

Quantum Weirdness

Part 5

The Uncertainty Principle

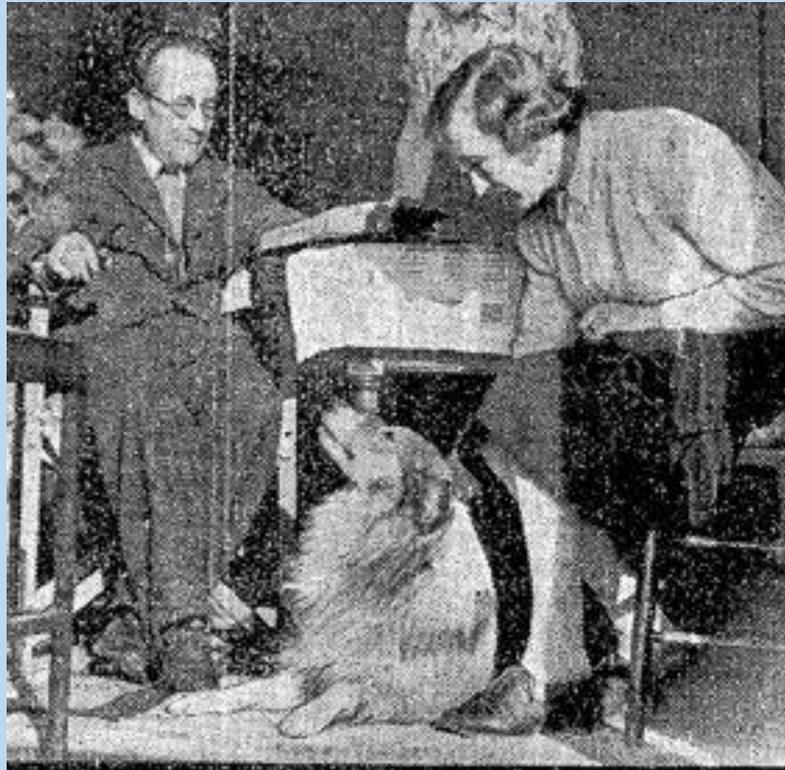
The Laser

Quantum Zeno Effect

Quantum Entanglement

Schrödinger's Dog

Burschie
"Laddie"



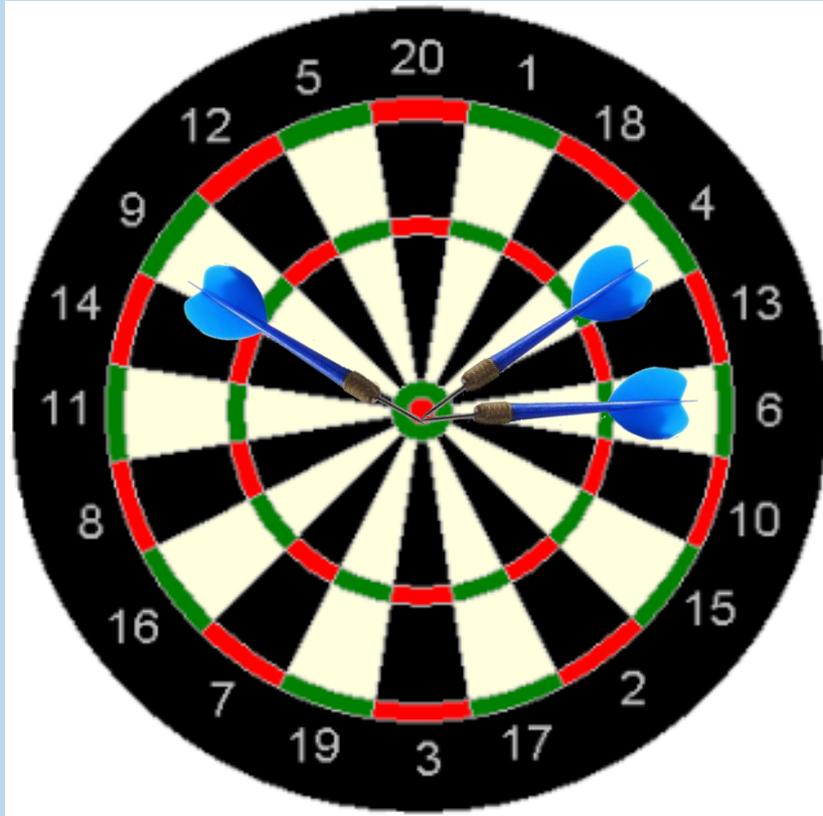
The Uncertainty Principle

The Limits of Measurement

Accuracy and Precision

- Accuracy – how close are we to the right answer?
- Precise – if we make a measurement, how reproducible is it?
- Can we repeat it to get the same result?

If I aim for the centre , and hit it with three darts, I am accurate **and** precise



I reproducibly hit the target that I aimed for



$\pm 0.5 \text{ mm}$



$\pm 0.05 \text{ mm}$



$\pm 0.01 \text{ mm}$

In classical physics, there are no theoretical limits on the limits of precision

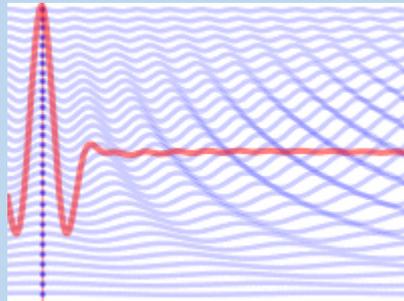
Build a better measuring device!

Newtonian Physics: Determinism

- Classical physics it is possible to predict the position, velocity and momentum etc. of all particles in the universe in the future, provided that the current values are known
- It should always be possible to make “perfect” measurements
- However, quantum physics does not allow complete determinism, as there is a finite amount of uncertainty in any measurement or prediction

Quantum Particle

- The Quantum Particle is also a wave
- It is not possible to define exactly where the wave is



https://upload.wikimedia.org/wikipedia/commons/transcoded/e/ee/Quantum_particle_Vs_Classical.ogv/Quantum_particle_Vs_Classical.ogv.480p.vp9.webm

Additional Explanations

- Chad Orzel's Explanation

<https://www.youtube.com/watch?v=TQKELOE9eY4>

- Particle in box simulation, showing the waveform bouncing around inside the potential well
- <https://www.youtube.com/watch?v=Xj9PdeY64rA>

