

# Quantum Weirdness

Part 4

Interpretations Of Quantum Mechanics  
Quantum Tunnelling

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# Interpretations of Quantum Mechanics

What does it mean?

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## The Copenhagen Interpretation



Niels Bohr 1885-1962  
Danish Physicist

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- A wavefunction describes the quantum system completely, in a probabilistic manner
- Any act of observation of the system causes the wavefunction to collapse into a definite state

• There must be unanswerable questions as to the quantum state before the measurement

This contradicts the classical view of physics: that it is always possible to know everything, if you measure it precisely enough

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## Who Invented the Term?

- The name appears to have been invented by Werner Heisenberg in the 1950s, when alternative interpretations appeared



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## Correspondence Principle

- Quantum mechanics must produce the same results as classical physics, if there are enough particles.
- Bohr was first to originate this in 1913, in his hydrogen atom model
- Special relativity (particles moving fast) reduces to Newtonian physics when the particles move slowly
- General relativity reduces to Newtonian gravity, when dealing with weak gravitational systems
- Inheritance from chromosomes reduces to Mendelian inheritance in organisms

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## Pilot Wave Theory/Bohm Interpretation

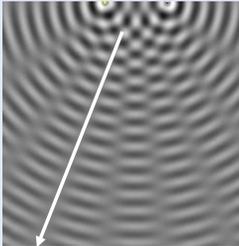
- de Broglie
- Bohm




David Bohm, FRS 1917-1992

Sometimes called a "hidden variable" theorem – not a good name!

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- There are real particles, which ride on pilot-waves which govern where they go
- Particle can only go where there is a wave

If there is no wave, then the particle can't go to that position

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- The Pilot Wave model got a boost in 2006, when Couder and Fort noticed that bouncing droplets, could be "walked" along the wave that they generated

<https://www.youtube.com/watch?v=nmC0ygr08tE&feature=youtu.be>



Stationary Bouncing Particles      Walking particles

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- Very recent experiments (2015-2016) have cast doubt on this

The experiments were done by Tomas Bohr – the grandson of Nils Bohr

<https://www.youtube.com/watch?v=5TypwAwmPew&feature=youtu.be>

<https://www.quantamagazine.org/famous-experiment-dooms-pilot-wave-alternative-to-quantum-weirdness-20181011/>




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## Many Worlds Interpretation

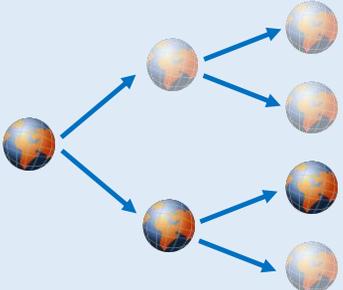
- Hugh Everett III (1930-1982) → 
- Popularized by Bryce Seligman Dewitt



<https://blogs.scientificamerican.com/observations/the-difficult-birth-of-the-many-worlds-interpretation-of-quantum-mechanics/>

Everett did not believe that the underpinnings of quantum mechanics lead naturally to the correspondence principle.

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A new parallel universe is created after each quantum event

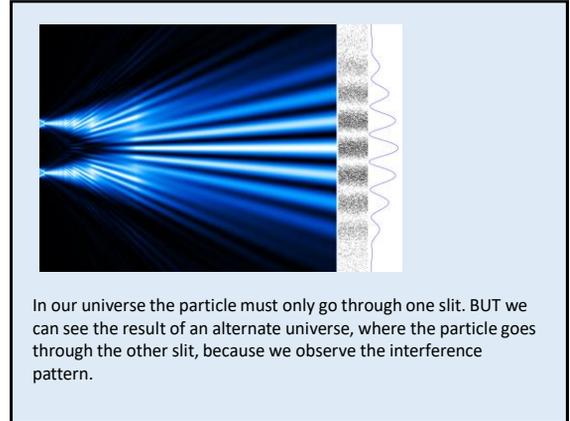
We can see the results from our own timeline

