BPhO Physics Challenge

September/October 2023

Instructions

Time: 1 hour.

Questions: Answer ALL questions.

Marks: Total of **50 marks**.

Instructions: You are allowed any standard exam board data/formula sheet.

Equipment: Any standard non-graphical calculator may be used.
Ruler and pencil may be needed.

Solutions: These questions are about problem solving. Draw diagrams in order to understand the questions. You must write down the questions in terms of symbols and equations; then try calculating quantities in order to work quickly towards a solution. In these questions you will need to explain your reasoning by showing clear working. Even if you cannot complete the question, show how you have started your thinking, with ideas and, generally, by drawing a diagram.

Clarity: Solutions must be written legibly and set out properly with a "narrative" which links one step to the next (and, so, therefore, hence, but, also, using equ 5, etc.).

Important Constants

Constant	**Symbol**	**Value**
Speed of light in free space	c	$3.00 \times 10^{8}\,\mathrm{m\,s^{-1}}$
Elementary charge	e	$1.60 \times 10^{-19}\,\mathrm{C}$
Mass of electron	m_e	$9.11 \times 10^{-31}\,\mathrm{kg}$
Atomic mass unit	u	$1.66 \times 10^{-27}\mathrm{kg}$
Earth's gravitational field strength	g	$9.81\,\mathrm{N\,kg^{-1}}$
Atmospheric pressure at the Earth's surface	P_0	$1.01 \times 10^{5}\,\mathrm{Pa}$
Planck constant	h	$6.63 \times 10^{-34}\,\mathrm{J\,s}$
Avogadro constant	N_{A}	$6.02 \times 10^{23}\,\mathrm{mol^{-1}}$

Qu 1. This question is about estimations.

Especially at the start of research or when solving a complex problem, it is useful to have an estimate of the sort of outcome to expect; making approximate calculations is a useful skill. Use the information given and any other estimated values of your own to answer the following:

a) (i) What is the cost of the electrical energy used in heating the water to make a cup of tea? (For this purpose, assume that the cost of domestic electrical energy is $45\,\mathrm{p}$ per kilowatt hour.)

[2]

(ii) According to 2021 measurements, 3×10^6 people became infected with COVID virus every day. The infection is active for about 5 days before most people recover and are no longer infectious; during this time a victim carries about 10^{10} virus particles. Each particle has a diameter of about $100\,\mathrm{nm}$. Estimate the total volume of coronavirus particles present in Earth's population at any one time during 2021.

[3]

b) A rectifier is a device for converting AC to DC. Figure 1 shows two circuits for achieving this.

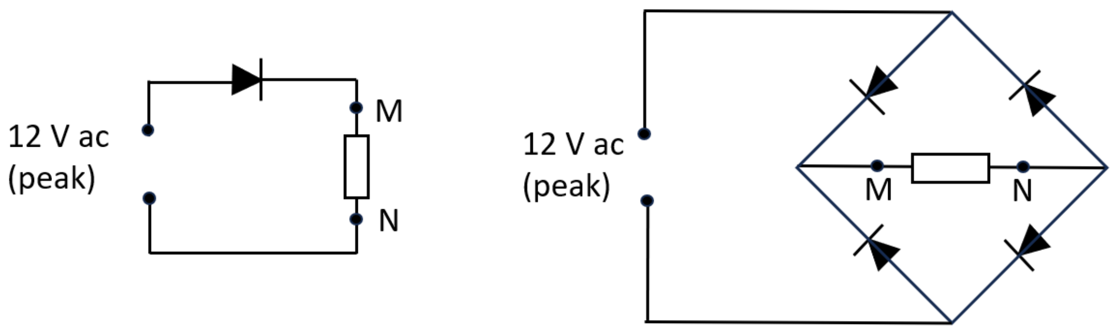

Figure 1: Two rectifier circuits.

(i) Sketch the current-voltage characteristic curve for a typical silicon diode and mark on a typical voltage value when it starts conducting.

(ii) Sketch a voltage versus time graph for each of the two circuits of **Figure 1** and mark on each of them an estimated value of the maximum voltage across the resistor (between **MN**), using your previous graph for the silicon diode.

[5]

[10 marks]

Qu 2. This question investigates of a number of electro-magnetic phenomena.

a) (i) Draw a diagram to show the magnetic field lines around an electric current, as viewed for the current flowing into the page.

(ii) Add to your diagram a parallel current to one side of the original one. By use of one of Fleming's rules or otherwise, determine the direction of the force experienced by the second current.