Adding Two Sound Waves Together

Generation of a single frequency

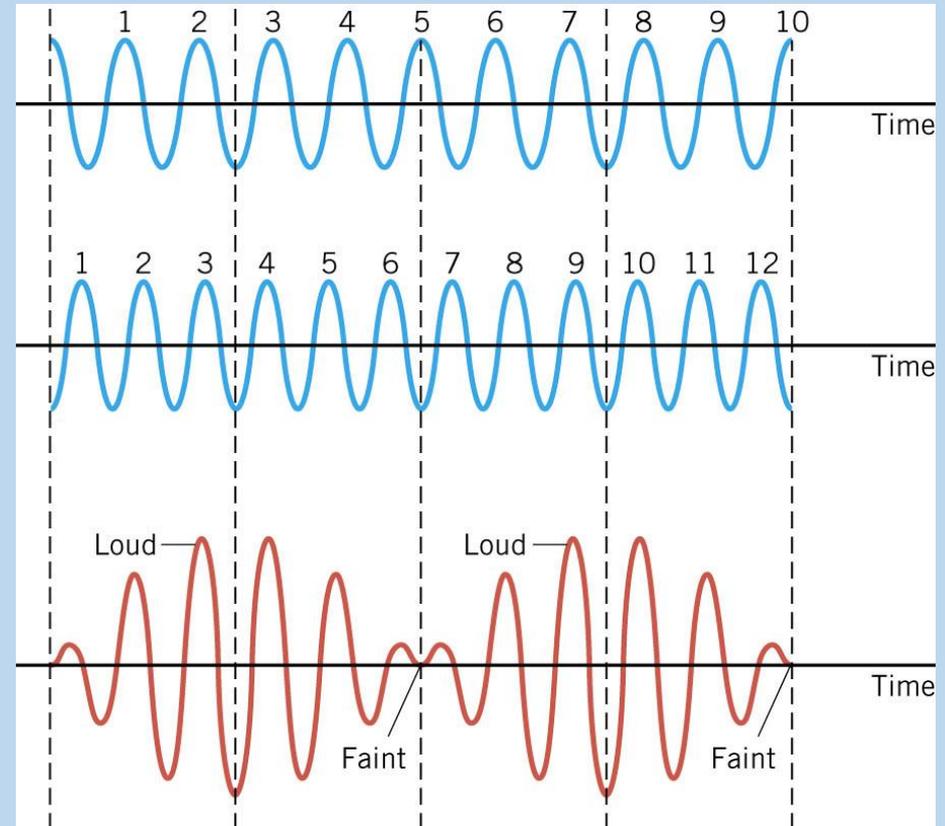
<http://onlinetonegenerator.com/432Hz.html>

Add two frequencies together to get a beat frequency

<http://onlinetonegenerator.com/binauralbeats.html>

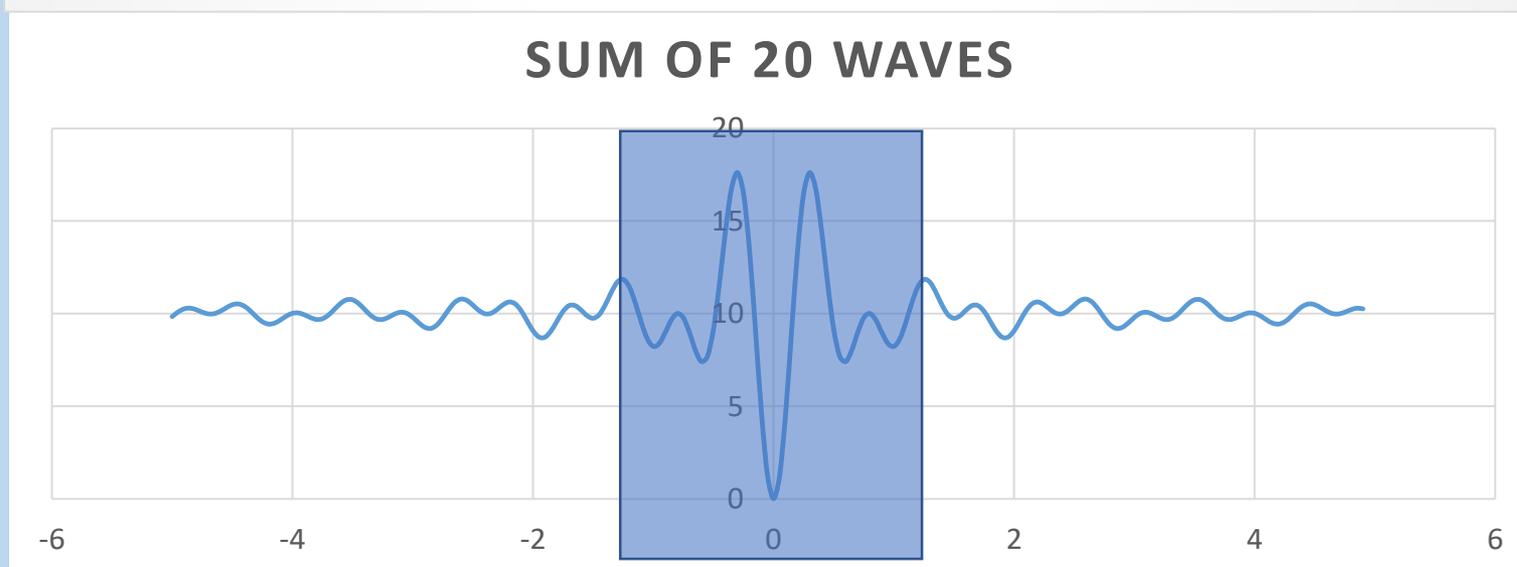
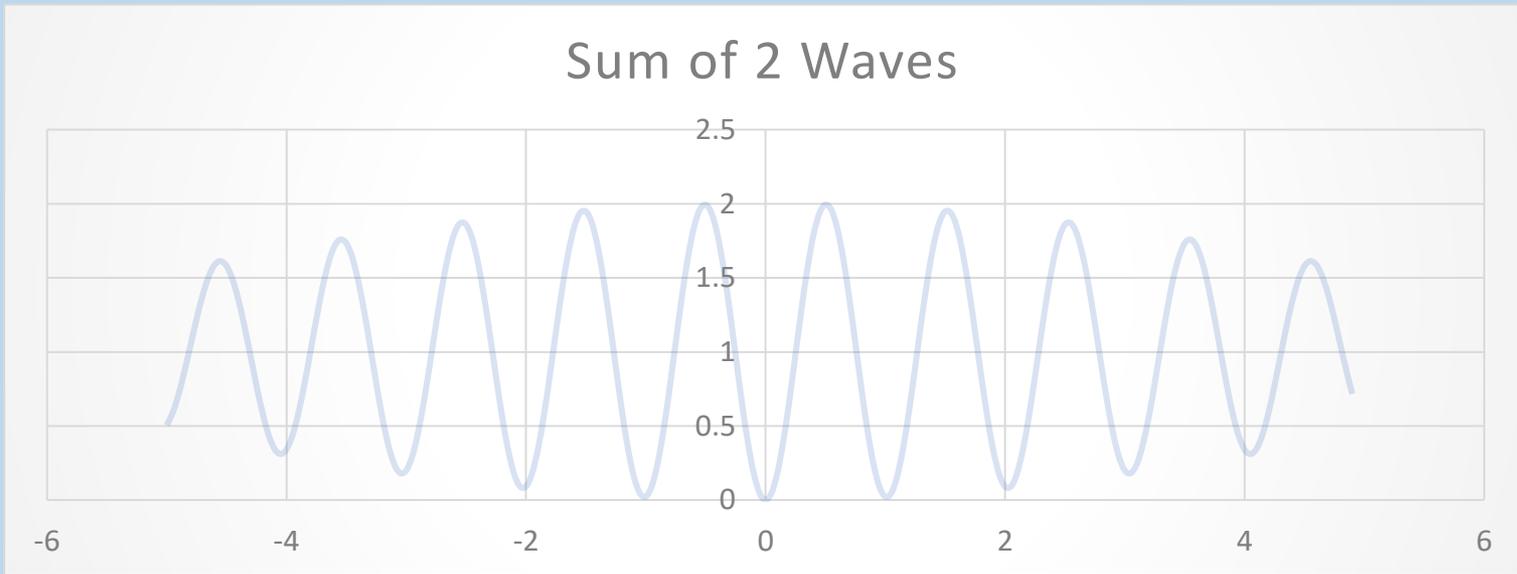
Beat Frequency

