The Philosophy of Physics
Lecture Seven

Introduction to Quantum Mechanics

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Introduction to Quantum Mechanics

The Particle-like Behaviour of Light

The Wave-like Behaviour of Particles

Introduction to Hilbert Spaces

Quantum Mechanics: The Basics

The Copenhagen Intepretation

Schrödinger's Cat

Light as an Electromagnetic Wave

- We are all familiar with the idea that light is an electromagnetic wave
- That discovery was an important first step on the road to the Special and General Theories of Relativity
- However, in the early 20th Century, a number of experiments demonstrated that light sometimes behaves more like a particle than a wave

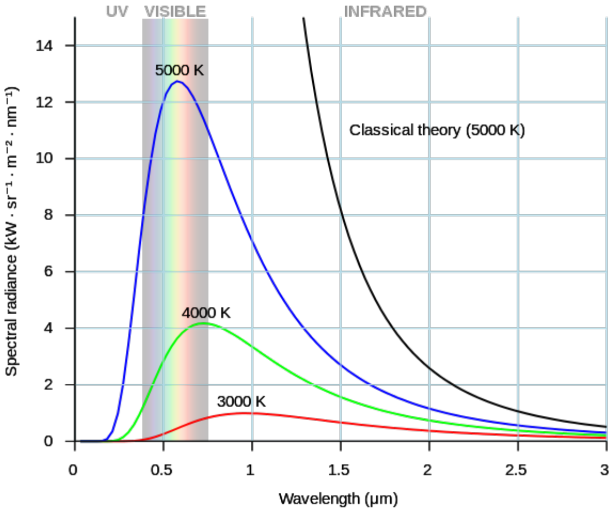
Black-Body Radiation

- A **black-body** is an idealised physical body, which does not reflect any electromagnetic waves; it absorbs all incoming electromagnetic waves
- A black-body kept at a constant temperature gives off electromagnetic radiation, known as **black-body radiation**
- The spectrum and intensity of that radiation depends solely on the temperature of the black-body
  - A black-body at room temperature gives off mostly infra-red radiation
- But hotter black-bodies give off visible light, and still hotter black-bodies give off ultra-violet light
  - The Sun is a good approximation of a hot black-body

The Ultra-Violet Catastrophe

- According to classical physics, which is built on the idea that light is a wave, the intensity of light at a given frequency should be proportional to the square of that frequency
- But that does not fit with the experimental evidence
  - If it were right, then even a cold object should be emitting visible light, and ultraviolet light too
- Worse than that, it means that the total energy radiated by a black-body would be infinite
  - There is no upper limit to the frequency that a light wave can take
- This problem was known as the **Ultra-Violet Catastrophe**

The Ultra-Violet Catastrophe



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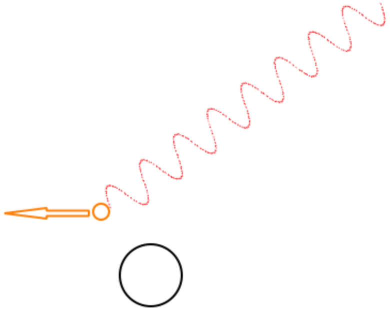
Planck's Constant

- Planck solved the problem of black-body radiation in 1900 (and won the Nobel Prize in 1918)
- It takes more energy to emit higher frequencies of light, and so low-energy systems will tend not to emit high-frequency light
- However, Planck's solution required the assumption that light energy comes in discrete packets, called **quanta**, not continuously
- The relationship between energy and frequency is given with this equation: $E = hf$
  - E is the energy in a given packet of light
  - f is the frequency of the associated electromagnetic wave
  - h is Planck's constant, $h \approx 6.626070 \times 10^{-34} Js$

Introducing Photons

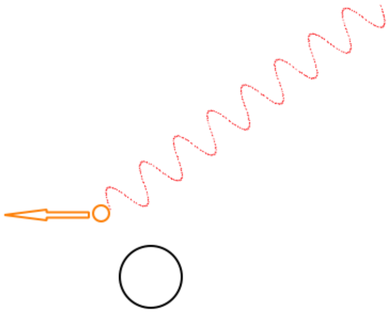
- It is very odd to think of electromagnetic energy as coming in quanta if electromagnetic radiation is a kind of wave
- As Einstein realised, it makes a lot more sense if we think of a beam of light as a stream of particles
- These particles are now known as **photons**

The Photoelectric Effect



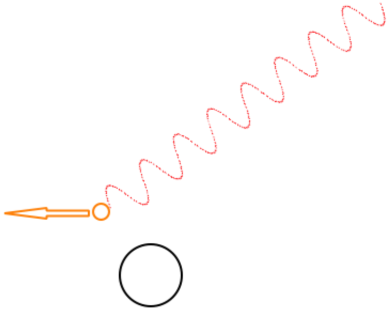
- In certain circumstances, when we shine a light on a body, that body emits an electron

The Photoelectric Effect



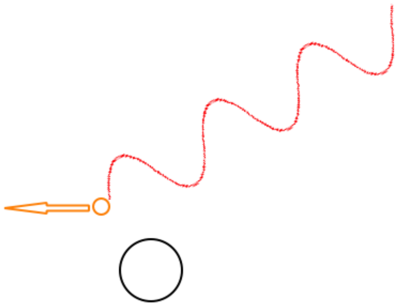
- This is known as the **photoelectric effect**

Classical Predictions



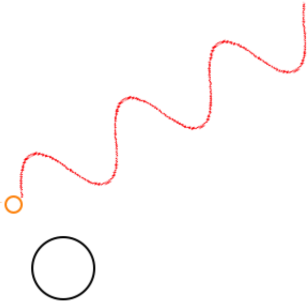
- According to classical physics, it should not matter what frequency the light has...

