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QUESTION PAPER

(June – 2019)

(Solved)

MODERN PHYSICS

Time: 2 Hours] *[Maximum Marks: 50*

Note: *Attempt **all** questions. You may use log tables and calculator. The values of physical constants are given at the end.*

Q. 1. Answer the following questions:

***(a)* Two galaxies are receding in opposite directions at speeds of 0.4c. What speed would an observer in one of these galaxies observe for the other galaxy?**

Ans. Let S be frame of reference attached to the earth from where we observe. Then the velocity of galaxy is:

$$V_x = 0.4c, V_y = 0, V_z = 0$$

Let S' be the frame attached to galaxy to moving in opposite direction then

$$V_x = 0.4c, V_y = 0, V_z = 0$$

$$V_x^1 = \frac{V_x - V}{1 - V_x \dfrac{V}{C^2}} = \frac{0.4c - (-0.Yc)}{1 + \dfrac{0.09C^2}{C^2}}$$

$$= \frac{0.6c}{1.09} = 1.65 \times 10^8 \text{ m/s}.$$

***(b)* Use de-Broglie's relation for the wavelength of a particle of momentum p to derive Bohr's angular momentum quantization condition.**

Ans. Ref.: See Chapter-4, Page No. 48, Q. No. 1.

***(c)* A particle of mass m is confined to a line of length L. From arguments based on the uncertainty principle, show that the energy of the particle can never be zero.**

Ans. Let us consider a one dimensional system and confine a particle between $n = 0$ and $x = \text{L}$. Then ground state energy is given by:

$$E_n = \frac{n^2\pi^2\hbar^2}{2m\text{L}^2} \quad n = 1, 2, 3 \ldots$$

This is contrasts with classical systems, where the particle can have zero energy. This can be explained in terms of the uncertainity principle.

The particle is confined to a box of length L means, the uncertainity in the position is L. Now, uncertainity in momentum is:

$$\Delta p = \frac{\hbar^2}{2\text{L}}$$

So, we can write

$$\text{E} = \frac{\hbar^2}{4m\text{L}^2} \quad (\because \text{P}^2 = 2m\text{E})$$

which agrees with the result obtained.

***(d)* State the selection rules for X-ray spectra. Draw the energy level diagram for L and M shells and show all the allowed transitions.**

Ans. Ref.: See Chapter-11, Page No. 102, 'X-Ray Spectra and Selection Rules' and Page No. 104, Q. No. 2.

***(e)* State Pauli's Exclusion Principle. Obtain the electronic configuration for atoms with atomic number Z = 19 and Z = 38.**

Ans. According to Pauli's Exclusion principle, No two electrons in an atom can have the same four quantum numbers. (n, l, ml, ms)

Electronic Configuration for:

Z = 19, is $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^1$

Z = 38 is $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^6\ 5s^2$

***(f)* How much time is required for 5mg of ^{22}Na to reduce to 1 mg? ($T_{½}$ for Na = 2.60 years)**

Ans. Using

$$\text{N} = \text{N}_o \left(\frac{1}{2}\right)^{t/\text{T}} \quad (\text{Here, T = half life})$$

$$\Rightarrow \quad 1\text{mg} = 5\text{mg} \left(\frac{1}{2}\right)^{t/2.60}$$

$$\Rightarrow \quad \frac{1}{5} = \left(\frac{1}{2}\right)\frac{t}{2.60} \Rightarrow t = 2.8$$

years.

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***(g) (i)* Classify the following elementary particles into leptons, baryons and mesons:**

$\pi°, \Sigma, \upsilon_e, \lambda$

Ans. Laptons $\Rightarrow$ Ve

Baryons $\Rightarrow$ Σ^+, Λ

Mesons $\Rightarrow$ π^o

***(ii)* Explain whether the following reaction is allowed or not :**

$$\boldsymbol{\pi \rightarrow e + \upsilon}$$

Ans. $\Lambda^- \rightarrow e^- + V$

Baryon No. – 1 – 1 + 1

This reaction is not allowed.

Q. 2. Answer the following questions :

***(a)* Explain why we do not observe the effects of time dilation in everyday phenomena. A galaxy is receding from the earth at a speed of 1.5 × 10^7 ms^-1 . If it emits light of characteristic wavelength ms 550 nm, what is the corresponding wavelength measured by astronomers on earth?**

Ans. Ref.: See Chapter-2, Page No. 22, Q. No. 7.