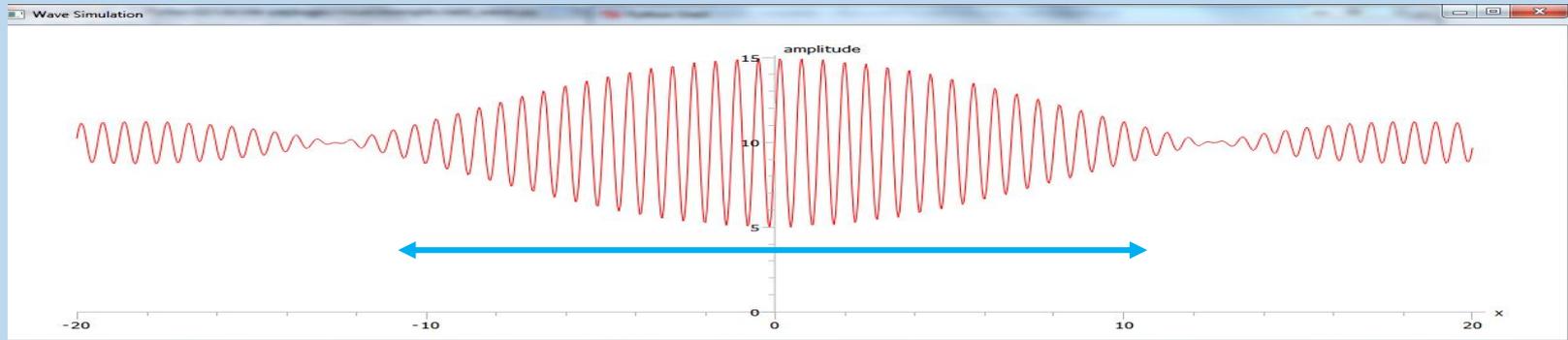
- When we add two frequencies which are close together, they combine to form a new waveform with a modulated amplitude



<http://birdglue.com/music-class/beats/index.html>

- Summing Waves





- Inside the packet, there is an average wavelength (from all of the different wavelengths of the individual waves).
- This average wavelength is the wavelength associated with the particle in the energy equation

$$E = hf = \frac{h\lambda}{c}$$



Our particle is a combination of lots of waves

Heisenberg's Uncertainty Principle

- The German Physicist Werner Heisenberg (1901-1976) formulated the nature of this indeterminacy

Uncertainty in position measurement

$$\Delta x \Delta p_x \geq \frac{h}{4\pi}$$

Uncertainty in momentum measurement $p = mass \times velocity$



- In Newtonian Physics, we could determine both position and momentum exactly

$$\Delta x \Delta p_x \geq \frac{h}{4\pi}$$

- For a quantum particle, we can't determine both momentum and position perfectly.
- In fact if we know one of the pair perfectly, then the other one has infinite uncertainty!

- Suppose we measure the position of a ping-pong ball, with an uncertainty of $\pm 1.5 \times 10^{-11} m$

$$\Delta x = 1.5 \times 10^{-11} m$$

$$\Delta x = 0.0000000000015 \text{ m}$$

- Calculate the uncertainty in the speed of the ping-pong ball, mass 2.0 grams



The lowest possible uncertainty in velocity is

$$\Delta v_x = \frac{h}{4\pi m \Delta x}$$

$$\Delta v_x = \frac{6.63 \times 10^{-34} \text{ J}\cdot\text{s}}{4\pi \times 2.0 \times 10^{-3} \text{ kg} \times 1.5 \times 10^{-11}}$$

$$\Delta v_x = 2 \times 10^{-21} \text{ m/s}$$

Much smaller than the precision of any possible measuring device

For most objects, the uncertainty in velocity is very small, and we do not need to worry about the Uncertainty Principle

- If the calculation is repeated for an electron, with a much lower mass, 9.1×10^{-31} kg

$$\Delta v_x = \frac{6.63 \times 10^{-34} \text{ J}\cdot\text{s}}{4\pi \times 9.1 \times 10^{-31} \text{ kg} \times 1.5 \times 10^{-11}}$$

$$\Delta v_x = 4 \times 10^6 \text{ m/s}$$

- An extremely large uncertainty in the speed. Uncertainty Principle important for low mass particles



