SENIOR PHYSICS CHALLENGE
March 2022
SOLUTIONS

Marking

The mark scheme is prescriptive, but markers must make some allowances for alternative answers. It is not possible to provide notes of alternative solutions that students devise, since there is no opportunity to mark a selection of students' work before final publication. Hence, alternative valid physics should be given full credit. If in doubt on a technical point, email rh584@cam.ac.uk .

A positive view should be taken for awarding marks for good physics ideas are rewarded. These are problems, not mere questions. Students should be awarded for progress, even if they do not make it quite to the end point, as much as possible. Be consistent in your marking.

Benefit of the doubt is NOT to be given for scribble.

The worded explanations may be quite long in the mark scheme to help students understand. Much briefer responses than these solutions would be expected from candidates.

A value quoted at the end of a section must have the units included. Candidates lose a mark the first time that they fail to include a unit, but not on subsequent occasions, except where it is a specific part of the question.

The paper is not a test of significant figures. Significant figures are related to the number of figures given in the question. A single mark is lost the first time that there is a gross inconsistency (more than 3 sf **out**) in the final answer to a question. Almost all the answers can be given correctly to 2 sf. The mark scheme often give 2 or 3 sf: either will do, or even less. If there is some modest rounding error in their answer then give them the mark. There is time pressure and so if they are on track for the answer then award the mark.

ecf: this is allowed in numerical sections provided that unreasonable answers are not being obtained.

owtte: "or words to that effect" – is the key physics idea present and used?

Section A: Multiple Choice

Question 1. C
Question 2. C
Question 3. D
Question 4. D
Question 5. D

There is 1 mark for each correct answer.

Maximum 5 marks

Multiple Choice Solutions

Qu. 1 $\frac{4}{3}\pi R^3\rho$ or $R^3\rho \approx (6.4 \times 10^6)^3 \times 5000 \approx 10^{24}$ kg

Qu. 2 θ_3, θ_4 are irrelevant. In equilibrium. Resolve ∥ to slope → $F_f = mg\sin\theta_1 = mg\cos\theta_2$

Qu. 3 KE $= \frac{1}{2} \times 10^{-3} \times \left(\frac{0.01}{10}\right)^2 \left(\frac{e}{1.6\times10^{-19}\text{ C}}\right)$ J $= \frac{1}{2} \times \frac{10^{-9}}{1.6\times10^{-19}}$ e$\frac{\text{J}}{\text{C}}$

$= 3 \times 10^9$ eV

Qu. 4 D - it is the energy density that is the significant factor.

Qu. 5 Frequency remains the same, so $\lambda = \frac{c}{f} = \frac{330}{60\times10^3} = 5.5$ mm

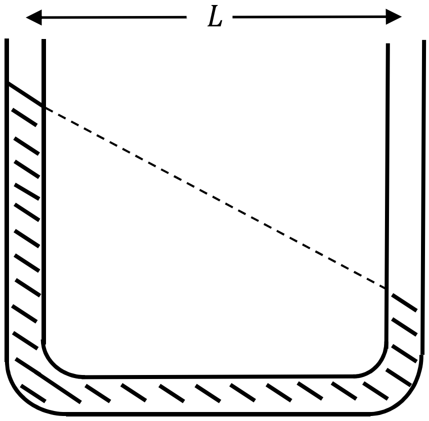
Total 5

Question 6.

(a) i H $T \sin\theta = ma$ ✓
V $T \cos\theta = mg$ ✓
[2]

ii Dividing the equations, $\tan\theta = \frac{a}{g}$ ✓
(or $\theta = \arctan\frac{a}{g}$)
[1]

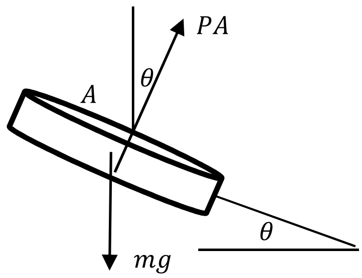
(b) i



- diagram with water levels different ✓
- higher on the left ✓
- water surfaces lined up along the slope ✓

[3]

ii More than one method allowed



M1. Mark for a model of some kind ✓
Thin disc with forces to keep it in equilibrium: the force on the disc in equilibrium is mg downwards and PA (pressure x area) acting at angle θ upwards. Resolving,
V $mg = PA\cos\theta$
H $ma = PA\sin\theta$

So $\frac{a}{g} = \tan\theta = \frac{h}{L}$ ✓
[2]

OR

M2: Mark for a model of some kind ✓
Take the slug of liquid in the bottom tube: the force required to accelerate it is $(\rho A\, L)a$ and this is equal to the weight of the extra water in the left tube, $(\rho g h)A$ which gives $a = g\frac{h}{L}$ ✓

OR

Using the equivalence Principle, the accelerated system (to the right) behaves as if in a gravitational field of strength a. So the resultant field is in the direction $\tan\theta = a/g$ and this works for both examples, in the second giving you the tilt angle of the liquid (or the tube with level liquid) in the "new" field. **Total 8**

Question 7.