Classical Predictions



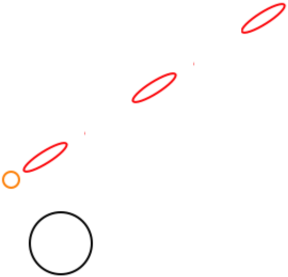
- ...So long as the light is bright enough (has a big enough amplitude), then an electron will be emitted

Observed Results



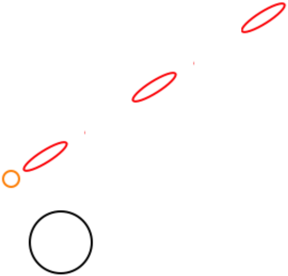
- But in fact, if the light does not have a high enough frequency, then no electron is emitted, no matter how bright the light is

Einstein's Photons



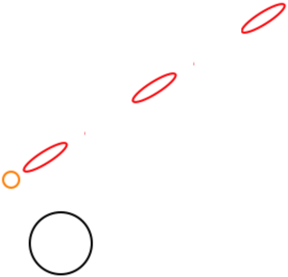
- Einstein realised that we could explain what was happening here if we thought of light as a beam of photons, not a wave

Einstein's Photons



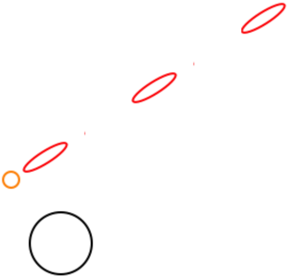
- The energy of each photon is proportional to the frequency of the light ($E = hf$)

Einstein's Photons



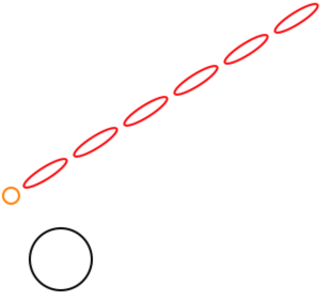
- The photons in a low frequency beam of light simply do not have enough energy to knock an electron out

Einstein's Photons



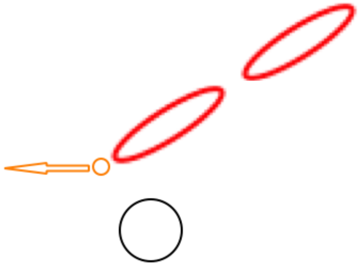
- And increasing the brightness (intensity) of the light does not increase the energy of any individual photon...

Einstein's Photons



- ...It simply increases the number of photons in the beam, but none of them have the energy to knock an electron out

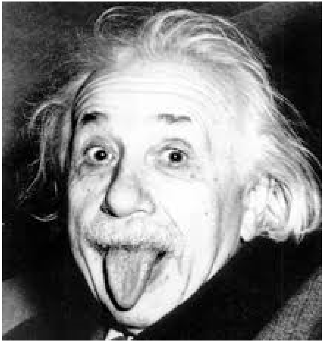
Einstein's Photons



- To knock an electron out, we need to send higher-energy photons, i.e. a higher frequency beam of light

The Particle-like Behaviour of Light

- Einstein's won the Nobel Prize for his explanation of the photoelectric effect in 1921
  - He actually published his theory in 1905, the same year he published his Special Theory of Relativity!!!
- This is further clear evidence that light sometimes behaves like a beam of particles



Albert Einstein

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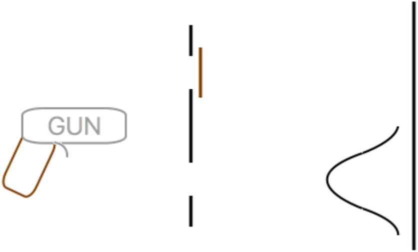
The Double-Slit Experiment on Bullets

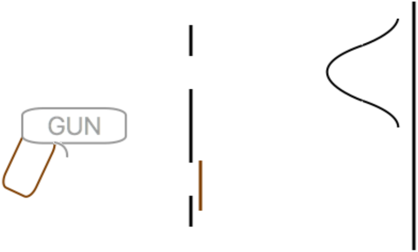
- If we fired a gun at a wall with two slits in it, where would we expect to find the bullets in the wall behind the screen?