- Calculate the uncertainty in my velocity, if $\Delta x = 1 \times 10^{-3} m$

$$\Delta v_x = \frac{h}{4\pi m \Delta x}$$

$$\Delta v_x = \frac{6.63 \times 10^{-34} J \cdot s}{4\pi \times 100 \text{ kg} \times 1 \times 10^{-3}}$$

$$\Delta v_x \approx 10^{-34} \text{ m/s}$$

Extremely small, and cannot be measured by any known device

Time-Energy Uncertainty

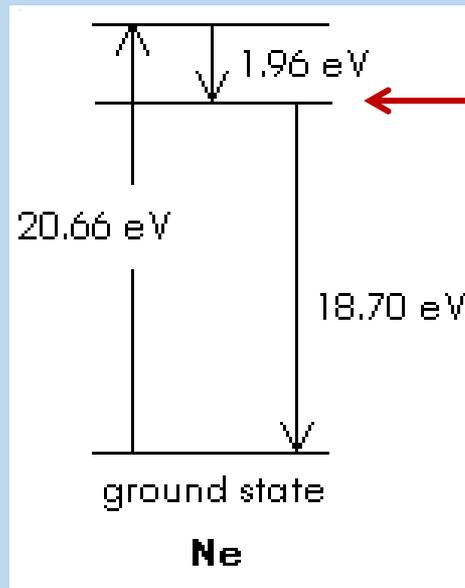
- The position-momentum uncertainty has a counterpart in the energy-time uncertainty

$$\Delta x \Delta p_x \geq \frac{h}{4\pi} = \frac{\hbar}{2} \quad \leftarrow \text{“h-bar”}$$

$$\Delta E \Delta t \geq \frac{1}{2} \hbar$$

$$\Delta E \Delta t \geq \frac{1}{2} \hbar$$

- If we know the energy of the quantum particle, then we can never know the lifetime of the quantum state



$$\Delta E \Delta t \geq \frac{1}{2} \hbar$$

The ΔE is the uncertainty in the value of these energy levels
Similar to experimental error, except that this is a fundamental error which cannot be reduced

Virtual Particle

- The Uncertainty Principle adds another layer of quantum weirdness:
- The Virtual Particle
- Every particle spends some time as a combination of other particles in all possible ways. (Superposition)

- One particle can become a pair of heavier particles (the so-called virtual particles), which quickly rejoin into the original particle as if they had never been there.

$$\Delta E \Delta t \geq \frac{1}{2} \hbar$$

- As long as the process happens within the time uncertainty!
- Temporary borrowing of energy at the quantum level

- A charged particle can create a virtual photon
- Usually, this virtual photon just gets reabsorbed by the parent particle



Charged particle creates a virtual photon for a very short period of time

- But, if it is close to another charge, then the virtual photon may be absorbed by that charge instead
- Carries energy and momentum
- This accounts for the electromagnetic force between charged particles. It is the exchange of virtual photons



Quantum Electrodynamics (QED)

- Dirac extended Maxwell's Electromagnetism Formulations to allow for collections of quantum particles.
- This could account for the annihilation processes
- Requires the virtual particles allowed by the Uncertainty Principle
- <https://www.youtube.com/watch?v=crfY2vzVMbl>

Quantum Zeno Effect

A Watched Pot Never Boils

Zeno of Elea 495 BCE – 430 BCE?

- Greek philosopher



<https://www.youtube.com/watch?v=skM37PcZmWE&feature=youtu.be>

Zeno's Paradox

It takes 1 second to get halfway

It takes $\frac{1}{2}$ second to cover half that distance



It takes $\frac{1}{4}$
second to cover
a quarter of
that distance

- It will take an infinite number of steps to cover the complete distance.
- Hence, you can never get there!

- Fortunately mathematics comes to the rescue. Zeno's Paradox is not correct because
- An infinite sum of terms can have a finite answer!

$$1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \frac{1}{16} + \dots$$

$$\sum_{n=0}^{\infty} 2^{-n} = 2$$

- If you add up all the terms, it takes 2 seconds to get across the room

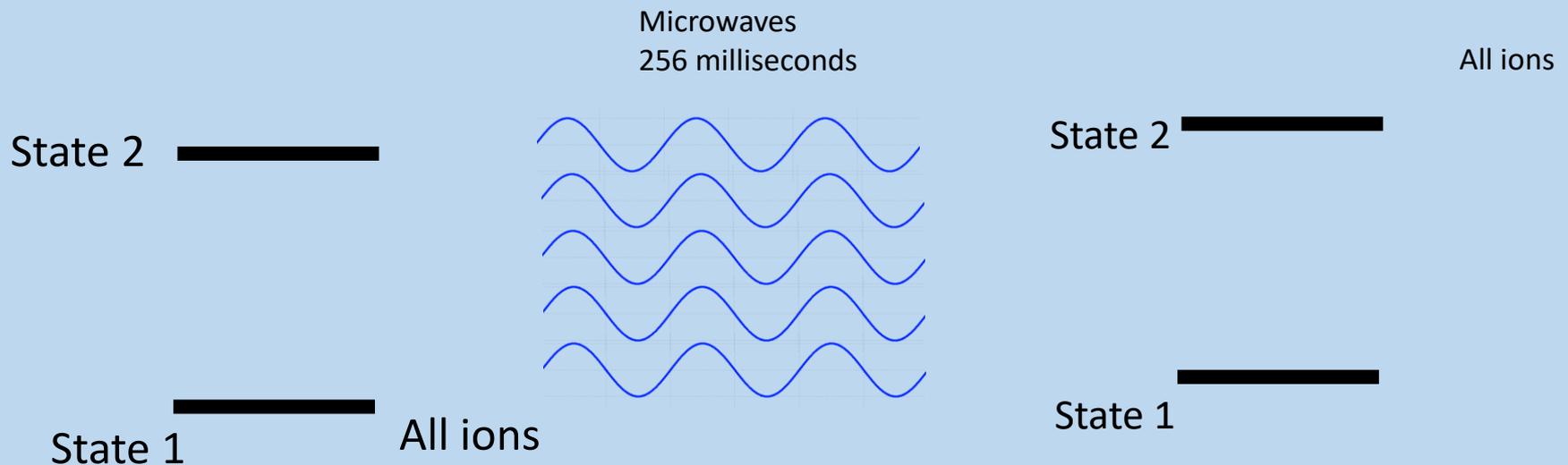
Quantum Zeno Effect

- Can you stop radioactive decay by continually observing the quantum state?
- Collapses the wavefunction back to the initial state – decay never happens!

