Ideas of Modern Physics

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Last Week

Electromagnetic Waves

Special Relativity

General Relativity
The Quantum World
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• Planck’s Law
• Atomic Structure and emission lines
• Matter waves
• Uncertainty principle
• Particles and waves: diffraction experiments
• Schrodinger: Probability distribution
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• Quantum Entanglement
• Applications
Our World

- Our world is Newton’s world. It is:
  - Continuous
  - Observable
Failure of Classical Physics

• In the 1870’s everything in physics was known

• The area of work was the somewhat ‘applied’ field of thermodynamics
  – Practical applications
  – New mathematical tools
  – Money ....

• There remained a few issues to be ‘tidied up’
Failure of Classical Physics

- The ultraviolet catastrophe
  - Heated material gives off light
  - The hotter the material, the shorter the ‘more blue’
  - i.e. the hotter = shorter wavelength
- Blackbody radiation
Failure of Classical Physics

However classical theory incorrectly predicted the spectrum
Max Planck

• Took on the problem
• Spent many years trying to derive the actual curve shape
• He eventually got frustrated and tried to fit the data to a mathematical expression so he would know the type of answer he was trying to get
  – It took him one evening (without a computer)
Max Planck

• Planck’s curve fit required a constant (i.e. a fudge factor) he represented by ‘\( h \)’

• The then-current model was based on vibrating particles vibrating more rapidly as they became hotter
Max Planck

- Planck could only get the data to fit if he allowed light to be emitted only in energies that were *multiples of his constant $h$*

- First published in 1900 it is known as Planck’s Law

- We now call $h$ Planck’s constant and we now know it as one of the basic constants of nature
Planck’s Law

\[ U(\lambda, T) = \frac{8\pi hc}{\lambda^5} \frac{1}{\frac{hc}{e\lambda kT} - 1} \]

Niels Bohr and Max Planck (right)
Planck’s Law

• Planck didn’t believe that this was the final answer but was an ‘act of desperation’

• Nobody else believed it either
  – It didn’t meet with common sense
Photoelectric Effect

- Einstein 1905
- Energy of electron created by light hitting a material depends on the frequency
- More light at the same frequency means more electrons all of the same energy
Photoelectric Power
Photoelectric Effect

• Light must be in ‘packets’ with energy proportional to their frequency

• Experimentally verified by Millikan
  – He didn’t like the explanation
  – Called it ‘reckless’

• So it was set aside from the main stream
  – for a while ......
Atomic Structure

• Static electricity had long been known
• Maxwell derived his equations for electromagnetic waves in 1862
• Electrolysis showed that there were positive and negative parts
• Crookes (1862) demonstrated you could separate the negative part
• Thompson (1896) demonstrated they were particles with a specific charge to mass ratio
Crooke’s Tube

Electrolysis of Water
Atomic Structure
Atomic Structure

• Thompson model:

‘Plum Pudding’

Smaller electrons (negative) embedded in an amorphous positive charge
Rutherford Experiment

- Alpha particles bombarded a gold foil

- Expected result was that they would pass through undisturbed
Rutherford Experiment

• However ..... 

• However, some alpha particles were ‘scattered’ backwards and some were ‘scattered’ sideways
Since Alpha particles are much heavier than electrons ...

This was only possible if there was a dense centre for the particle to bounce off.
Atomic Structure

- Which led to the ‘Bohr’ model of the atom
- Electrons outside a positively charged nucleus
- Electrons require planetary-like motion
The Bohr Model
Atomic Spectra

• It has been known for centuries that light, when it passes through a prism, is split into a colourful spectrum

• We have seen that the colour is related to temperature or energy
However pure gases do not produce a continuous spectrum
Bohr Model (1913)

• Electrons orbit the nucleus in fixed orbits
  – There is a minimum energy orbit
• Each orbit represents increasing energy
• Orbits energies are integers of the frequency and Plank’s constant
• Loss of energy occurs when a packet of light is given off
The model predicted the spectral lines of hydrogen to better than 1 part in 10,000.
Bohr Model (1913)

