Chapter 1 - Introduction

- QED was first developed in 1929 in order to ratify Maxwell's theory with QM. However, calculations often resulted in infinities.
- Dirac's description of the electron predicted a magnetic moment of about 1. Further experimentation found more precise values of this, which became a test for any theory.
- QED describes all phenomena except gravitation and nuclear forces.

Light

- White light is a mixture of 'pure colours', which cannot be further separated (excluding polarisation).
- We will consider monochromatic light.
- Light is made of particles (corpuscles) - the photoelectric effect provides evidence for this.
- Single photons of light can be detected with a photomultiplier.

\[
\text{photons} \rightarrow \text{electron} \rightarrow \text{amplifier} \rightarrow \text{speaker, which clicks because of the avalanche of electrons.}
\]

- One incident photon liberates an electron, which is attracted to another plate. This starts a 'chain reaction'.

Partial reflection

- When light hits a boundary, it is partially reflected. For example, when light is incident normally on glass, 4% is reflected.
- One theory to account for this was that the surface of glass was made up of 'holes' and 'spots'. However, this was empirically untrue as glass is polished by grinding.
- It turns out that the behaviour of these photons is probabilistic.
However, this figure (4%) is changed when another surface of glass is added. There is a sinusoidal relationship between % reflected and the thickness of the glass.

This is explained by the wave theory of light, through the idea of interference, but light has been proven not to be a wave. However, we can explain this in terms of probability amplitudes. A probability amplitude $\Phi$ is a complex number (i.e., a small arrow). The square of its length is the probability that the event happens, i.e., $P = |\Phi|^2$.

If an event has multiple possible ways of happening, we add the arrows. For glass, light can reflect off the front or the back surface, for each arrow, $|\Phi| = 0.2$.

The direction of the arrow depends on the time taken: the direction length of the hand on an imaginary stopwatch.

However, we must reverse the direction for the arrow reflecting off the front surface.

Thus, varying the thickness of the glass varies the direction of the arrow (i.e., the phase angle), and may result in the complex numbers cancelling or being amplified.
At the correct thickness, the amplitudes will add to form a straight line. \( |\psi_1 + \psi_2|^2 = 0.4^2 = 0.16 \).

This idea can be used to explain the 'rainbow' of colours when there is oil in a puddle:
- the oil forms a layer of uneven thickness
- hence, monochromatic light would result in some dark areas and some coloured areas
- different colours of light have different stopwatch speeds
Hence, white light will reflect off the surface to form many colours, a phenomenon known as iridescence.

Chapter 2 - Photons: Particles of Light

All observed properties can be derived from probability amplitudes.

Reflection off a mirror

Consider a setup to test the idea of reflection

- the screen prevents light travelling directly from \( S \) to \( D \),
- the expected path from optics is one for which \( \theta_{\text{incidence}} = \theta_{\text{reflection}} \).
- However, in QM we must consider all possibilities, then add prob amplitudes.

We can consider that all these possible paths have equal probability of occurring, i.e \( |\psi_1| = |\psi_2| = |\psi_3| \ldots \)
- some paths are clearly longer than others.

This means that the directions of arrows will be different.
This is the curve
\[ t = \sqrt{ \frac{3c^2h^2}{a^2} + \frac{(d-x)^2 + h^2}{c} } \]
where \( h \) = height of \( JS \) and \( d = \) distance from \( JS \) to \( PD \).

- We then add these arrows together:

  \[ \Delta \]

- The major contribution to the final arrow is from small arrows \( D, E, F, G \). The timing of their paths is nearly the same, so the arrows add constructively.
- This coincides with the position of least time \( \frac{dt}{dx} = 0 \).
- This implies that \( \theta_i = \theta_r \), and it also shows that the edges of the mirror are irrelevant.

Although there is reflection happening, the arrows cancel out by forming a circle.

However, we can scrape away the mirror in some areas to result in a sizeable final arrow — such an etched mirror is called a diffraction grating.
This grating is designed specifically for monochromatic light. However, moving the photomultiplier to a different angle will allow it to work for other colours. This also allows us to split white light into pure colours. Salt crystals are a natural example of a diffraction grating. Shining X-rays on them allows us to deduce atomic separation.

**Refraction**

- Once again, we must consider all possible routes.
- The major contribution comes from the path of least time. This is not the same as a straight line, because light travels slower in water.
- Finding the actual path is a simple optimisation problem.

**Mirage**

- Over a hot surface (e.g. tarmac), the air is warmer.
- The air progressively gets cooler as you move up.
- Light travels faster in warmer air (since it is less dense).
- The path of least time will result in a compromise between travelling through warmer air and not deviating so much; the resulting path is a curve.
- The classical explanation is that refraction occurs by different amounts at different heights: refractive index is a function of height so the path curves.
- The human brain associates the reflection with water, hence the mirage.
Light travels in straight lines

- Consider a source S and photomultiplier P. We then draw possible paths.

For the bendy paths (e.g. A), there is a nearby path that is straighter and distinctly shorter (i.e. it takes significantly less time). These arrows may cancel.
- However for straighter paths (e.g. C), nearby paths take almost the same time, so arrows add constructively.

Heisenberg's uncertainty principle

- Consider a setup with two blocks reasonably far apart (i.e. a wide aperture).

If the gap is big enough to allow for many neighbouring paths, the arrows to P add up, but not the arrows for Q (these paths have a sizeable difference in time).
• However, as the gap size decreases, there are fewer neighbouring paths. As such, the arrows to Q also add since there isn't a large time difference. However, the final arrows are still smaller.

• Hence a decreased aperture increases the uncertainty of the vertical component of light's momentum.

The converging lens

• We will simplify the way light can travel from a source to a detector into paths made of two straight lines.

• The paths in the middle are shorter and take less time, so they are the biggest contributor to the final length. But we can artificially make all paths take the same time by adding the right thickness of glass - this is a lens.
Compound events

- To find the arrow for compound/sequential events, instead of multi adding the arrows, we multiply them according to the rules of complex numbers, i.e., we add arguments and multiply moduli, i.e., we 'shrink and turn' the arrows.

- We will now consider reflection/transmission in more detail.

1. We assume no shrinking for step 1, but there is some turning.

2. There is a sizeable shrink from 1 to 0.2 and half a turn (this explains why you must reverse the direction of the arrow reflecting off the front).

3. No shrinking, but turning.

- For a photon being transmitted to B, step 2 involves a shrinking of 0.98. The final arrow squared will give x 0.96.

- Even for more complex scenarios, we apply these simple rules:
  - Reflection from air to air involves shrink of 0.2 and half turn.
  - Reflection from glass to glass: shrink of 0.2, no turn.
  - Transmission: shrink of 0.98, no turning.

- In actual fact, light does spread out as it goes along, resulting in a shrink. The length of an arrow is inversely proportional to the distance the light travels - this explains the inverse square law.

- We also multiply arrows for simultaneous independent events

\[
\begin{align*}
\text{sources} & \quad X \rightarrow A \quad X \rightarrow A \\
& \quad Y \rightarrow B \quad Y \rightarrow B
\end{align*}
\]

There are two ways that 2 photons can be detected.

For this situation, the resultant arrow is
\[
(X \rightarrow A) \times (Y \rightarrow B) + (X \rightarrow B) \times (Y \rightarrow A).
\]

- However, since we have to add arrows, there is a possibility that the arrows cancel - the Hanbury-Brown-Twiss effect.