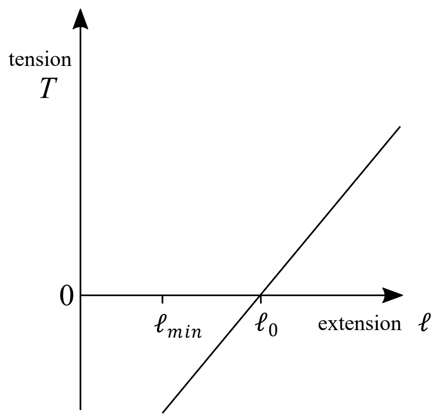
(a) Assuming a simple cubic arrangements of the sodium atoms in the crystalline structure, estimate the diameter of a sodium atom.

(b) What would be the energy of a photon with this wavelength?

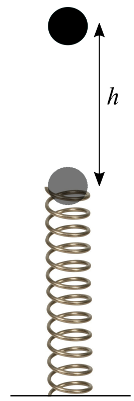
(c) Hence determine the accelerating voltage required to produce such photons.

[5]

11. A spring with spring constant k and of negligible mass has a linear force-extension graph as shown in **Fig. 4a**. The natural length of the spring is ℓ_0 and the spring can be compressed to a minimum length $\ell_{\min}$ when the coils are squeezed together. The compression factor f by which the spring is compressed from ℓ_0 to $\ell_{\min}$ is given by $f = \left(1 - \dfrac{\ell}{\ell_0}\right)$. The spring can also be stretched beyond ℓ_0, for which the same formula for f is applicable.
The spring is fixed to a rigid surface and points vertically upwards, as in **Fig. 4b**.



(a)



(b)

Figure 4

(a) Sketch a graph of f against the length of the spring, ℓ, over the range $\ell = 0$ to $\ell = 2\ell_0$.

(b) Explain, using the tension-extension graph of **Fig. 4a**, why the energy stored in a spring stretched or compressed to length ℓ is given by $\frac{1}{2}k(\ell_0 - \ell)^2$.

(c) A ball of mass m is lowered slowly on to the spring, which decreases to a length ℓ' with a compression factor f' when at equilibrium. Obtain an expression for the spring constant k in terms of ℓ_0, m, f' and g.

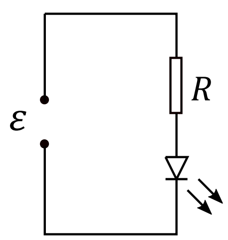
(d) A ball of mass m is released from a height h above the top of the spring and is caught in the spring, as in **Fig. 4b**. Sketch a graph of the force acting on the ball against height above the ground, as it falls, compresses the spring to a length $\ell > \ell_{\mathrm{min}}$, and then rebounds back to height h.

(e) The ball is held at the top of the uncompressed spring, at a height ℓ_0 above the table. It is released and at its lowest point it compresses the spring to length $\ell > \ell_{\mathrm{min}}$. Derive an expression, explaining your physics ideas, to relate the compression factor f to f'. Hint: eliminate k from your equations.

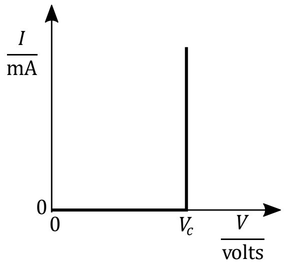
(f) The spring is now hung from the ceiling instead, and the same ball is attached to the spring, and held with the spring at its natural length, ℓ_0. When the ball is released, what will be the value of f in terms of f' when the ball reaches the lowest point of its motion (whilst remaining attached to the spring)?

[10]

12. An ideal LED is connected in series with a resistor R and a supply of e.m.f. ε and zero internal resistance, shown in **Fig. 5a**. The characteristics of an ideal LED are shown in the graph of **Fig. 5b**, with the conduction of the LED being infinite when the potential across it is equal to V_c. V_c is known as the *forward conduction voltage*.



(a)



(b)

Figure 5

(a) If $V_c = 1.8\,\text{V}$, the e.m.f. is $5.0\,\text{V}$ and the resistor limits the current in the LED to $24\,\text{mA}$, what is the value of the series resistor R that is required?

(b) Calculate the fraction of the power from the supply that is dissipated in the LED.

(c) The supply is replaced with one that varies as a sawtooth, with a linear rise in voltage and a vertical fall, with a period of $40\,\text{ms}$, as shown in **Fig. 6**. If the peak voltage applied is $5.0\,\text{V}$, calculate (i) the time at which the LED first switches on, and (ii) the fraction of time for which the LED is lit.

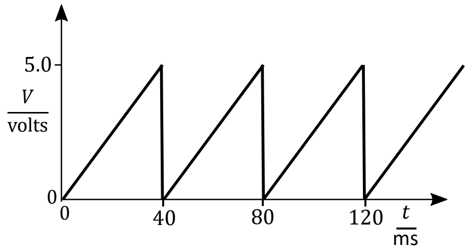


Figure 6

(d) Sketch a graph of the current through the LED against time, for two cycles. Mark numerical values on both of your axes.

(e) Calculate the average power of the LED in this circuit with the sawtooth e.m.f.

A real LED has an approximate linear $I - V$ characteristic above V_c, but the line is not vertical. This is shown in **Fig. 7** with $V_c = 1.8\,\mathrm{V}$. The LED is now connected without the series resistor R in the circuit, directly to the power supply. The gradient of the slope has a value of $0.040\,\mathrm{A\,V^{-1}}$.

(f) If the maximum current now permitted to flow through the LED is $10\,\mathrm{mA}$, what would be the e.m.f. of the power supply? Hint: you might redraw the graph in **Fig. 7**.

[10]

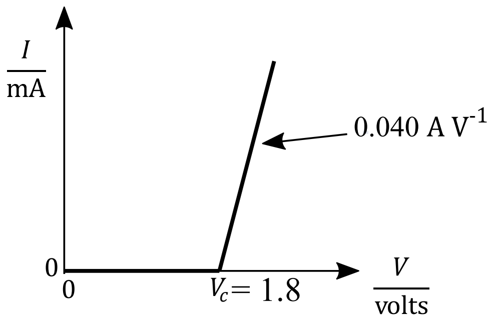


Figure 7

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