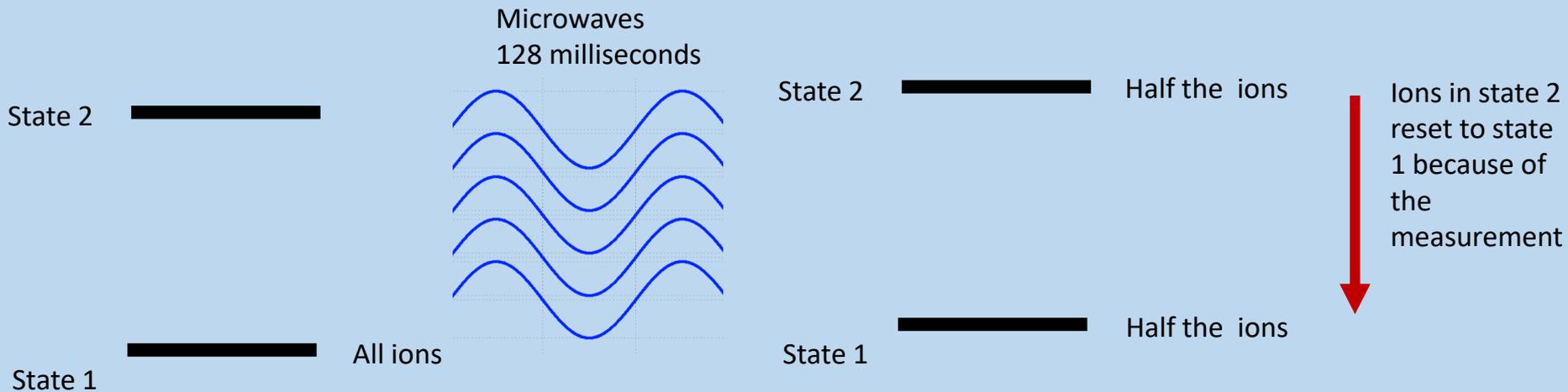
<https://www.newscientist.com/article/mg12517072-800-science-a-watched-atom-never-decays/>

A Watched Pot Never Boils

- Can you stop a quantum process from happening by continually observing it?



- Laser probe half way through the process
- Resets the process back to the start!



- If they probed after shorter periods of time, they reset the quantum levels to the lower state more frequently

- To be effective
 - Probe the quantum system at times shorter than the lifetime for complete transition
 - The probe has to change the quantum state of the upper level
-
- Difficult for Radioactivity
 - The differences in the energy levels are very small, and would need to be with gamma rays

Lasers

Light **A**mplification by **S**timulated **E**mission of **R**adiation

Lasers

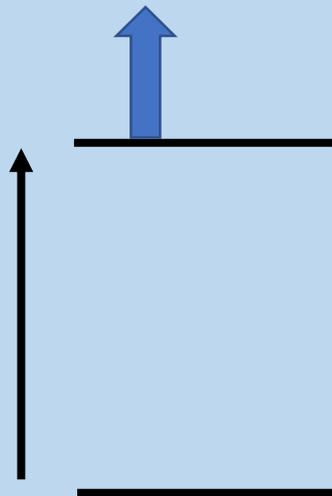
- A laser beam is a narrow beam of photons of the same wavelength
- Same colour
- It does not spread out much over a long distance



Spontaneous Emission

- If an electron is in a high energy state, it decays spontaneously down to a lower state
- The direction is random

Electric current pumps the electron up into the upper energy level

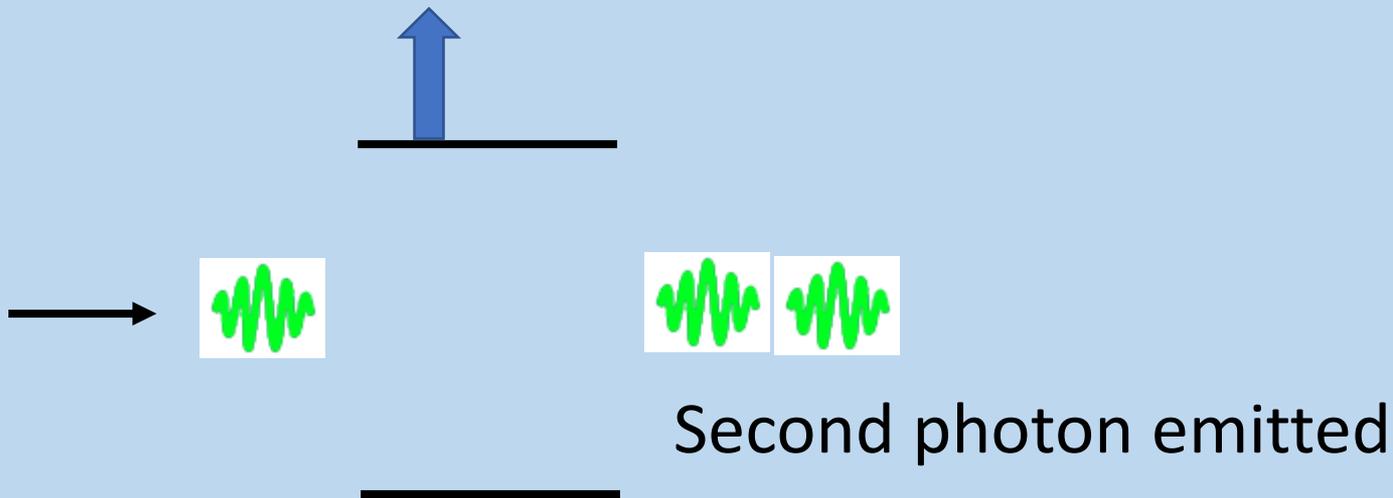


Photon emitted

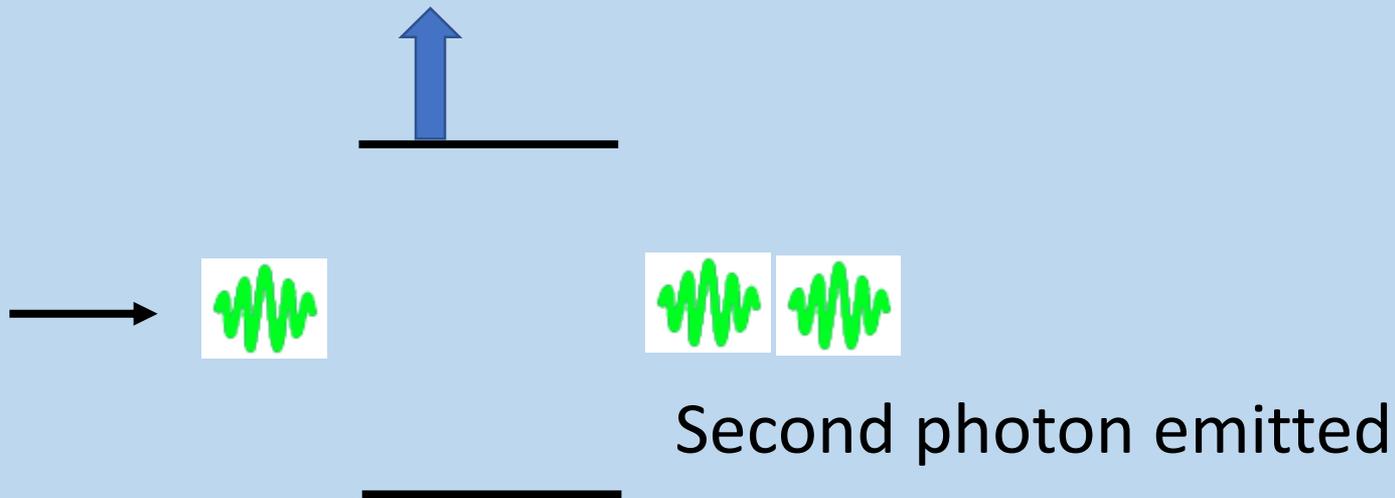


Stimulated Emission

- An excited state which has a relatively long lifetime (a metastable state) it may encounter another photon before undergoes spontaneous emission