But we must be able to see the results of other timelines

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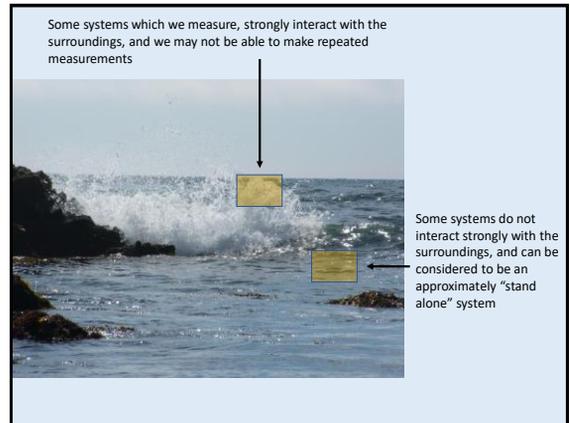


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## Chad Orzel's Interpretation

- <https://www.forbes.com/sites/chadorzel/2019/09/17/many-worlds-but-too-much-metaphor/#50a5e5db625d>
- The universe exists as one huge (exceptionally complicated) wavefunction, and we can only ever sample a small part of that wavefunction

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## Still No Agreement on Interpretation!

- We can use Schrodinger's Equation to calculate many things, even if we don't understand the interpretation
- The physicist David Mermin describes his attitude to the Copenhagen Interpretation as



"Shut up, and calculate"

<https://www.quantamagazine.org/why-the-many-worlds-interpretation-of-quantum-mechanics-has-many-problems-20181018/>

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## Special Relativity

When things move very fast

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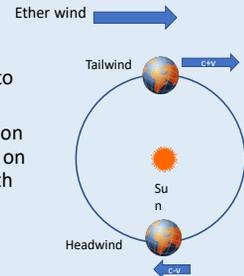
## The Speed of Light

- Maxwells equations predict that the speed of light in a vacuum is  $c = 3.00 \times 10^8$  m/s
- This was confirmed in many experiments
- Most waves seen at this time (1880s) were mechanical waves. They needed a propagation medium
- e.g. sound needs air to propagate through
- Physicists assumed that EM waves must have some propagation medium – the luminiferous ether

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## The Ether Wind

- The earth was not expected to be stationary in the ether
- The speed of light measured on earth should vary depending on the relative speed of the earth with respect to the ether
- Headwinds and Tailwinds



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## The Michelson-Morley Experiment

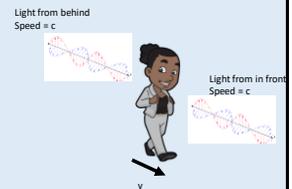
- Albert Michelson and Edward Morley
- Measured the speed of light using a 35 km long interferometer at various points in the year (different places on the orbital path of the earth)
- A NULL RESULT
- No difference in the speed of light at any time of the year
- NO LUMINIFEROUS ETHER



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## Einstein's Special Theory of Relativity (1905)

- The laws of physics must be the same for all non-accelerating observers
- The speed of light in a vacuum has the same value regardless of the velocity of the observer and the velocity of the source
- There is no unique inertial frame (everything is relative!)



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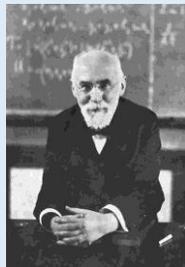
- At high speeds, near to the speed of light, the familiar equations in classical mechanics need to be modified by an extra factor  $\gamma$

• The Lorentz factor  $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$

Momentum =  $mv$  (Newton)

Momentum =  $\gamma mv$  (Relativistic)

Hendrik Antoon Lorentz  
Nobel Prize 1902



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- When an object moves very quickly, time appears to move at a different rate according to an outside observer
- A clock travelling with the moving object does not change speed



To the stationary observer, the moving clock has moved more quickly. Less time elapses for the moving clock than the stationary clock

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## The Twin Paradox



Scott Kelly (left) and his twin brother Mark Kelly (right). Both astronauts



Scott spent a year on the International Space Station, moving at 27,000 km/h with respect to the Earth. His body clock slowed down very slightly compared to his twin Mark  
Mark aged slightly more than Scott (a few microseconds per day)

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## Quantum Mechanics and Special Relativity

Quantum Particles Moving Very Quickly

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## P.A.M. Dirac

- Paul Adrien Maurice Dirac
- British mathematician, physicist and engineer
- Combined the Schrödinger Equation with Special Relativity to deal with quantum systems with particles moving at high speeds.



