# Indian National Physics Olympiad (INPhO)-2023 HOMI BHABHA CENTRE FOR SCIENCE EDUCATION Tata Institute of Fundamental Research V. N. Purav Marg, Mankhurd, Mumbai, 400 088

# **Question Paper**

Date: 29 January 2023 Time: **09:00-12:00 (3 hours)** 

Instructions

Maximum Marks: 60

Roll No.:

- 1. This booklet consists of 6 pages and total of 5 questions. Write roll number at the top wherever asked.
- 2. Booklet to write the answers is provided separately. Instructions to write the answers are on the Answer Booklet.
- 3. Non-programmable scientific calculators are allowed. Mobile phones **cannot** be used as calculators.
- 4. Please submit the Answer Sheet at the end of the examination. You may retain the Question Paper.

| Table of Constants                |                |   |  |  |  |  |  |  |
|-----------------------------------|----------------|---|--|--|--|--|--|--|
| Speed of light in vacuum          | c              | $3.00 \times 10^8 \text{ m} \cdot \text{s}^{-1}$                        |  |  |  |  |  |  |
| Planck's constant                 | h              | $6.63 \times 10^{-34} \text{ J} \cdot \text{s}$                         |  |  |  |  |  |  |
|                                   | $\hbar$        | $h/2\pi$  |  |  |  |  |  |  |
| Universal constant of Gravitation | G              | $6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2 \cdot \text{kg}^{-2}$  |  |  |  |  |  |  |
| Magnitude of electron charge      | e              | $1.60 \times 10^{-19} \text{ C}$  |  |  |  |  |  |  |
| Rest mass of electron             | $m_e$          | $9.11 \times 10^{-31} \text{ kg}$                                       |  |  |  |  |  |  |
| Value of $1/4\pi\epsilon_0$       |                | $9.00 \times 10^9 \text{ N} \cdot \text{m}^2 \cdot \text{C}^{-2}$       |  |  |  |  |  |  |
| Avogadro's number                 | $N_A$          | $6.022 \times 10^{23} \mathrm{mol}^{-1}$                                |  |  |  |  |  |  |
| Acceleration due to gravity       | g              | $9.81 \text{ m} \cdot \text{s}^{-2}$                                    |  |  |  |  |  |  |
| Universal Gas Constant            | R              | $8.31 \text{ J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1}$              |  |  |  |  |  |  |
|                                   | R              | $0.0821 \text{ l}\cdot\text{atm}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$ |  |  |  |  |  |  |
| Boltzmann constant                | $K_B$          | $1.3806 \times 10^{-23} \text{ J} \cdot \text{K}^{-1}$                  |  |  |  |  |  |  |
| Permeability constant             | $\mu_0$        | $4\pi \times 10^{-7}$ H·m <sup>-1</sup>                                 |  |  |  |  |  |  |
| 1 Angstrom unit                   | $1\text{\AA}$  | $1 \times 10^{-10} \mathrm{m}$  |  |  |  |  |  |  |
| 1 micro unit                      | $1\mu$         | $1 \times 10^{-6}$ units  |  |  |  |  |  |  |
| 1 electron volt                   | $1\mathrm{eV}$ | $1.6 \times 10^{-19} \text{ J}$   |  |  |  |  |  |  |

| Q No          | 1 | <b>2</b> | 3  | 4  | 5  | Total |
|---------------|---|----------|----|----|----|-------|
| Maximum Marks | 6 | 6        | 16 | 16 | 16 | 60    |

### 1. [6 marks] Dancing on the floor

There are various apps that record the intensity of an audio signal. An app (WaveEditor<sup>TM</sup> here) displays the audio signal as a wave, whose amplitude is proportional to the audio signal's loudness. A smartphone with this app recording the sound signal is kept on a uniformly built flat floor of a classroom.



A perfectly small spherical steel ball is thrown up such that it almost touches the ceiling and comes back without hitting. The ball hits the floor and thereafter it keeps bouncing. The app records the sound signal produced when the ball hits the floor on every bounce. A screenshot of the recording is shown. The timestamps (in seconds) of the first eight consecutive bounces are also shown next to the peak. For example, the app records a peak at 10.260 s when the first time the ball hits the floor.

Make reasonable assumptions, when the ball hits the floor and calculate the height of the classroom from the given data. State your assumptions clearly.

### 2. Knock it off!

Consider a 100 W small isotropic source of blue light of wavelength 4500Å. A metallic surface of  $1.00 \text{ cm}^2$  and work function 2.20 eV is kept at a distance of 1.00 m from the source and oriented to receive normal radiation.

- (a) [2 marks] Assume that all the energy is uniformly absorbed by atoms on the top layer of the surface. Also, all the energy absorbed by an atom on the surface is taken up by one electron. The radius of the atom is 1.00Å. Estimate the time  $\tau_{\rm e}$  needed by the electron to receive 1.00 eV of energy.
- (b) [1 marks] According to the above classical model, how many electrons are emitted by the metallic surface in time  $\tau_{e}$ ?
- (c) [2 marks] In quantum theory, photons are emitted and absorbed as quanta. Assuming photoelectric efficiency of 1%, calculate the rate of emission of electrons  $(N_e)$  from the surface.
- (d) [1 marks] Assuming further that all the emitted photoelectrons move normal to the surface what would be the maximum current density  $(J_{max})$  one may expect?

#### 3. [16 marks] Work in progress

One mole of an ideal monoatomic gas goes through a linear process from A to B as shown in the pressure-volume (P-V) diagram. The temperature at A is  $T_A = 227^{\circ}$ C. The process is such that, the temperature decreases and the heat is continuously supplied to the gas. The ratio of the specific heat at the constant pressure to that at the constant volume is 5/3. Obtain the expression for the maximum work  $(W_{\text{max}})$  the gas can perform in such a process. Calculate  $W_{\text{max}}$ .