• The existence and role of the quantum was firmly established (circa 1913)

• The issue of why and how there were quantum jumps was still perplexing

• The answer had to wait until after WW1
Compton Effect

• When waves reflect off a surface the frequency doesn’t change

• However: when electromagnetic waves bounce off an electron their frequency changes
Compton Effect

- The electromagnetic wave is behaving like a particle and transferring energy to the electron
Compton Effect
The Duality

Light is a wave

Light is a Particle

“Every Tom, Dick and Harry thinks they know what a photon is, but they’re wrong”

Albert Einstein
It is all How You Look at It

- Different experiments give different answers
  - Are they really looking at the same thing?
Matter Waves

- De Broglie (1923)
- A symmetrical relationship
- If light waves can demonstrate both particle and wave properties, then so should matter
- Electron orbits are then an integral number of half wavelengths
Matter Waves
• So, if you can accept that something can be two things at once it all makes sense

• For now .....
Motion of a Particle/Wave

• If Newton could describe the motion of a particle then there should be an equation of motion for the new ‘quantized’ particle

• Schrodinger formulated the mathematics in 1926.
  – He was motivated to try to understand Bohr’s quantum jump
The Schrödinger Wave Equation

- Takes on the same form as the classical description of a travelling wave (such as that we see for water waves)
- It all works out mathematically, the problem is connecting the mathematics with the physical world

The cat comes later
The Schrödinger Wave Equation
The Schrödinger Wave Equation

• A particle is described by a ‘wave function’
  – A wave function is a spread out wave

  ![Wave Functions Diagram](attachment:image.png)

  – It is these wave functions that interact

Some mathematics by Fourier
Lost Yet?
The Schrödinger Wave Equation

• The ‘amplitude (height) of the wave indicates the probability of observing the particle at that spot.
  – It doesn’t mean that the particle is there all the time

• Schrödinger (and others) were able to use the equations to describe the orbits of an atom
The Schrödinger Wave Equation

• They idea of a probability of a particle being in a specific place was new

• It came from work in thermodynamics by Albert Einstein
Schrödinger’s Equation

\[ i\hbar \frac{\partial}{\partial t} \psi(\mathbf{r}, t) = -\frac{\hbar^2}{2m} \nabla^2 \psi(\mathbf{r}, t) + V(\mathbf{r}, t)\psi(\mathbf{r}, t) \]

- \(i\) is the imaginary number, \(\sqrt{-1}\).
- \(\hbar\) is Planck's constant divided by \(2\pi\): 1.05459 \times 10^{-34}\) joule-second.
- \(\psi(\mathbf{r}, t)\) is the wave function, defined over space and time.
- \(m\) is the mass of the particle.
- \(\nabla^2\) is the Laplacian operator, \(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\).
- \(V(\mathbf{r}, t)\) is the potential energy influencing the particle.
Yet?
The Schrödinger Wave Equation

Bohr’s Orbits

Become probability clouds known as orbitals that actually define the shape of the atom
Quantum Tunneling

• An example of the probability distribution of a particle

• It really does happen
Quantum Tunneling

• Consider a classical particle propelled at a wall
  – It bounces back

• In a quantum world it ‘tunnels’
Quantum Tunneling

Quantum tunneling:

In quantum mechanics, an electron has a non-zero probability of tunneling through a potential barrier.
Quantum Tunneling

This effect is used in the tunneling microscope which can actually visualize an atom.
Uncertainty
Uncertainty

Heisenberg’s uncertainty principle
(paraphrase)

For any particle there is a limit to the precision with which you can simultaneously know both its position and its velocity
Uncertainty