Units need to be converted: $0.1 \times 10^{-9} = h \times 1000 \times 10^{-4}$

$$h = 10^{-9}\text{ m}$$ ✓

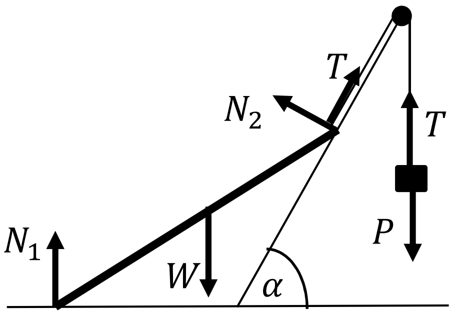
Sorting out the mixed units ✓

[2]

Total 2

Question 8.

Correct shape of diagram with some suitable symbols ✓



- N_1 and N_2 normal to the planes ✓
- Same tensions (T) in the string ✓
- All six forces marked and the angle α (even if symbols not matching) ✓

[4]

Total 4

Question 9.

The factor S is the factor that is how much the radiation is reduced to when it passes through material. So, for $x = 2a$ it is reduced to $\frac{1}{4}$ of its initial intensity.

Intensity after lead is $I_0 2^{-\frac{x}{12}}$ with x in mm.

Intensity after concrete is $I_0 2^{-\frac{y}{60}}$ with y in mm.

Require $I_{\text{lead}} = \frac{1}{8} I_{\text{concrete}}$

Hence $2^{-\frac{x}{12}} = \frac{1}{8} 2^{-\frac{y}{60}}$

Solving $2^3 2^{\frac{y}{60}} = 2^{\frac{x}{12}}$, $3 + \frac{y}{60} = \frac{x}{12}$ and with $y = 1000$ mm we obtain

$$x = 236\text{ mm}$$

OR

You can also do this in two parts: the absorption length in lead is $5 \times$ that in concrete, so for similar reduction over 1000 mm we need only 200 mm of lead. For a further factor of 8, we need $2^{\frac{x}{12}} = 2^3$ which means that $\frac{x}{12\text{ mm}} = 3$ and so $x = 36$ mm resulting in $200 + 36 = 236$ mm of lead in total.

3 marks for the answer ✓✓✓

from 1 mark for getting the factor of 1/8 the right way round

1 mark setting up the equation to be solved. **[3]**

Total 3

Question 10.

(a) With no thermistor, the cold filament will allow a large current that reduces as the bulb heats up. ✓

The thermistor is a high resistance when cold / so the current is limited to a low value ✓

As the thermistor heats up its resistance lowers and the current increases ✓

The resistance (temperature) of the bulb increases as the current increases, limiting the current through the thermistor (it would burn out) ✓

Three of these points required – thermistor is key here **[3]**

(b) $P = \frac{V^2}{R}$ so $R_{hot} = \frac{230^2}{50} = 1060\ \Omega$ ✓

$\frac{R_{hot}}{2250} = \frac{R_{cold}}{273+27}$ ✓

Hence $R_{cold} = 141\ \Omega$ ✓

[3]

(c) i Need to eliminate V_C

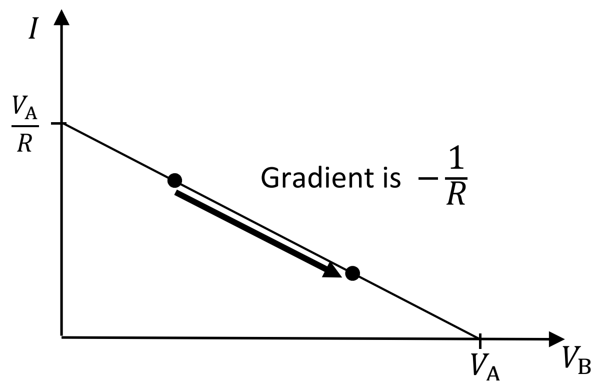
$I = \frac{V_\text{A}}{R+R_\text{C}}$ and $V_B = IR_\text{C}$ two equs. with R_C ✓

so eliminating V_C we obtain $I\left(R + \frac{V_\text{B}}{I}\right) = V_\text{A}$.

Thus $IR + V_\text{B} = V_\text{A}$ and then in suitable form

OR directly, $V_\text{A} - V_\text{B} = IR$ (✓✓), so that $I = \frac{V_\text{A}}{R} - \frac{V_\text{B}}{R}$ (either form) ✓

ii



- Straight line ✓
- Axes marked ✓

iii Arrow showing correct direction and from one point to another (not the whole line as the bulb changes from one resistance to another) ✓

[5]

(d) i The LDR has a high resistance in the dark. So the potential across the coil is small and the current through the coil will be small. So the bulb is off.