Also Add: Given, wavelength of light, λ = 550 nm

Speed of light, v = 1.5 × 10^7 ms^{-1}

$$\lambda_{abs} = \lambda_s \sqrt{\frac{1+\frac{4}{c}}{1-4/c}}$$

$$= 550 \times 10^{-9} \sqrt{\frac{1+\frac{1.5\times10^7}{3\times10^8}}{1-\frac{1.5\times10^7}{3\times10^8}}}$$

$$= 550 \times 10^{-9} \times \sqrt{\frac{21}{19}}$$

$$= 5.76 \times 10^{-7}$$

$$= 576 \text{ nm.}$$

***(b)* The rest mass of proton is 1.67 × 10^–27kg. Determine the force required to give the proton an acceleration of 10^15 ms^-2 in the direction of motion when *v* = 0. 8c.**

Ans. Using

$$F = \frac{m_o}{\left(1-\frac{v^2}{c^2}\right)^{3/2}} \bar{a}$$

For m_o = 1.67 × 10^{-27} kg, a = 1 × 10^{15} m/s^2, V = 0.8c

$$|\vec{F}| = \frac{1.67\times10^{-27}}{\left(1-\frac{0.64c^2}{c^2}\right)^{3/2}}\times10^{15}$$

$$= \frac{1.67\times10^{-12}}{0.36}$$

$$= 4.63 \times 10^{-12} \text{ N.}$$

Q. 3. Answer the following parts *(a)* and *(b)* :

***(a) (i)* State the properties of a wave function. Can the following wave function represent a Physical System :**

$$\psi(x) = N(1+ix)e^{-x} \quad \text{for } x > 1$$
$$= 0 \quad \text{for } x<1$$

Ans. Ref.: See Chapter-6, Page No. 60, 'Boundary Conditions and Acceptable Solutions' and Page No. 62, Q. No. 2.

***(ii)* Evaluate $\left[xp_x, P_x^2\right]$**

Ans. Using

[AB, C] = A [B, C] + [A, C] B

$[xP_x, P_x^2] = Px\,[Px, x] + [x, Px]\,Px$

as $[Px^2, xPx] = [Px, Px, x]$

$\therefore$ $[xPx, Px^2] = 2\,ihPx$

Similarly,

$[xPx, Px^3] = 3\,ih\,Px^2$

$[xPx, Px^n] = nih\,Px^{n-1}$

So we have

$[f(x), Px) = ih + zih\,Px + 3ihPx^2ihPx + 3ihPx^2 + ...$

$$= ih\,\frac{\partial f(x)}{\partial(x)}$$

Similarly,

$$[Px, f(Px) = ih\,\frac{\partial f(Px)}{\partial Px}.$$

***(b) (i)* Write the time-dependent Schrodinger equation and deduce the time independent Schrodinger equation from it.**

Ans. Ref.: See Chapter-6, Page No. 59, 'Time Independent Schrodinger Equation'.

***(ii)* Define the parity operator. Show that the parity operator is a Hermitian operator.**

Sample Preview
of
The Chapter

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MODERN PHYSICS

THE SPECIAL THEORY OF RELATIVITY

Emergence of Special Relativity 1

INTRODUCTION

We study Newtonian Mechanics in school science. There we studied inertial frames of reference, Newton's Laws of motion are the same in all inertial frames of references. All motions e.g., walking, driving car, running train or flying aeroplane and relative to earth and surroundings and laws of mechanics are the same in all inertial frames of references. This is called the classical principle of relativity.

However, all successful above Mechanics cannot explain. The propagation of electromagnetic waves and as such its application leads to inconsistence. To remove them, Albert Einstein proposed his 'Special Theory of Relativity' in 1905. We shall first give the classical relativity and backdrop of failure of the same at Wave Motion and subatomic particle level and finally we shall study the Einstein's Special Theory of Relativity.

CHAPTER AT A GLANCE

CLASSICAL RELATIVITY

We have studied displacement, velocity acceleration etc., in two inertial frames of reference and their mutual relationships. We have studied Laws of Newtonian Mechanics and the classical relativity which is called Galilean relativity.

Let us consider a physical event. An event's idealized version is something happening at a point of space at and instant of time, e.g. and electric bulb getting lighted or an explosion taking place. We can fix the position of an events by (x, y, z) i.e., Three coordinates of x-axis, y-axis, z-axis and time t, i.e. by four numbers for (x, y, z, t) which established an inertial frame of reference describing the event to answer where and when the event took place. We define: 'An inertial frame of reference is a frame of reference in which Newton's first law holds True'. Moreover, any frame of reference that move, with a constant velocity relative to an inertial $\hat{i}$ frame of reference is also an inertial frame.

If an event observed in an inertial frame of reference and has measurements in it, needs to be described in another inertial frame of reference, we shall use Galilean transformation which has been given below.