#### 4. Electrostatic TikTok

Consider a fixed infinite vertical thin rod (shown by the red color in the figure below) of linear charge density  $\lambda$  along the z-axis at the origin (see figure below). A uniformly charged ring of total charge Q, mass M, and radius a is placed with its center at the origin in the x-y plane. Point P is an arbitrary point on the ring. The projection of point P on x-y plane makes an angle  $\theta$  with respect to the x-axis in the anticlockwise direction as seen from the top.

The ring is now given an initial angular velocity  $\omega_0$  about the x-axis. We define the angle  $\alpha$  which the plane of the ring makes with the x-y plane. This is illustrated by drawing line segment AB in the plane of the ring. Initially  $\alpha = 0$ . Ignore gravity.



You may find the following differentiation useful

$$D = \frac{d}{d\theta} [\tan^{-1}(q \tan \theta)] = \frac{1}{1 + (q \tan \theta)^2} [q(\sec^2 \theta)]$$
(4.1)

- (a) [1 marks] State an expression for the electric field  $(\vec{E}_0)$  due to the infinite rod at a point on the ring when  $\alpha=0$  in terms of x, y and  $\theta$ , and related quantities.
- (b) [2 marks] At some instant the ring makes an angle  $\alpha$ . Derive an expression for the electric field  $\vec{E}$  due to the infinite rod at a point on the ring in terms of  $\theta$ , and  $\alpha$ .
- (c) [1 marks] Find the net force  $\vec{F}$  acting on the ring.
- (d) [5 marks] Find the net torque  $\vec{\tau}$  acting on the ring in terms of  $\alpha$  and the constants only. Qualitatively plot torque as a function of  $\alpha$ .
- (e) [2 marks] Let the ring is in equilibrium with respect to  $\alpha = 0$ . Derive an expression for the time period T of small oscillations of the ring in terms of  $\lambda$ , and Q. Take  $\lambda = 0.1 \mu$  C/m,  $Q = 2.0 \mu$ C, M = 50.0g, radius a = 5.0 cm, and  $\omega_0 = 1.0$  rad/s. Calculate T.
- (f) [2.5 marks] Find an expression for the potential energy U of the ring in terms of  $\alpha$ . Qualitatively plot U as a function of  $\alpha$ . Take the zero of potential energy to be at  $\alpha = 0$ .
- (g) [2.5 marks] Obtain the expression of maximum value of  $\alpha$  ( $\alpha_{max}$ ) in terms of  $\omega_0$ . Calculate  $\alpha_{max}$ .

## 5. If Prof. Snell had a smartphone

A typical smartphone screen is made up of mainly two components: a sheet of touch-sensitive glass (where you move your finger to operate the phone) of thickness t at the top and a LCD screen below it consisting of a regular array of "RGB elements" that emit light. These elements have a separation of d between them. There is a thin air gap of depth h between the touch-sensitive glass and the LCD screen (see Fig. (1)for a cross sectional view). We estimate the value of h from the following experiment.



We use two smartphones (S-I and S-II) in this exercise - S-I is the target instrument in which we want to estimate h, and S-II is the measuring instrument that can capture photos of the screen of S-I which we then analyse using a image-processing software.

A digital image captured by the camera of a smartphone (S-II here) consists of discrete picture elements called pixels. The image captured by S-II is processed through a software. A red color reference line is drawn on the image (see Fig. 3(a)). The software plots the "brightness value" at every point of the reference line as a function of the number of pixels from the left end of the line. Thus, pixel number is a marker for distance here. First, we need to calibrate distance in terms of pixel number.

The phone S-I is kept horizontal and the display is kept ON. A ruler is placed on its screen. S-II is fixed above S-I to capture images. The image of the screen captured is shown in Fig (2).



Figure 2

Figure 3(a) shows a part of the image of the ruler and its brightness value profile along the red reference line in Fig. 3(b).



- (a) **[2 marks]** State the number of pixels used by the camera of S-II to capture one centimeter of the screen of S-I.
- (b) [5 marks] We keep the setup the same as the last part. Next, a few small water drops are placed on the glass screen of S-I beside the ruler (see Figs. 4(a) and 4(b) for a top and side view, respectively). We model every drop as a hemispherical lens of radius R that magnifies the array of RGB elements of the LCD screen of S-I (see Fig. 4(c); the figure is not to scale).



Figure 4(d) shows the magnified image of the array of the RGB elements of the screen as viewed from the top through one of the drops. This image is captured by S-II keeping the camera settings and distance same as in the previous part. The brightness value profiles of the images of the five chosen drops along the reference lines are shown in Fig. (5) on the next page.

Using the profile plots, write the radius of the water drop (R in mm) and the corresponding magnification (M) of the separation d between the array of RGB elements of S-I for each waterdrop lens. Use the table in the Summary Answer sheet to report your data. Describe the method you have used and the calculations in the Detailed Answer sheet.

(c) [9 marks] For the given smartphone, t = 0.50 mm, the refractive indices of the touch-sensitive glass, water drop, and the air to be 3/2, 4/3, and 1 respectively. Using the data table of the previous part, plot a suitable linear graph to obtain the distance (h) of the RGB elements from the touch-sensitive glass. Use the table given in the summary answer sheet to enter the data used to plot the graph. Show your detailed theoretical calculation in the Detailed Answer sheet.



\*\*\*\* END OF THE QUESTION PAPER \*\*\*\*