The Double-Slit Experiment on Bullets



- If we covered up the top slit, we would expect most the bullets to hit the wall behind the bottom slit

The Double-Slit Experiment on Bullets



- And if we covered up the bottom slit, we would expect most the bullets to hit the wall behind the top slit

The Double-Slit Experiment on Bullets

- So if we left both splits open, this curve describes where we would expect to find the bullets

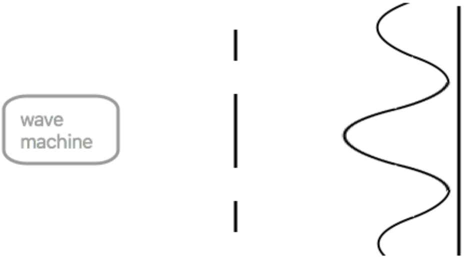
The Double-Slit Experiment on Waves

- But now imagine that we fire some waves at the screen instead of bullets

The Double-Slit Experiment on Waves

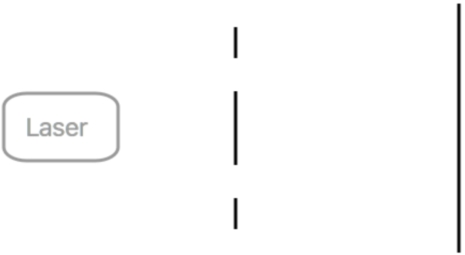
- The waves would diffract through the slits, and then interfere with each other

The Double-Slit Experiment on Waves



- As a result, we get this **interference pattern** on the far wall

The Double-Slit Experiment on Light

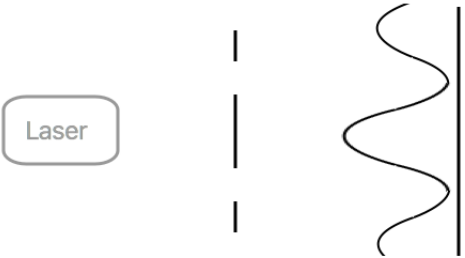


- What sort of pattern should we expect to see if we shot a laser at the slits?

The Double-Slit Experiment on Light

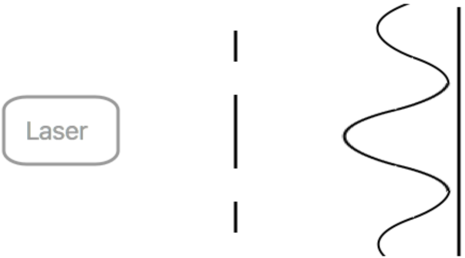
- I just told you that a ray of light can be thought of as a beam of photons, so you might expect this

The Double-Slit Experiment on Light



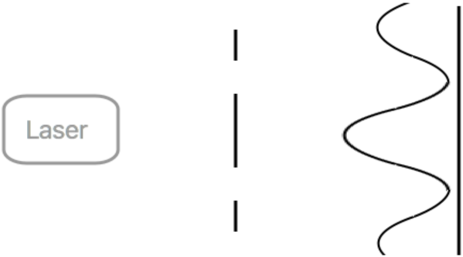
- But we actually get this pattern; light behaves like a wave in this set up

The Double-Slit Experiment on Light



- This might not yet seem too weird: maybe the individual photons interact with each other as they pass through the slit?

The Double-Slit Experiment on One Photon at a Time



- But this is the pattern we get even if we fire **one** photon at a time

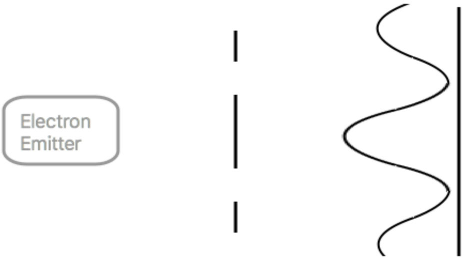
What on Earth is Happening?

- **The photon is not passing through just one slit**
  - If it were, then we would not see interference patterns
- **The photon is not passing through both slits**
  - If we were to stop the experiment and check where the photon is, we do not find 'half' a photon going through one slit and 'half' going through the other, or anything like that
- **The photon is not passing through neither slits**
  - If it were passing through neither slit, then nothing would get through to the far wall
- **But does that exhaust all the options!?**

Superposition

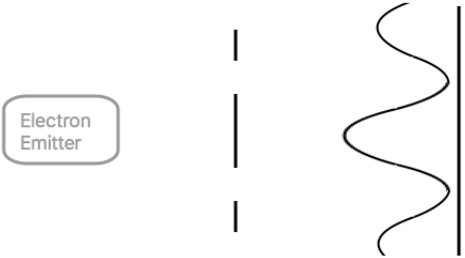
- In this situation, physicists say that the photon is in a **superposition** of passing through one slit and passing through the other
- Right now, that is just a label for a mystery!
- It is clearly meant to bring to mind something about waves
  - One wave can be the result of superimposing two distinct waves
- But until we say more, that is nothing more than an intriguing metaphor

The Double-Slit Experiment on Electrons



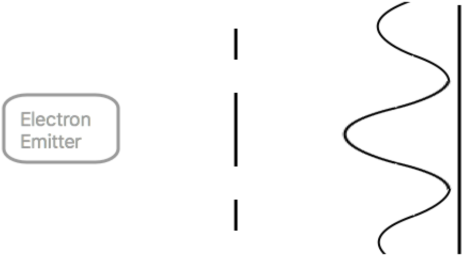
- These effects are not limited to photons: this is the pattern we get if we fire **electrons** at the slits

The Double-Slit Experiment on One Electron at a Time



- Again, we get this pattern even if we fire **one** electron at a time

Superposition



- The individual electron is in a superposition of passing through one slit and passing through the other

Introducing Quantum Mechanics

- Quantum Mechanics (QM) is the branch of physics which deals with these weird superpositions
- The mathematics of QM ‘explains’ these phenomena, in the sense of predicting exactly what is observed
- But by itself, we might worry that this is not enough of an explanation
  - We do not just want to predict **what** photons and electrons will do, we want to explain **why** they do it
- To get this kind of explanation, we need to give an **interpretation** of QM
- Richard Feynman warned against seeking such an interpretation

Feynman's Warning

Electrons, when they were first discovered, behaved exactly like particles or bullets, very simply. Further research showed, from electron diffraction experiments for example, that they behaved like waves. As time went on there was a growing confusion about how these things really behaved — waves or particles, particles or waves? Everything looked like both.

