Quantum nature of light and matter

Let's review human understanding of the nature of light

Ray optics: light is a stream of light particles travelling in straight lines. Brighter beam — more particles. Color... big question, probably different types of particles?

↓ improved technology

Wave optics: light is a wave (originally — unknown nature, then — electromagnetic). Color = frequency of E/B field oscillations.

Superposition principle: adding two identical waves can lead to any result: constructive / distructive interference.

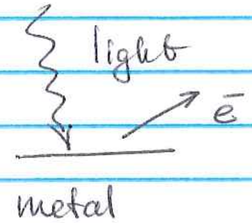
↓ improved technology

several phenomena are in odds with classical Maxwell's theory

That indicates that this theory is not complete, and does not work under certain conditions (even though it works well under others)

Demonstrations of non-~~classic~~ wave nature of light

1. Photo electric effect



Light falls onto metal and is absorbed, electrons are released.

This effect can be understood from a classical point of view: Electrons are accelerated by an e-m wave, breaking loose from the surface.
However, in this case more powerful light should have produced more energetic electrons.
Experimental behavior is very different: the energy of electrons is proportional to the <u>frequency</u> of e-m field, and its amplitude only changes the <u>number</u> of emitted electrons.
Kinetic energy of an electron

$$K = hf - \varphi$$

h – Plank's constant $h = 2\pi \cdot 10^{-34}$ J·s

φ – work function, how much energy an electron should spend to escape from the material

The ecxperimental behavior can be explained if light is a particle with energy hf, then the expression is just an energy conservation.

2. Black body radiation

Black body absorbs all e-m waves falling on it, thermalizes and emits this energy as a thermal radiation.

Experimentally observed spectrum is very different from theory that predicts huge amount of radiation emitted in a short wavelength range (ultra-violet catastroph).

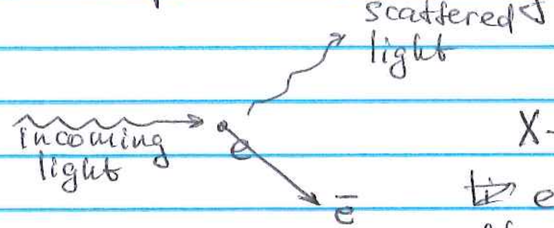
Problem with classical approach: if all possible oscillations are allowed to be excited, than even a tiny oscillations at high frequencies produces unlimited energy (since $P \sim f^4$)

Desperate solution: energy is quantized, i.e there is no "tiny" oscillations, the particular mode is not excited at all unless it has sufficient energy

$$E_{\substack{light\\quanta}} = hf = \hbar\omega$$

$$\hbar = h/2\pi$$

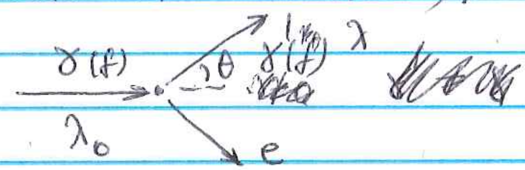
3. Compton scattering



X-ray (very high energy) e-m wave scattering off an electron

Experimentally observed that the outgoing e-m wave has changed its frequency

Problem with classical description: e-m wave can excite the atom only on its own frequency (since e does not have any internal structure).



$$\lambda - \lambda_0 = \frac{h}{mc}(1-\cos\theta)$$

However, if one solves this problem as an elastic collision of two particles, it works perfectly, if a light particle – photon – has energy $E_p = hf = \hbar\omega$ and momentum $\vec{p} = \hbar k$

These experiments indicate that in some processes light acts as a stream of massless particles ~~while remaining~~ carrying quanta of energy and momentum.

That means the description of light must be updated.

The birth of quantum mechanics

Light is a wave and a particle...
but maybe these are not proper
terms to use in general?

Particle — precise known location
Wave — precise known direction of motion
(plane wave is completely delocalise)

These are two extremes, and reality
lays somewhere in between

~~B~~ de Broglie's idea — ~~all~~ everything
is both a particle and a wave.
For each particle with momentum $\vec{p}$
its "wavelength" $\lambda = h/p = 2\pi\hbar/p$

So why don't we see wave nature of
particles? Normally their wavelength
is too small!
However they can be observed → electron
diffraction on crystals.