When light is shone on the LDR, its resistance decreases. ✓

So the potential across the coil will increase. ✓

A larger current will flow through the coil, and the bulb is turned on. But NOT just "more current flows". Plenty of current flows already, but we want to drive more of it through the coil instead.

[2]

ii $P = \frac{V^2}{R} \rightarrow R = \frac{12^2}{24} = 6.0\ \Omega$ ✓

$R = \frac{\rho\ell}{A} \rightarrow A = \frac{\rho\ell}{R} = \frac{66\times10^{-8}\times0.12}{6.0} = 1.32\times10^{-8}\ \text{m}^2$ ✓

$m = d\times V \rightarrow m = dA\ell = 19\,300\times1.32\times10^{-8}\times0.12$
$= 3.06\times10^{-5}\ \text{kg}$ ✓

$$t = \frac{mc\Delta T}{P} \rightarrow t = \frac{3.06\times10^{-5}\times134\times(2300-300)}{24}$$

$t = 0.3(4)\ \text{s}$ **OR** <u>$f = 3$ Hz</u> ✓

<u>OR in symbolic form</u>:

$$t = \frac{mc\Delta T}{P} = \frac{dA\ell.c.\Delta T}{\frac{V^2}{R}} = \frac{dA\ell.c.\Delta T.R}{V^2} = \frac{dA\ell.c.\Delta T}{V^2}.\frac{\rho\ell}{A}$$

$$t = \frac{d.\ell^2.c.\Delta T.\rho}{V^2} = \frac{19300\times0.12^2\times134\times(2300-300)\times66\times10^{-8}}{12^2} = 0.34\ \text{s}\ /\ f = 3\ \text{Hz}$$

[4]

The model is very simplistic; the bulb does not need to fully light, the ambient light matters, the proximity of the bulb is significant, the resistivity varies by a factor of ten, the bulb heats non-linearly with time, and it cools at a certain rate, etc. But in the end the result is about right when you operate the bulb in this way. The relay itself can switch much faster.

<u>Total 17</u>

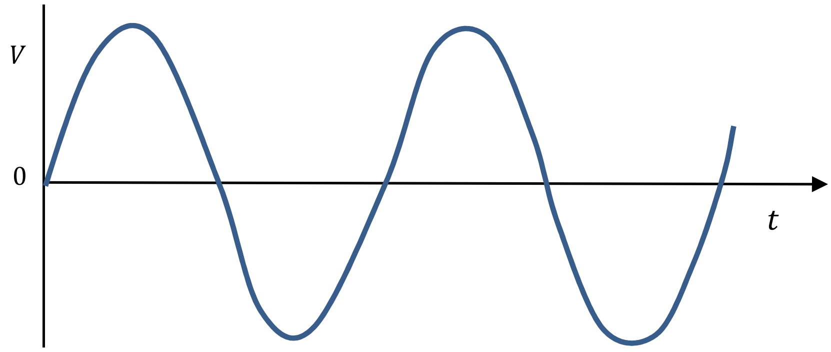
Question 11.

(a) i $E = 5\ \text{eV} = 5\times1.6\times10^{-19} = 8.0\times10^{-19}$ J ✓

ii $N = \frac{2}{8\times10^{-19}} = 2.5\times10^{18}$ ✓

[2]

(b) i



✓

- Two cycles
- Any shape – could be a square wave (an engineering challenge!)

ii $2V_0$ ✓

iii For the polarity on a tube to reversed whilst an electron is drifting through, the time is half a cycle $T = \frac{1}{2f}$ ✓

[3]

(c) i KE = electrical energy $\frac{1}{2}m_e v_1^2 = e.2V_0$ ✓

$v_1 = \sqrt{\frac{4eV_0}{m_e}}$ ✓

ii $\ell_1 = v_1 T = \frac{1}{2f}\sqrt{\frac{4eV_0}{m_e}}$ ✓

[3]

(d) i $\frac{1}{2}m_e v_2^2 = \frac{1}{2}m_e v_1^2 + e.2V_0$ ✓

$= e.2V_0 + e.2V_0$

$= 4eV_0$

Hence $v_2 = \sqrt{\frac{8eV_0}{m_e}}$

ii $\ell_2 = v_2 T = \frac{1}{2f}\sqrt{\frac{8eV_0}{m_e}} = \sqrt{2}\ell_1$ ✓

$\frac{1}{2}m_e v_3^2 = \frac{1}{2}m_e v_2^2 + e.2V_0$

$= 4eV_0 + e.2V_0$

$= 6eV_0$

$\ell_3 = v_3 T = \frac{1}{2f}\sqrt{\frac{12eV_0}{m_e}} = \sqrt{3}\ell_1$ ✓

[3]

Ecf: If they start off with $\frac{1}{2}m_e v_1^2 = e.V_0$ without the factor of 2 they only lose 1 mark, and everything carries through but with $\sqrt{\frac{2eV_0}{m_e}}$ and then the other brackets, with 4 not 8, and then 6 not 12. The relative lengths remain the same.

Total 11

END OF SOLUTIONS