(iii) Now determine, with your reason, the direction of the force experienced by the original current and therefore complete the following rule with"attract" **or** "repel": "Parallel currents ....; anti-parallel currents ....".

(iv) It is a common observation that the hum produced by transformers, operating on $50\,\mathrm{Hz}$ supplies, is a little more than an octave below the note middle C (Middle C = $256\,\mathrm{Hz}$). Apply the rule you have just devised to current in the coils of a transformer and determine the frequency at which they vibrate, thus explaining why $50\,\mathrm{Hz}$ is not the observed frequency of the sound emitted.

[5]

b) How might you make a bar magnet with a north pole at both ends? As it is generally accepted that north and south poles come as N-S pairs, what has happened to the south poles? (Gluing two magnets together by their south poles is not an acceptable solution)

[2]

c) You are provided with three metal bars of equal density, identical dimensions and painted to be indistinguishable. One is non-magnetic, another is magnetic but unmagnetised while the third is magnetised with opposite poles at its two ends. With NO other apparatus, suggest how you might reveal the differing identities of the three bars.

[2]

d) This section suggests the principle of a method for finding the sign of the charge on the charge-carriers in a metal.

Figure 2 shows a conducting block through which a current is passed between two opposite faces, while it is placed in a strong, downward, uniform magnetic field. Let us suppose that the moving charge carriers have a positive charge.

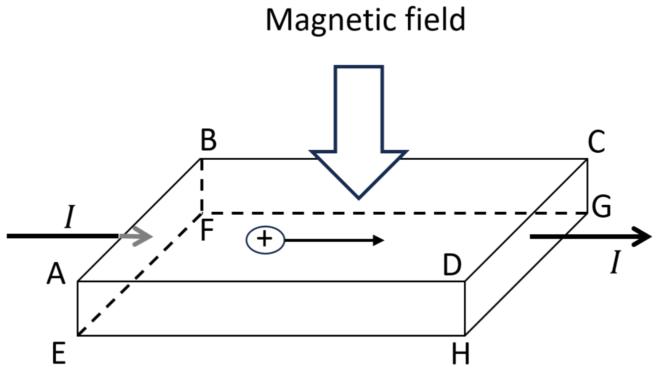

Figure 2: A conducting rectangular block carrying a current I and showing a positive charge carrier in motion.

(i) Using one of Fleming's rules or otherwise, determine the direction of forces experienced by the charge-carriers when the magnetic field acts vertically downwards on the block. (you may find that the labels on the vertices of the block give a convenient means of expressing such a direction)

(ii) Therefore, two faces of the block will become charged: state the signs of the charges on the two faces so affected.

(iii) Now repeat the exercise above with the starting assumption that the charge carriers carry a negative charge.

(iv) Use your results to suggest how this process may be used to determine the sign of the charge carriers actually present in a metal.

[5]

(What is described above is the Hall Effect; the "Hall Voltage" generated is extremely small even if a very strong magnetic field is used, so highly sensitive apparatus is needed)

[14 marks]

Qu 3. This question constructs a much simplified model which leads to the laws of friction.

a) (i) A cubic block of metal, of side a and density ρ, rests on a horizontal surface. Give an expression for the pressure you would expect the block to exert on the surface.

(ii) However, any surface, however carefully prepared, cannot ever be truly flat. Explain why this is so.

(iii) Hence comment on the true contact area of the block on the surface and why the pressure calculated above can only be an average value.

[3]

b) (i) Sketch the stress vs strain graph for a ductile metal (such as copper, aluminium or gold).

(ii) Indicate on your graph, the yield stress, σ_{y} and the ultimate stress, σ_{u}.

(iii) Write two inequalities to indicate the ranges of values of stress σ for which

i. elastic,
ii. plastic deformation occurs.

[4]

c) We will now examine the consequences of the irregularities in surfaces, known properly as asperities. We will start by looking at just one such asperity impinging on a surface, as in **Figure 3**.