Feynman's Warning

This growing confusion was resolved in 1925 or 1926 with the advent of the correct equations for quantum mechanics. Now we know how the electrons and light behave. But what can I call it? If I say they behave like particles I give the wrong impression; also if I say they behave like waves. They behave in their own inimitable way, which technically could be called a quantum mechanical way. They behave in a way that is like nothing that you have seen before. Your experience with things that you have seen before is incomplete. The behaviour of things on a very tiny scale is simply different. [...]

Feynman's Warning

It will be difficult. But the difficulty really is psychological and exists in the perpetual torment that results from your saying to yourself, 'But how can it be like that?' which is a reflection of uncontrolled but utterly vain desire to see it in terms of something familiar. I will not describe it in terms of an analogy with something familiar; I will simply describe it. [...]

Feynman's Warning

> *I think I can safely say that nobody understands quantum mechanics. So do not take the lecture too seriously, feeling that you really have to understand in terms of some model what I am going to describe, but just relax and enjoy it. I am going to tell you what nature behaves like. If you will simply admit that maybe she does behave like this, you will find her a delightful, entrancing thing. Do not keep saying to yourself, if you can possibly avoid it, 'But how can it be like that?' because you will get 'down the drain', into a blind alley from which nobody has escaped. Nobody knows how it can be like that.*
>
> *(Feynman, 1965, The Character of Physical Law, pp. 128–9)*

Feynman's Warning Unheeded

- For better or for worse, we are going to ignore Feynman's warning
- We will ask how the world would have to be if it is to be described by the mathematics of QM
- But first, we will try to understand some of the basics of that mathematics

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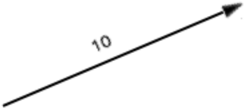
Representing States in QM

- QM represents possible physical states of a system using an abstract mathematical model
- The basic idea of doing that is very familiar
  - We can use a graph to represent how your height changes over time
- But QM uses a particularly abstract model
- Physical states are represented by **vectors** in a **Hilbert space**
- So the first thing we need to do is go over the basics of these kinds of space
  - For a very clear introduction to all this, see David Albert's *Quantum Mechanics and Experience*, ch. 2

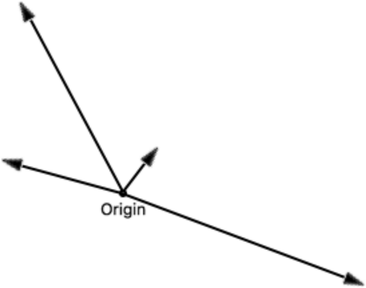
What is a Vector?

- We can visualise vectors as arrows
- Vectors have a direction
- Vectors have a length (or **norm**)



What is a Hilbert Space?

- Pick some point, and call it the **Origin**
- Consider all the possible vectors we can draw from the Origin
- The set of these vectors determines a **vector space**
- A **Hilbert space** is a vector space which is complete and has a complex inner product



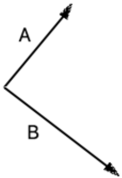
What Does ‘Complete’ Mean?

- *Roughly:* a vector space is **complete** iff it has no gaps
- *A little more precisely:*
  - Suppose that there is a convergent sequence of vectors in the vector space
  - If the vector space is complete, then there will always also be a limit vector in the space

What is a Complex Inner Product?

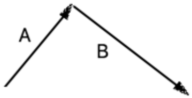
- An **inner product** is a kind of multiplication for vectors
  - It is also known as the **dot** product, rather than the cross product
- A **complex** inner product is an inner product which always yields a complex number (i.e. a number which is either real or imaginary)
- Before we explain how to multiply vectors, it will be helpful to start with the simpler process of adding them together

Adding Vectors



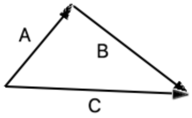
- Consider two vectors, $|A\rangle$ and $|B\rangle$

Adding Vectors



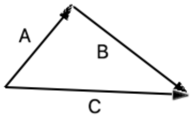
- To add them together, we simply move the start point of $|B\rangle$ to the end point of $|A\rangle$

Adding Vectors



- $|A\rangle + |B\rangle = |C\rangle$

Adding Vectors



- It turns out that the ability to add vectors in this way is crucial to understanding superposition