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- Dirac used matrices to modify Schrödinger's Equation to handle Special Relativity

$$(i\hat{\phi} - m)\psi = 0$$

The Dirac Equation

- He noticed that it was possible to get negative energy solutions from the equation.
- This was the first prediction of anti-matter

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## Antimatter

- Solutions to the Dirac Equation predicted that for every particle of matter, there must be an antiparticle (antimatter).

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- The antimatter counterpart of the electron is the positron
- It has exactly the same mass as the electron, but has a positive charge instead of negative

+

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## Matter-Antimatter Annihilation

- If a matter particle meets the antimatter counterpart they annihilate each other
- For the electron-positron reaction, the matter disappears and is replaced by two gamma ray photons. (This conserves momentum and energy)
- A free positron never has to go far in order to meet an electron.

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- When the positron and the electron annihilate each other, energy and momentum must still be conserved
- A pair of gamma ray photons, moving in opposite directions are produced

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- We use this pair production to localize the site of cancer tumour
- Tumours have a fast metabolism, so take up sugars faster than normal tissue
- Fluorodeoxyglucose (<sup>18</sup>F) is a glucose analogue with a radioactive fluorine-18 substituted instead of an -OH

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- It concentrates at the site of the tumour
- It decays with a half-life of 110 minutes into oxygen, a positron and a neutrino

$${}^{18}_9F \rightarrow {}^{18}_8O + e^+ + \nu$$

Beta+ decay:  
Proton becomes a neutron, a positron and a neutrino

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- More positrons are produced in the tumour than in the surrounding normal tissue
- They annihilate with electrons giving off gamma rays
- More gamma rays produced at the tumour than elsewhere

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### Positron Emission Tomography

- An imaging technique using the production of the gamma rays to determine the site of the emission

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Dr Heather Williams (Medical Physicist at the Christie Hospital in Manchester)

Normal Brain scan: false colour image

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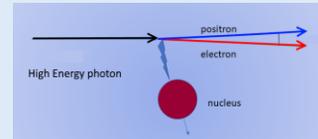
## Creating Matter Out of Energy

More Quantum Weirdness

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## Pair Production – Mass From Energy

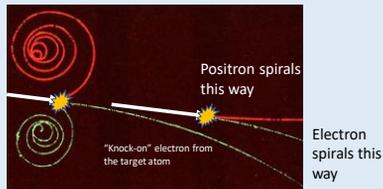
- Pair Production, the reverse process to pair annihilation is possible
- A highly energetic photon, passing close to a nucleus can transform itself into a pair of particles, an electron and a positron
- Mass is created during this process, since the photon has no mass



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- Charged particles follow a spiral path in a magnetic field.
- Opposite charges spiral in opposite directions



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## Quantum Tunnelling

How to get out of a box by quantum cheating

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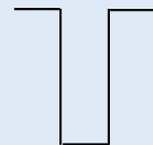
## Quantum Tunnelling

- In classical physics, a particle trapped inside a potential well (the particle in the box) can never get out, unless extra energy is supplied, so it can "climb over" the wall.
- Quantum physics allows us to cheat!

- Minute Physics
- <https://www.youtube.com/watch?v=cTodS8hkSDg&feature=youtu.be>

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- Physicist talk about objects in "Potential Wells"



Gravity Well

- Objects trapped in the well caused by the gravitational field of the earth

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- In classical physics, the only way to get out of the well, is to have some supply of external energy



Gravity Well

- Haul the dog out with a crane
- OR
- dog jumps out if it uses energy reserves in muscles

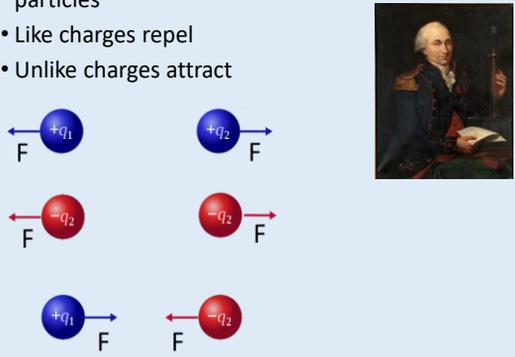
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# Potential Wells in Atoms