Galilean Coordinate Transformations

Let us consider and inertial frame S and another frame's which moves at a constant velocity u with respect to S as shown below:

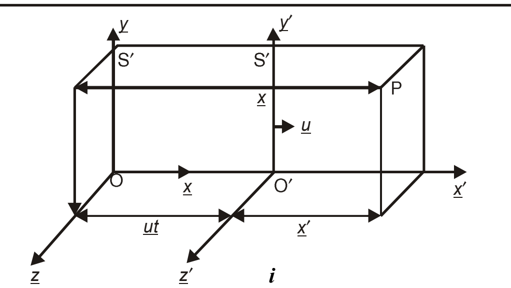

Fig.1.1: Two inertial frames of reference S and S′. S moves with a constant velocity $\underline{u}$ (= $\underline{u}\,\hat{i}$) with respect to S so that the x-x′ axis is common and the $\underline{y\text{-}y'}$, $\underline{z\text{-}z'}$ axes are parallel. As seen from frame S′, S moves with a velocity $-\underline{u}$, i.e., at a speed $\underline{u}$ in the negative $\underline{x}$ direction. Point P represents an event whose space-time coordinates can be measured by observers in S and S′. The origins O and O′ coincide at time $\underline{t}$ = o and $\underline{t'}$ = o. You can see that $\underline{x} = \underline{x'} + \underline{ut}$, $\underline{y'} = \underline{y}$ and $\underline{z'} = \underline{z}$.

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We define x-axis and x'-axis to be along the direction of u, the direction of motion. Let us assume two other axes (y, z) and (y', z') to be parallel to each other where y is parallel to y' and z is parallel to z' respectively. Also, let the origin O of time be at $t = 0$ so that the two instants coincide i.e., O′ and O coincide.

If an event E occurs at P and any measurement in the two frames of references are made by observers who have jointly calibrated their meter sticks and clocks. The observer attached to S given coordinates x, y, z, t to P where as s' gives $x', y'\ z', t'$ to the same event at P, so that in S, (x, y, z) is position of P and (x', y', z') is position of P in S' find to make things simple, let their clocks read $t = 0$ at the instant of 0.

By Galilean coordinate transformation (x, y, z , t) and (x', y', z', t') have following relationships

$$x' = x - ut$$
$$y' = y$$
$$z' = z$$
$$t' = t$$

Hence, we can write generalized transformation in vector notation as follows

$$\vec{r}' = \vec{r} = \vec{u}t$$
$$t' = t$$

where $\vec{r}$ is the position vector of P in S and $\vec{r}'$ in S'. Under our simplifying assumption $\vec{u} = u\hat{i}$.

Now differentiating $\vec{r}' = \vec{r} - \vec{u}t$ w.r.t t, we have

$$\frac{d\vec{r}'}{dt} = \frac{d\vec{r}}{dt} = \vec{a}' = \vec{a}$$

As $\vec{u}$ = constant.

$$\therefore\ m\vec{a}' = m\vec{a} = \vec{F}$$

Hence the law of motion is the same in S and S′.

We note $x'_p - x'_Q = x_p - x_Q$, $y'_p - y'_Q = y_p - y_Q$, $z'_p - z'_Q = z_p - z_Q$ i.e., $\vec{r}'_P - \vec{r}'_Q = \vec{r}_P - \vec{r}_Q$ and $\vec{v}'_P - \vec{v}'_Q = \vec{v}_P - \vec{v}_Q$

and $t'_A - t'_B = t_A - t_B$

Hence, forces do not change under Galilean Transformation Mechanics, i.e., Forces remain invariant under Galilean Transformation.

Galilean Principle of Relativity

The Laws of Mechanics can be written in the same form in all initial frames. If they hold in one inertial frame, they will hold in all inertial frames too.

The above principle can also be interpretated as

'There is no prepared inertial frame of reference in which alone the classical laws have the most basic form i.e., there is not absolute frame of reference'.

Absolute Space and Absolute Time

In Newtonian mechanics and Galilean relativity, the length mass, time are independent of relative motion of observer and do not depend on which inertial observer measurer them. Hence, there are absolute space intervals and time intervals in it. So space is like empty box which contains material objects and physical phenomenon and is unaffected by them, whereas time is absolute, flows equably without relation to anything external; in nutshell.

Newtonian ideas treat space and time existing by themselves independent of each other and do not depend on material bodies located in space or physical phenomenon occurring therein.

ELECTROMAGNETISM AND CLASSICAL RELATIVITY

When principle of classical relativity is applied to electromagnetism and optics, we find they do obey them, e.g., Maxwell's equation.