Multiplying Vectors by Numbers

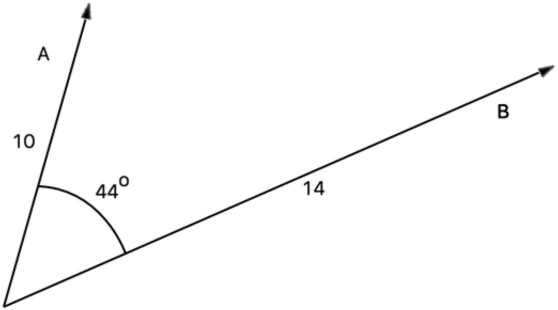
- We can also multiply vectors by numbers
- $5|A\rangle$ is that vector which has the same origin and direction as $|A\rangle$, but is 5 times the length as $|A\rangle$
- In the case where n is a natural number, we can represent $n|A\rangle$ as a sum:

$$5|A\rangle = |A\rangle + |A\rangle + |A\rangle + |A\rangle + |A\rangle$$

Inner Products (Multiplying Vectors by Vectors)

- When you add together two vectors, you get another **vector**, and you also get a **vector** when you multiply a vector by a number
- But when you multiply two vectors by each other (i.e. take their inner product), you get a **number**
- $\langle A|B\rangle = ||A|| \times ||B|| \times cos\theta$
  - $\langle A|B\rangle$ is the inner product of $|A\rangle$ and $|B\rangle$
  - $||A||$ is the length (or norm) of $|A\rangle$
  - $||B||$ is the length (or norm) of $|B\rangle$
  - θ is the angle between $|A\rangle$ and $|B\rangle$

Inner Products (Multiplying Vectors by Vectors)



- $\langle A|B\rangle = 10 \times 14 \times \cos 44^\circ = 100.71$

Some Handy Things to Bear in Mind

- $||A||^2 = \langle A|A\rangle$
  - The angle between $|A\rangle$ and $|A\rangle$ is 0°
  - $cos 0^\circ = 1$
  - $\langle A|A\rangle = ||A|| \times ||A|| \times 1 = ||A||^2$
- $\langle A|B\rangle = 0$ iff A and B are orthogonal
  - $|A\rangle$ and $|B\rangle$ are orthogonal iff the angle between them is 90°
  - $cos 90^\circ = 0$
  - $\langle A|B\rangle = ||A|| \times ||B|| \times 0 = 0$

What is an Operator?

- An operator is a function which takes vectors in the Hilbert space to vectors in the Hilbert space
- If $\hat{O}$ is an operator, then we write the result of applying $\hat{O}$ to $|A\rangle$ as $\hat{O}|A\rangle$
- Here are some examples of operators:
  - The identity function, which maps every vector to itself
  - The *times by 5* function, which maps every vector $|A\rangle$ to $5|A\rangle$
  - The *map to* $|A\rangle$ function, which maps every vector to some particular function $|A\rangle$

What is a Linear Operator?

- An operator $\hat{O}$ is linear iff:
    - (i) $\hat{O}(|A\rangle + |B\rangle) = \hat{O}|A\rangle + \hat{O}|B\rangle$
    - (ii) $\hat{O}(n|A\rangle) = n(\hat{O}|A\rangle)$
- All the operators we are going to be interested in are linear

Eigenvectors and Eigenvalues

- Sometimes an operator, $\hat{O}$ maps a vector $|A\rangle$ onto a vector which is pointing in the same direction as $|A\rangle$
- In this case we call $|A\rangle$ an **eigenvector** of $\hat{O}$
- When $|A\rangle$ is an eigenvector of $\hat{O}$, we have the following for some number n:

  $$\hat{O}|A\rangle = n|A\rangle$$

- n is here called the **eigenvalue** of the eigenvector $|A\rangle$

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Physical States

- In QM, we represent physical states of a system with vectors of length 1
- Every possible physical state of the system is represented by some such vector
- Every such vector represents some physical state of the system
- Importantly, though, different vectors do not always represent different states

  $|A\rangle$ always represents the same physical state as $-1|A\rangle$

Measurable Properties

- Every measurable property of a system is associated with a linear operator
- Let $\hat{P}$ be an operator representing property P, and $|A\rangle$ be a vector representing state A
- Now suppose that $|A\rangle$ is an eigenvector of $\hat{P}$, such that $\hat{P}|A\rangle = n|A\rangle$
- In that case, A has property P to degree n
  - Suppose that P is the property of quantum spin, and A is a system containing a single boson
  - If $\hat{P}|A\rangle = 2|A\rangle$, then that boson has spin 2

A Bit of Notation and terminology

- We can write the eigenvectors of $\hat{P}$ in the form $|P = p_i\rangle$
- The idea is that $|P = p_i\rangle$ has eigenvalue p_i
  - So returning to our earlier example of spin, $|P = 2\rangle$ would be a vector representing something as having spin 2
- If $|A\rangle$ is an eigenvector of $\hat{P}$, then we will call the state represented by $|A\rangle$ an **eigenstate** of that operator
  - So $|P = p_i\rangle$ represents an eigenstate of $\hat{P}$, namely a state in which the system has property P to degree p_i