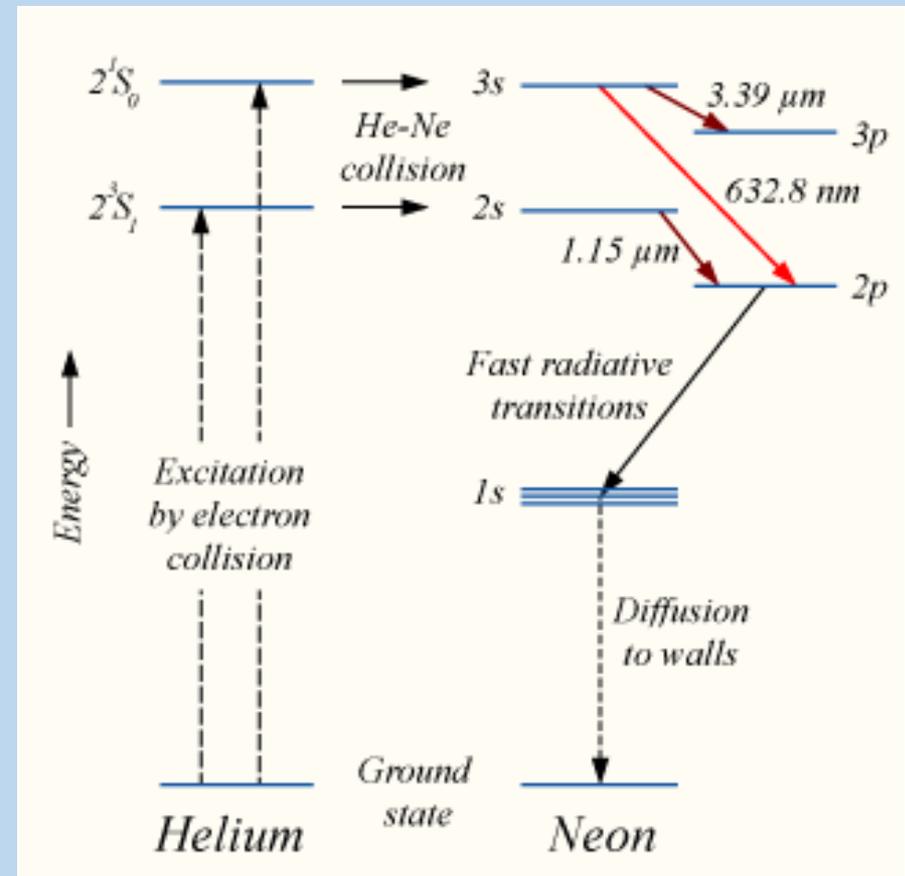


- The stimulating photon must be exactly the same energy as the gap between the two levels.
- Both photons are emitted in the same direction