Prablems of Relativity vis-a-vis Laws of Relativity

Let two equal positive charges q carrying points as shown below be examined in frames of references S and S'.

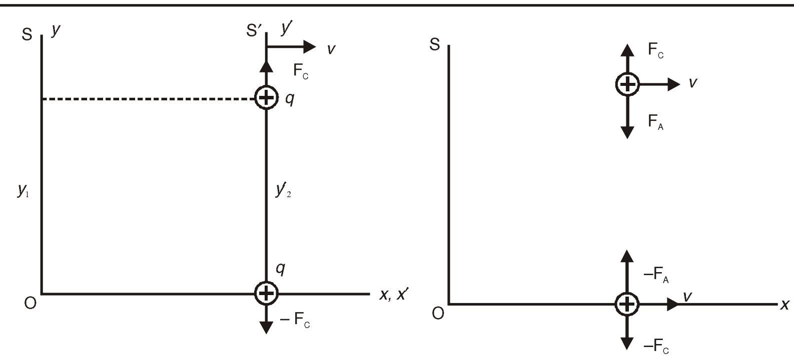

Fig. 1.2: *(a)* **Two equal positive point charges (carrying charge q) at rest on the y' axis of the frame of reference S′. In S′ the charges repel each other with a force of magnitude F_C; *(b)* as seen in S the charges are moving to the right with a velocity v and attract each other with an additional force of magnitude F_A, giving a total force of magnitude $|F_C - F_A|$.**

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One charge rests at the origin of S' and other at y_2' distance on the y'-axis of S'. By using Coulomb's Law, the force F_c is given by

$$F_C = \frac{1}{4\pi\varepsilon_0}\frac{q^2}{y_2'^2}$$

Now we consider the electromagnetic force from point of view of S. Here $y_1 = y_2'$ so Coulomb's force for it is the same, but observer sees the charges q moving to the right at a speed v and altractive.

How can this be? This is inconsistency.

The above discussion and problem shows that there is an agreement missing between Maxwell's theory of electromagnetic fields, Newtonian mechanics and Galilean principle of relativity. In fact, 'The Problem of light' had had this disagreement historically.

Galilean Relativity and the Speed of Light

Huygens put forward wave theory with a fictitious rarefied, all space filling/pervading elastic medium called lumineferous ether. But this medium remained illusive even after almost two centuries. Works of Young and Fresnel assumed light or showed it so as of wave nature. Maxwell's description of light as of electromagnetic nature did not end the search of ether. The light propagated in the medium with speed $v = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$. Galilean principle of relativity applied to propagation of light in ether led to an inconsistence. To understand this inconsistency, let us consider a frame of reference S with respect to which light travels with velocity. If a frame S′ is moving with velocity with velocity v w.r.t. S then we can apply Galilean transformation to it to get, velocity of light v' in S′ as

$v' = c - u$ and $|v'| = \sqrt{c^2 + u^2 - 2c.\vec{u}}$

Where $|v'|$ = speed of light in S′

We note if direction of c and u are opposite,

$|v'| = c - u$ and in the same direction,

$|v'| = c + u$

Let us assume both the Galilean transformation and the laws of electromagnetic as correct, then there is a unique privileged inertial frame of reference, the absolute frame in which the Maxwell's equations are valid. This unique frame of reference has $c = \frac{1}{\sqrt{\mu_0\varepsilon_0}}$ whereas other frames would have different speed of light.

The situation at the end of 19th century was that the Galilean relativity does apply to Newtonian Mechanics and not to Maxwell's Laws of electromagnetism. That meant we could choose any one of the following three options:

1. Retain the relativity principle for mechanics but not for electrodynamics.

   That keeps Newtonian mechanics unchanged but laws of electromagnetism hold only in one privileged frame of reference i.e., ether frame. In this case, we should be able to find the ether frame experimentally.

2. Retain the relativity principle for both mechanic and electrodynamics but hold the electromagnetism not correct.

   This alternate needs to find deviations from electromagnetic theory experimentally. In that case, we need to reformulated the laws of electromagnetism so that the Galilean transformation applies to the new laws.

3. Retain the Relativity principle for both mechanics and electrodynamics but hold Newtonian mechanics is not correct.

   This alternative needs to find deviations from Newtonian Mechanics and then reformulate the Newton's Laws. Also Galilean transformation must be given up and some new transformation must be given up and some new transformation that is consistent with classical electromagnetism and new laws of mechanics.