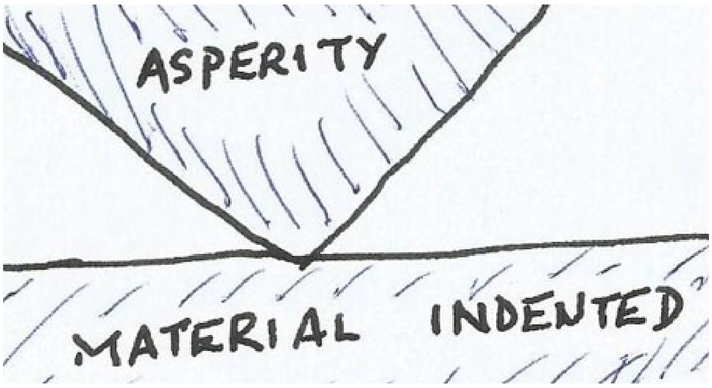

Figure 3: An example of an asperity - an irregularity in the surface of a material.

(i) In qualitative terms, comment on the area of contact between the asperity and the surface below. Therefore can you say about the stress under the asperity?

(ii) While this stress is greater than the yield stress, σ_{y}, what will happen? Also, what will happen when the stress becomes equal to σ_{y}?

From this point on, we simplify the argument by ignoring the differences in the values for the stresses in tension, compression and shear.
Now consider what happens when surfaces with many asperities impinge in a similar

manner, as in **Figure 3**.

In this situation, the true area of contact is far less than the value which might have been assumed in part (a).

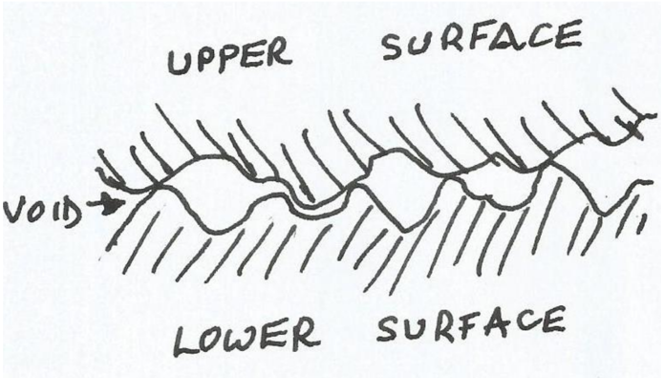

Figure 4: Two rough surfaces in contact.

(iii) Write down an expression using σ_y, for this true area of contact A when the surfaces are in equilibrium under the action of a force, R, pushing them together.

It is postulated that the asperities indenting each other get hot enough to weld together. The shearing force, F, needed to break these microscopic welds is the frictional force.

(iv) Calculate F in terms of any suitable variables already given, and hence demonstrate that $F \propto R$, where R is the normal reaction force between the two surfaces.

Here we have generated the familiar law of friction $F = \mu R$, where μ is the coefficient of static friction.

Amonton's Laws of friction are as follows:

- Frictional force depends on the nature of the two surfaces in contact.
- Frictional force is directly proportional to the normal reaction, and
- is independent of the area of contact.

(v) Indicate briefly how each of these laws is supported by your calculation.

(vi) In the 1980s, a specimen paper for the then new GCSE examination contained a question on vehicle stopping distances, where the 'correct' answer asserted that stopping distance would be greater for cars with bald tyres than ones with a good tread depth. Comment on this question in the light of Amonton's Laws.

[9]

[16 marks]

Qu 4. This question is about the displacement of a light beam by a parallel-sided block.

a) (i) Sketch a diagram of a thin ray of light passing through a rectangular glass block with an initial angle of incidence in air of i. (This is probably familiar from an experiment you may have done concerning refraction.) Mark on your diagram the angles of incidence and refraction at the initial point of incidence and where the light emerges from the glass. Also mark the dimension t, which is the thickness of the block in the direction of normal incidence.

(ii) It is often said that parallel-sided slabs cause "displacement without deviation". How does your diagram support this assertion?

(iii) Show that the sideways displacement of the ray, d, is given by the expression

$$d = t \sin i \left(1 - \sqrt{\frac{(1 - \sin^2 i)}{(n^2 - \sin^2 i)}} \right)$$

(Hint: draw a line perpendicular to the emergent ray at its point of exit. Where this intersects the original path of the ray, extended through the glass, it gives a convenient means to include d in your diagram.)

[6]

b) (i) Derive a reduced form of the relationship above, for small angles of incidence.

(ii) Use the following experimental data in order to find the refractive index of a glass block of thickness $10\,\mathrm{cm}$.

Table 1: Measurements of the sideways displacement of a light ray passing through a $10\,\mathrm{cm}$ glass block.

i / degrees	0	0.500	1.000	1.500	2.000
d / cm	0	0.029	0.058	0.087	0.116

[4]

[10 marks]

END OF PAPER