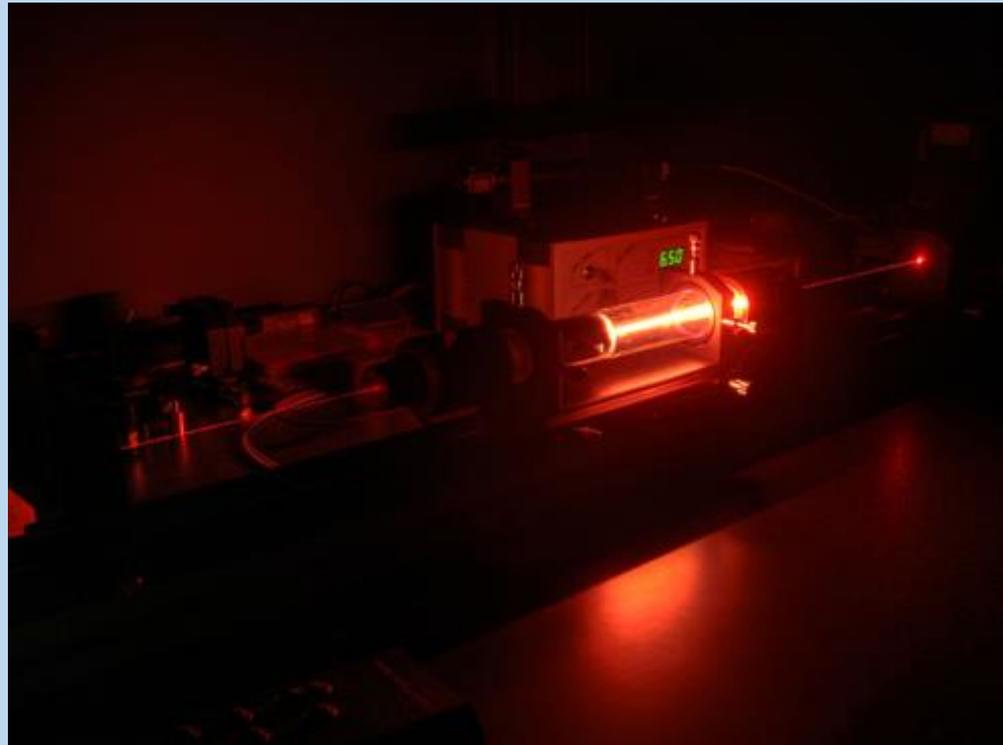


Pumping the Laser

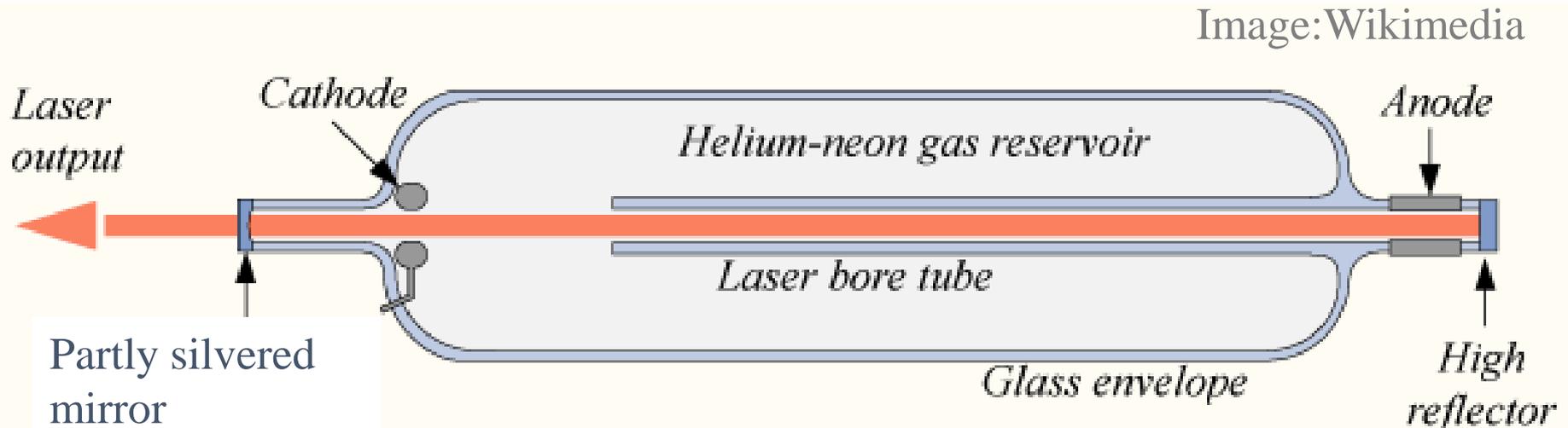
- Energy has to be put in, so that an electron is pumped into the higher stat
- In a mix of Helium and Neon, the helium can collide with the neon, pumping it into an excited state



- Helium-Neon laser
- Produces an intense red beam at a wavelength $\lambda = 650 \text{ nm}$



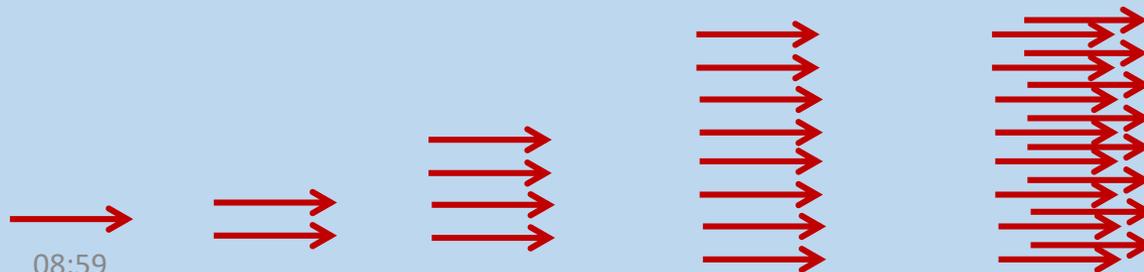
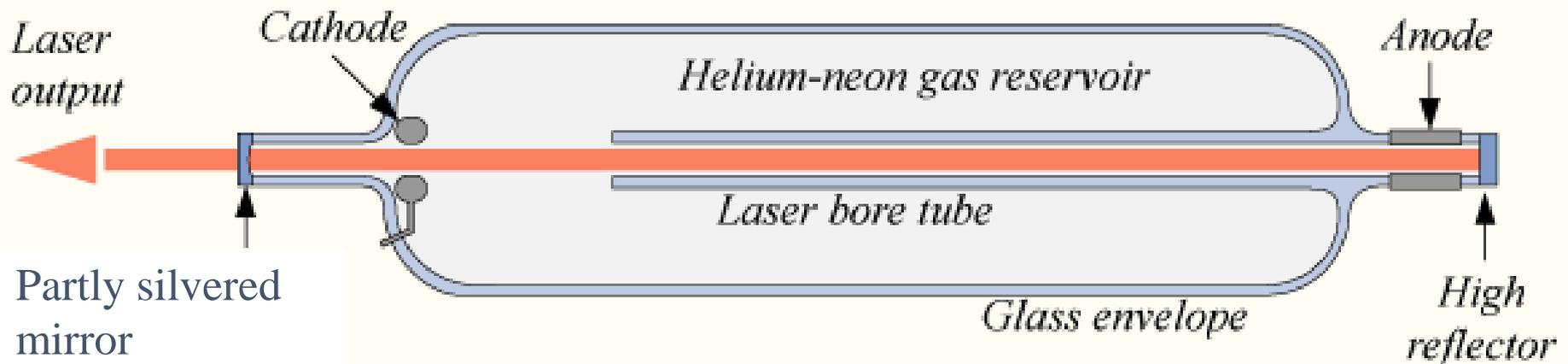
He-Ne laser



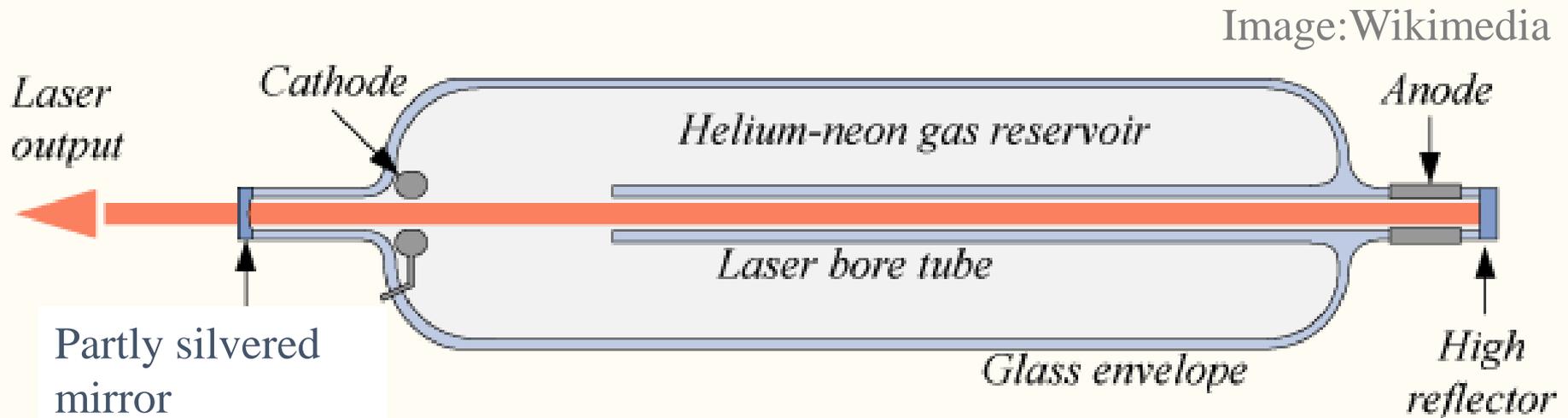
- Low pressure 15% Helium: 85% Neon
- One end of the tube is a perfect mirror, the other end is partially silvered, so allows some light out