- The principle can be explained from the wave nature of a particle

- In terms of an electron
Uncertainty

\[ \Delta p \Delta x \geq \frac{1}{2} \hbar \]

\[ \Delta E \Delta t \geq \frac{1}{2} \hbar \]

Incoming light wave scatters off electron.
Uncertainty

• The actual uncertainty constant (Planck’s constant/2) is very small: $10^{-34}$
• Does not affect day to day life
Quantum Mechanics

• We now have the conceptual tool box for a quantum mechanic
• There is also a tool box filled with a great deal of mathematics

• To many, quantum mechanics is the mathematics ... because it works ...
Quantum Mechanics

- Quantum mechanics has predicted all known sub-atomic particles (the ‘Standard Model’)
- Lasers
- Semiconductors
- Superconductors
Quantum Mechanics

• It is not necessary to understand the
  Why?

• To do the calculations

Before addressing the why ...
Interference Patterns

• Interference patterns are well known in acoustic and water waves
  – E.g. noise cancelling headphones

Constructive Interference
Single Slit
Double Slit Experiment

Waves passing through two slits will cause constructive and destructive interference
Double Slit Experiment
Double Slit Experiment

• As particles are waves you can get the same sort of interference pattern with electrons
Double Slit Experiment

• However, it is possible to reduce the incoming beam to a single electron at a time
• What will happen?

• One would logically expect a stream of single particles to produce two single slit patterns
However...

• As there should be no difference in behaviour because there are fewer particles, the pattern shouldn’t change

• Which would mean ...

• A single particle seems to know there are two slits

• Or...a single particle goes through both slits
Double Slit Experiment

• Because the pattern is the same!!!!!
The Copenhagen Interpretation

• Solvay conference 1927 Brussels, Belgium
  – All the major scientists were in attendance
  – Major discussion of the interpretation of quantum mechanics
  – Two opinions Bohr and the Copenhagen Group & Einstein
  – Einstein wanted an interpretation the could be founded in real objects, however he was unable to put forward something to refute Bohr
The Copenhagen Interpretation

Background

• Two realms:
  • Macroscopic: governed by classical physics
  • Microscopic: governed by Schrodinger’s eqn.

• All the instruments we used to ‘measure’ and ‘observe’ are macroscopic
The Copenhagen Interpretation

The Observation Produces the Observed Quantity
The Copenhagen Interpretation

• In other words, an atom does not exist until it is measured.
• What is measured depends on the measuring instrument.
  – E.g. Wave-particle duality.
• Since all our measuring instruments are classical.
  – Macroscopic approximations are what we can deal with.
The Copenhagen Interpretation:

Wave Function \( \Psi \) 

Measurement 

wave function "collapse"

Position in Space
Schroedinger’s Cat
Philosophical Implications

• What does it mean to ‘observe’?
• Is there a difference with conscious observation?
• Does a table appear only when it is being observed?
• What is there when no one is looking?
Traditional Response

• The Professor (and the granting agency) said:

  Shut up and calculate!
If I were forced to sum up in one sentence what the Copenhagen interpretation says to me, it would be 'Shut up and calculate!'

(David Mermin)
Bell’s Theorem

• First proposed as a counter example by Einstein in response to the Copenhagen Interpretation

• Stated as Bell’s Theorem in 1965
  – Any world that is observer-independent must have two conditions:
    • Reality (properties are not created by observation)
    • Separability (what happens at one object does not instantaneously affect another object)

• The quantum world denies these conditions
Quantum Entanglement
Quantum Entanglement

• Experimental verification 1970
  – Used polarized photon pairs
Quantum Entanglement

• In any current interpretation quantum entanglement requires information to be transferred faster than the speed of light
• Einstein referred to it as ‘spooky action at a distance
• There is no explanation at this time
Quantum Entanglement

• Now being further developed for uses in
  – Cryptography
  – Quantum computing

• A world without reality is very real in the 21st Century
"But you can't go through life applying Heisenberg's Uncertainty Principle to everything."