The Born Rule

- What happens if we try to measure property P of state A when $|A\rangle$ is **not** an eigenvector of $\hat{P}$?
- The outcome of that measurement is a matter of **probability**
- The probability that $P = p_i$ is calculated as follows: $|\langle A|P = p_i\rangle|^2$
  - The bars $|\ |$ denote **absolute value** (distance from 0); we need them because $\langle A|P = p_i\rangle^2$ may be negative, and negative numbers cannot represent probabilities
- This probability is always less than or equal to 1
- If $|A\rangle$ is an eigenvector of $\hat{A}$, then the probability of measuring $P = p_i$ is 1 if $|A\rangle = |P = p_i\rangle$; otherwise it is 0

The Projection Postulate

- Immediately after a measurement, the system changes its state to the eigenstate corresponding to the eigenvalue obtained by the measurement
- Imagine that the system is in state A, and that $|A\rangle$ is not an eigenvector of $\hat{P}$
- We measure property P of the system, and find that $P = p_i$
  - The odds of finding that value are given by the Born Rule
- The system immediately changes its state to the one represented by $|P = p_i\rangle$
  - So if you immediately measure P again, you are guaranteed to get $P = p_i$ again

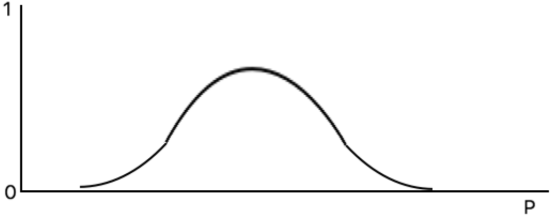
The Collapse of the Wave Function

- When a system changes its state as a result of a measurement, this is sometimes called a **wave function collapse**
- A **wave function** is a function which tells us how likely we are to find that the system has property P to degree p_i if we measured it
- Clearly, we can derive this wave function from the vector being used to represent the state of the system
- It turns out we can also derive which vector we should use to represent the system from its wave function

The Collapse of the Wave Function

- Imagine A is not an eigenstate of P
- In this scenario, we cannot say that A has any definite value of P
- The wave function for A would assign probabilities to all the different possible outcomes of measuring property P on the system
- We then measure P, and find that $P = p_i$
- At this point, the wave function collapses, in the sense that it now assigns probability 1 to measuring $P = p_i$, and probability 0 to measuring any other value

The Collapse of the Wave Function



- Before measurement, the wave function might look like this

The Collapse of the Wave Function

- After measurement, the wave function collapses to a single point

The Schrödinger Equation

- It is important to emphasise that the wave function collapse is inherently probabilistic (**stochastic**) process
  - There is no way to say in advance which outcome **will** happen, only how **likely** each outcome will be
- It is also important to emphasise that this is the **only** stochastic element in QM
- When the system is not being measured, it evolves from one state to another in accordance with a deterministic dynamics
- This dynamics is a kind of wave equation, and was formulated by Schrödinger

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Superposition

- When we were first discussing the double split experiment, we introduced the idea of **superposition**
  - The photon was in a superposition of passing through the top slit and of passing through the bottom slit

- We can now represent superpositions by **adding** vectors

- So if $|S = T\rangle$ represents the photon passing through the top slit, and $|S = B\rangle$ represents the photon passing through the bottom split, then the superposition is represented as their sum:

$$|S = T\rangle + |S = B\rangle$$

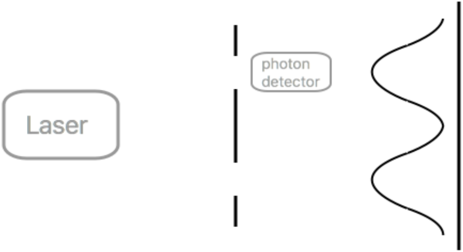
Superposition

- $|S = T\rangle + |S = B\rangle$ is not an eigenstate of property S, and so we cannot say that the photon has passed through the top slit, and we cannot say that it passed through the bottom
- However, if we measured this property (say by putting a photon detector behind one of the slits) then the wave function will collapse
- Either the photon will have passed through the top slit, $|S = T\rangle$, or it will have passed through the bottom, $|S = B\rangle$
- The probability of each of these outcomes will be given by the earlier Born Rule

The Double-Slit Experiment with a Photon Detector

- If we add the photon detector, we get the more particle-like pattern

The Double-Slit Experiment with a Photon Detector



- Really weird thought: the photon detector comes **after** the slits, but tells the photon how to pass through those slits!

The Measurement Problem

- We have two rules telling us how the state of a system evolves:
  - The deterministic Schrödinger equation, which is in force so long as no measurement takes place
  - The projection postulate (wave function collapse) when a measurement takes place
- What is a measurement? And why does it over-rule the otherwise totally general Schrödinger equation? After all, surely that equation governs the material that the measuring device is made of!
- This is known as the **measurement problem**

Born's Interpretation of the Wave Function

- It would be easy to explain what was happening with the measurement problem if we thought of a wave function as a mere representation of the probabilities that we will make certain observations
- Photons and electrons always have a full set of determinate properties (position, momentum, spin etc), but we just cannot know with certainty what their properties are
- The reason that the wave function "collapses" after measurement is just that we then **know** which property the particle has
- This was Born's original interpretation of the wave function

Born's Interpretation of the Wave Function

- But Born's way of looking at the wave function does not seem to do justice to what we actually observe
- In the double-slit experiment, an individual photon "interferes" with itself, as evidenced by the interference pattern
- This makes sense if we think of the wave function as a real physical thing (a wave!)
- But how could Born's non-physical probability "wave" interfere with itself?