Electrical Potential Wells

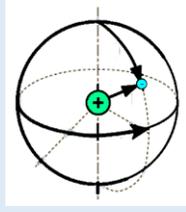
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- Coulomb Forces between charged particles
- Like charges repel
- Unlike charges attract



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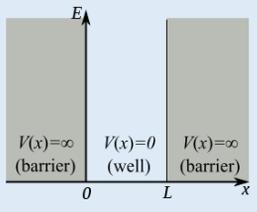
- In atoms and molecules, negative electrons move around a positive nucleus
- The electrons are in the potential well generated by the proton



The Hamiltonian Operator in the Schrodinger Equation defines the shape of the potential well

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- The simplest shape of well, is one with infinitely high walls, and a flat bottom



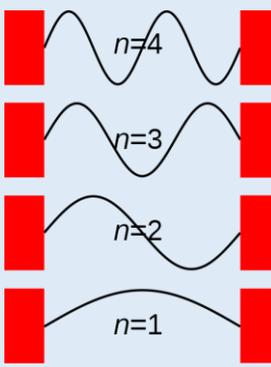
$V(x)=\infty$  (barrier)    $V(x)=0$  (well)    $V(x)=\infty$  (barrier)

0   L   x

- This is not a very realistic model
- The solutions to the Schrodinger equation are mathematically simple!

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- In an infinitely deep well, the quantum particle cannot get out
- The solutions to the Schrodinger Equation are standing waves
- Just like the waves on a string



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More realistic potential well.  
 Particles in the well can escape  
 In classical physics – they need extra energy from outside

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- In quantum physics the solutions to the Schrödinger equation predict a probability outside the well

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- Animation showing a quantum particle getting to a potential barrier

Most of the time, it hits the barrier and rebounds

Sometimes it tunnels through the barrier and escapes!

Stays in the well

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## Applications of Quantum Tunnelling

How we can use this

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### Scanning Tunnelling Microscope

- Directly observing positions of atoms, by looking at the electron clouds around them

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STM images of pentacene on a nickel surface

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Tungsten tip – so sharp that it ends in one atom

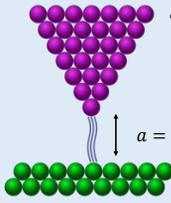
Tip potential well

Surface potential well

Electron tunnels from tip to the surface

<http://hoffman.physics.harvard.edu/research/STMintro.php>

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- Tunnelling probability is very sensitive to the distance between the tip and the surface

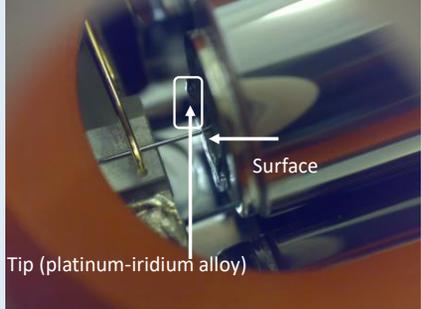
$a = 1.000 \text{ nm} = 1.000 \times 10^{-9} \text{ m}$

- Tunnelling increases as the tip passes over places with a high probability of an electron

[https://en.wikipedia.org/wiki/Scanning\\_tunneling\\_microscope](https://en.wikipedia.org/wiki/Scanning_tunneling_microscope)

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### Scanning Tunneling Microscope head

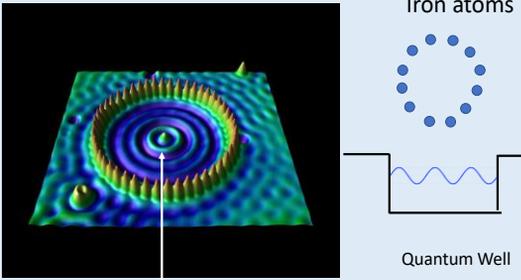


Tip (platinum-iridium alloy)

Surface

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### Quantum Corral



Iron atoms

Quantum Well

Ripples are the wavefunction of an electron trapped in the corral

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### Nanoscale Manipulation

- The STM tip can be used to move individual atoms around the surface and position them precisely

US National Institute of Standards and Technology



A 40-nanometre-wide NIST logo made with cobalt atoms on a copper surface.

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