Attempts to Locate the Absolute Frame: The Michelson-Moley Experiment

This experiment was being conducted in search of the long illusive ether. The basic principle used was as follows:

If some travels in still air at 340 m/s when we move in air at a speed of 30 m/s towards in oncoming sound then we can see that the speed of sound in 310 m/s. So we can see that the speed of sound varies with our speed relative to air.

Now if ether is all pervading medium in which the light travels then our earth is moving through ether as it rotates round the Sun. As earth orbits the Sun at the speed 30 km/s (approx), the speed of light in direction will increase by this value and after 6 months when earth moves in opposite direction, the speed of light will

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decrease by this amount. The Michelson-Morley Experiment is designed to detect such a change in the speed of light.

The principle of experiment was to send light signal from a source to a mirror and back nothing the total time taken. It was to be performed two times, once in the direction of earth's motion in ether and again at right angles to it.

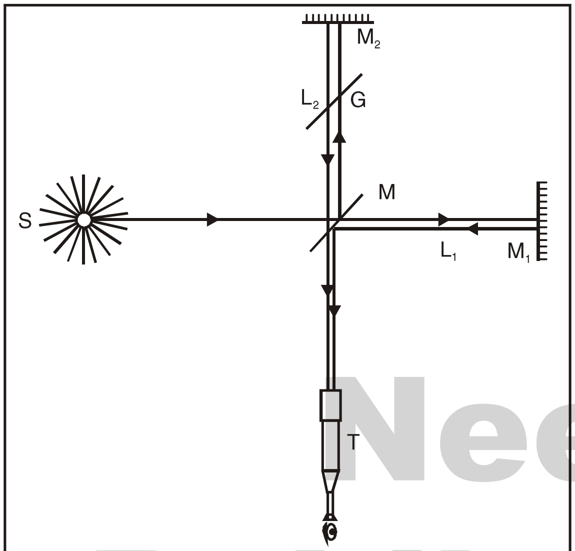

Fig. 1.3: Schematic representation of Michelson-Morley experiment

In this experiment, a beam of light from a fixed source S is separated into two coherent beams by a partially silvered mirror M inclined at an angle of 45º to the beam direction. Two mirrors M, and M*q* are placed at equal distance from M and at right angles to each other. They reflect the beam back to M. A part of the beams is recombined at M is observed through the telescope T. Here we note that two wave fronts will produce interference which will either be produce constructive or destructive, i.e., bright or black respectively. If t be taken by light to move from M to M_1 and t_1 be for M to M_2 then for constructive interference,

$$t \sim t_1 = n\text{T}, \qquad n = 1, 2, 3, ...$$

and for destructive interference

$$t \sim t_1 = (n + \frac{1}{2})\,\text{T}, n = 1, 2, 3, ...$$

Where T = time period of light wave.

Now if we rotate the apparatus by 90º in the plane of M, M_1, M_2 then the orientation MM_1 and MM_2 relative to the direction of earth's motion through ether will change, which will change the time taken along each path and fringe pattern will shift, as a result of rotation that was to be detected . The expected shift was to be of order of $\frac{4}{10}$th of a fringe.

They took all care to eliminate all possible errors, such as stresses and temperature effects. This shift was certainly observable.

But, no fringe shift was observed.

The experiment was repeated after 6 months. There was no change in the result. The implication was clear to Michelson as he then wrote.

The result of hypothesis of a stationary ether is shown to be incorrect.

Even though this experiment had been done by many even before. (by Michelson himself alone in 1881) in the preceding half century.

With various degrees of accuracy without any success but a few still tried to refute this latest result on several grounds which turned out to be false and all have to accept the result.

Various experiments to measure the speed of light over the years confirmed the result. The speed of light in free space is a constant at all times, irrespective of place where measurements are carried out. It is not affected by the frequency (or wave length), nature or motion of its source and direction of its propagation. It is constant in all inertial frames of reference and hence we have the following principle.

"The speed of light in free space is a Universal Constant". Obviously it contradicts the Galilean relativity principle, but laws of electromagnetism are upheld by it. Moreover, Newton's second law of motion was disobeyed by electrons emitted by radius active source (moving at nearly the light velocity) in electric and magnetic fields. Hence, classical relativity is incompatible with laws of electromagnetism. The experiment does not find ether so the ether hypothesis is untenable speed of light in free space is found to be a constant, experimentally. Here comes the conclusion that Galilean relativity principle needs to be replaced by some other. Hence, the laws of mechanics need to be modified.

THE SPECIAL THEORY OF RELATIVITY

Constancy of speed of light in all inertial frames of reference stands in contradiction with the Galilean transformation. In 1905, Albert Einstein presented his special theory of relativity to solve this problem. He

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