  (Maybe this isn't the end: Bohm has subsequently developed Born's view into an interesting alternative to standard QM)

Schrödinger's Interpretation of the Wave Function

- It would be easy to explain what was happening with the double-slit experiment if we thought of (e.g.) electrons as spread-out, wave-like entities
  - In other words: wave functions describe the electrons themselves
- We could even try saying that it's properties are spread out: partially spin-up, partially spin-down
- This is something like Schrödinger's original interpretation of the wave function

Schrödinger's Interpretation of the Wave Function

- But there are lots of problems with Schrödinger's interpretation
- **First:** it does not fit well with the fact that electrons often behave in particle-like ways
- **Second:** wave functions are complex and many dimensional, and thus cannot be a wave in ordinary space
- **Third:** this interpretation does not explain why wave functions collapse after measurement!

Epistemic or Ontological?

- The Born interpretation is **epistemic** in the sense that the wave function describes the state of our knowledge/ignorance of the world
- The Schrödinger interpretation is **ontological** in the sense that the wave function describes an independent world
- *Neither interpretation seems to work!*

The Copenhagen Interpretation

- The **Copenhagen** interpretation is a blend of the two
- The wave function is about the world **and** our knowledge of the world
- The Copenhagen interpretation originated from Bohr, but it is absolutely unclear whether it was Bohr's actual view
- We will set aside the historical question of what Bohr actually thought, and talk instead about an imaginary physicist called Copenhagen

Measurement and Classical Concepts

- According to Copenhagen, classical physics is still **prior** to QM
- We have to describe our **measurements** in classical terms
  - We can never say that our measurement device is in a superposition of different readings
- However, Copenhagen also insists there is no once and for all divide between the measuring and the measured: we can draw the divide where we like

  (It is unclear whether this really makes sense...)

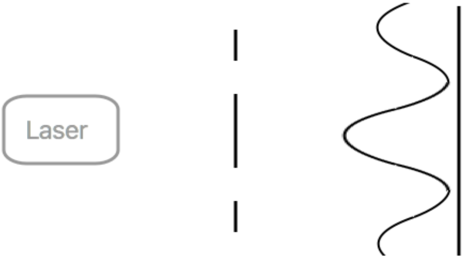
Complementarity of Classical Concepts

- The concepts of classical physics (e.g. position, momentum, etc) are not all simultaneously applicable to a quantum system
- They come in complementary pairs (e.g. position and momentum), and we cannot apply both concepts in one of these pairs to the same system at the same time
- If we have measured the position of a photon, then we cannot attribute it a definite momentum

The Effect of Measurement

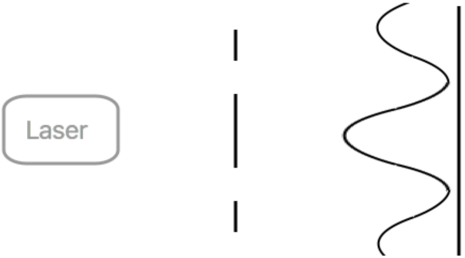
- Measurement does not merely record how particles are, it somehow **makes** particles be certain ways
- Suppose we have measured the position of a photon, so that it now has no definite momentum
- If we then measure the momentum of the photon, we thereby **make** it have a definite momentum
- Measurement is an **active** process, not the **passive** thing we assume in classical physics

Superposition (Again!)



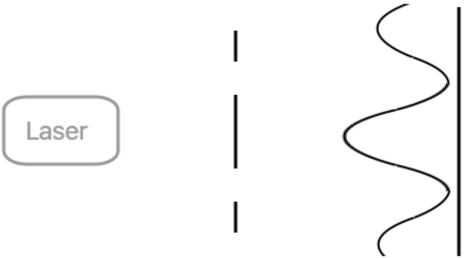
- Does the photon pass through the top slit or the bottom?

Superposition (Again!)



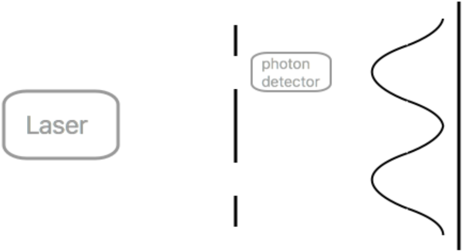
- According to Copenhagen, there is no answer to this question

Superposition (Again!)



- Until we perform a measurement, we cannot attribute any definite position to the photon

Superposition (Again!)



- If we do perform a measurement, that will **make** the photon have a definite position

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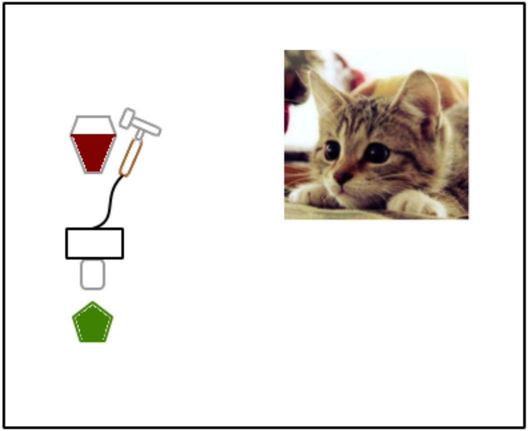
Assessment of the Copenhagen Interpretation

- The Copenhagen interpretation is an ingenious, subtle way of trying to understand QM, but it has lots of problems (physical and philosophical)
- Measurement is a primitive, and deeply mysterious, concept on this interpretation
- How can our **measuring** things change them in the way that Copenhagen suggests?
- We might try to comfort ourselves by saying that the weird effects of measuring only show up at the quantum level, never in the macro world
- But Schrödinger famously presented a thought experiment to show that this was wrong

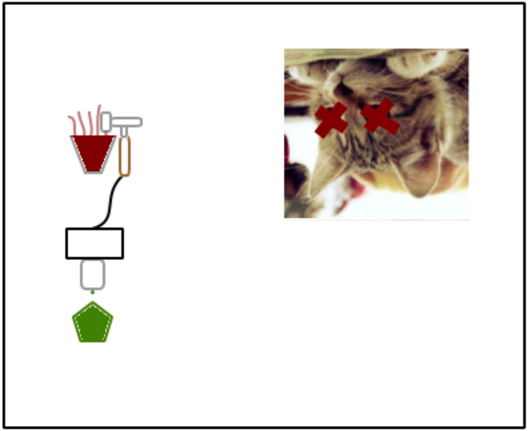
Schrödinger's Cat

One can even set up quite ridiculous cases. A cat is penned up in a steel chamber along with the following diabolic device (which must be secured against direct interference by the cat); in a Geiger counter there is a tiny bit of radioactive substance, so small, that perhaps in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for one hour, one would say that the cat still lives if meanwhile no atom has decayed. The first atomic decay would have poisoned it.

Schrödinger's Cat



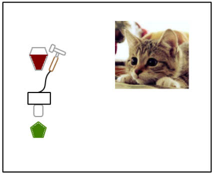
Schrödinger's Cat

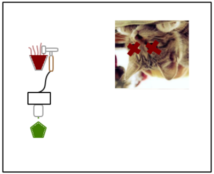


Schrödinger's Cat

> *The [wave function] of the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts.*
>
> *(Schrödinger 1935 pp. 156–7)*

Schrödinger's Cat





- Until we measure the whole system of the box, it is in a superposition of two states:
  - No atom decayed, and the cat is alive
  - An atom decayed, and the cat is dead
- On the Copenhagen interpretation, that means that until we open the box and see, there is no fact of the matter as to whether the cat is alive or dead!

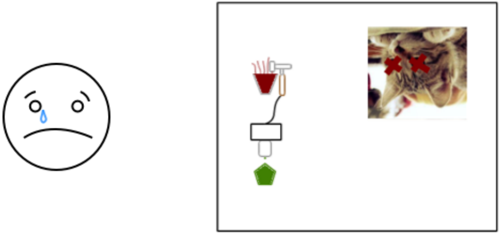
Wigner's Friend

- Schrödinger thought that this situation was absurd, and so was a *reductio* of the Copenhagen interpretation
- Other people disagree: they just think that cats really can be in superpositions of being alive or dead
- Wigner tried to make the situation even more obviously absurd by tweaking the story
- After the evil scientist sets up the situation, he leaves the room
- Another observer comes in, and looks into the box, and sees if the cat is alive or dead

Schrödinger's Cat

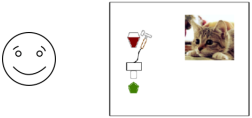
- He either sees that the cat is alive, and is happy...

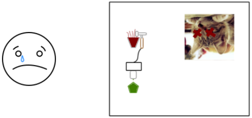
Schrödinger's Cat



- ...Or he sees that the cat is dead, and is sad

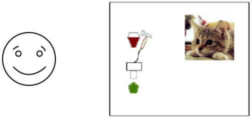
Wigner's Friend

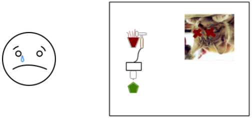




- We can think of everything in the box **and** this new observer as a new system
- Until we measure this system (by asking the observer what he saw), this system will also be in a superposition of two states:
  - No atom decayed, and the cat is alive, and the observer is happy
  - An atom decayed, and the cat is dead, and the observer is sad

Wigner's Friend





- But surely that is absurd: the observer can't be in a superposition of being happy and sad!

An Idealist Interpretation

- This led Wigner to a radical interpretation of measurement
- According to Wigner, a measurement is made at the moment that a **conscious** mind becomes aware of the results
- Given the important role of measurement in QM, this is a kind of idealism
- We **make** the world take on determinate properties by **consciously** observing it
- I leave it to you to decide what you think of this interpretation!

References

- Bohr, N (1934) *Atomic Theory and the Description of Nature* (Cambridge: CUP)
- Feynman, R (1965) *The Character of Physical Law*
- Schrödinger, E (1935) 'The Present Situation in Quantum Mechanics', translated by Trimmer and reprinted in Wheeler and Zurek (eds) *Quantum Theory and Measurement* (1983)

- For an **incredibly helpful** discussion of all of this, see:
  - Albert, D *Quantum Mechanics and Experience* (esp. chs 1 & 2)