- Single photon emitted by spontaneous emission parallel to the axis of the tube
- This then produces 2 photons by stimulated emission, moving parallel.
- At each step, the number of photons doubles

Image:Wikimedia



- When the photons get to the partly silvered mirror, some are reflected back into the laser and continue to produce more photons by stimulated emission
- Some pass through the mirror and are emitted as the laser beam

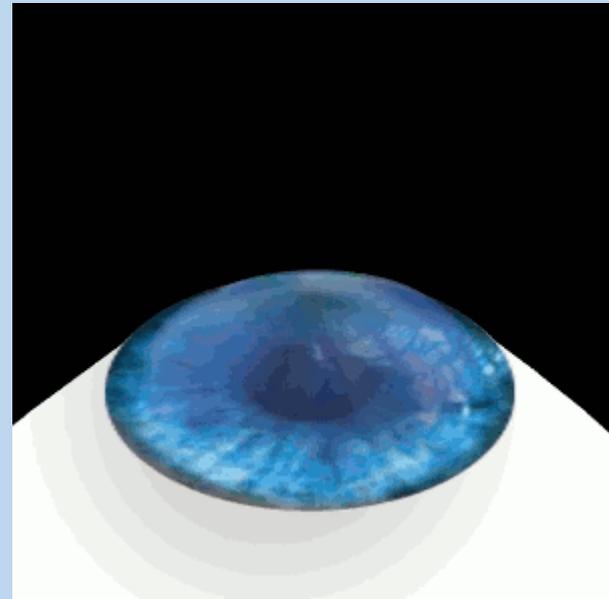


Laser Applications

- The laser produces a straight line beam
 - Surveying.
 - Laser pointers
 - Ranging
- The energy of the photons can be used
 - Cutting (by ablation) – materials, surgery
- The momentum of the photons can be used
 - Manipulation of matter (radiation pressure) using “optical tweezers”

LASIK Eye Surgery

- Create a flap in the cornea surface using laser pulses
- Open the flap
- Use laser pulses to reshape the corneal material
- Close the flap



- To do this requires very short, precise pulses of photons
- Half of the 2018 Nobel Prize in Physics went to Gérard Mourou and Donna Strickland for their work on [chirped-pulse amplification](#)



Distance to the Moon



- Apollo 11,14 and 15 left reflector mirrors on the moon.
- By firing an earth based laser to reflect from these mirrors and measuring the round trip time of the photons, the distance to the moon can be determined

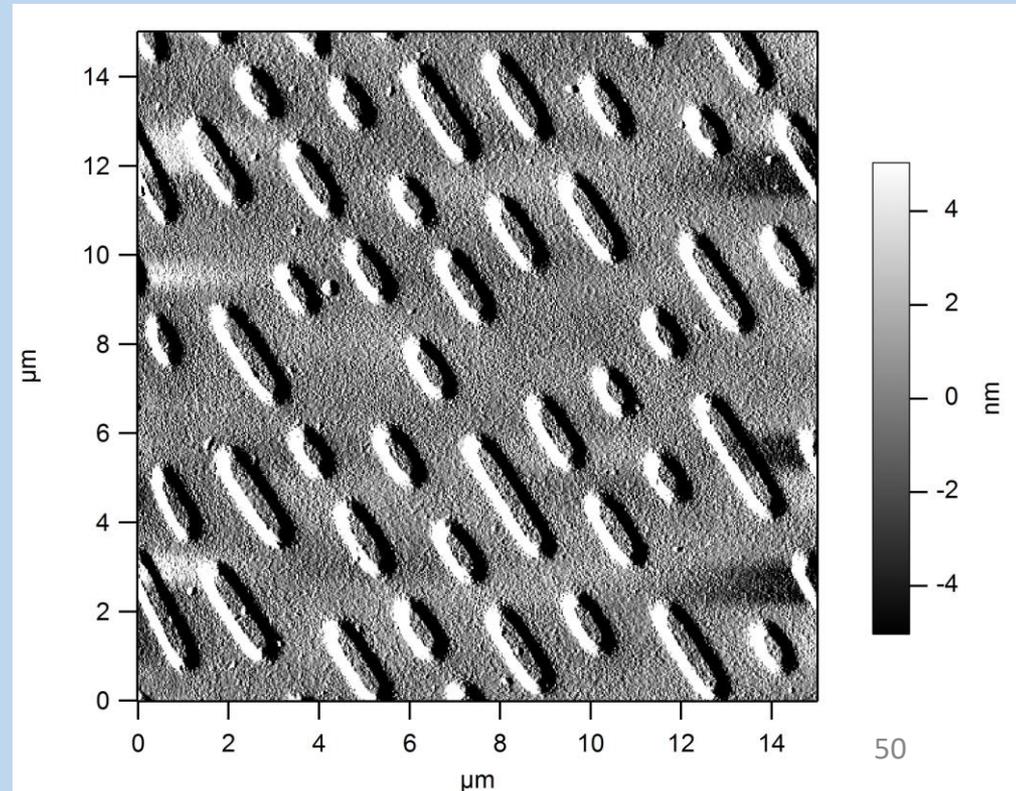
- There is enough dispersion of the beam that it is about 7 km in diameter when it reaches the Moon and 20 km in diameter when it returns to Earth
- The distance to the Moon can be measured to an accuracy of about 3 cm
- The average distance from the Earth to the Moon is about 385,000 km.



Image: NASA

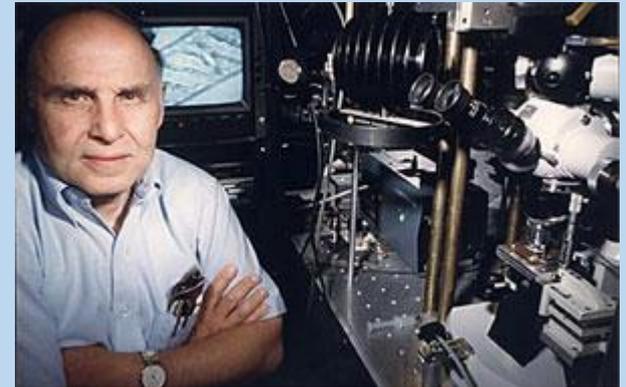
Compact Disc/DVD

- The surface of a CD/DVD is coated with Aluminium
- Laser light shines onto the surface, is reflected on the flat (constructive interference), not at the pit (destructive interference)
- The on-off response provides a digital encoding for the data



Optical Tweezers

- Arthur Ashkin was awarded half of the 2018 Nobel Prize in Physics for inventing this
- Uses the momentum of the photons to push objects around – enabling complex manipulation without physical contact



<https://www.youtube.com/watch?v=paSWFnfv1n4&feature=youtu.be>

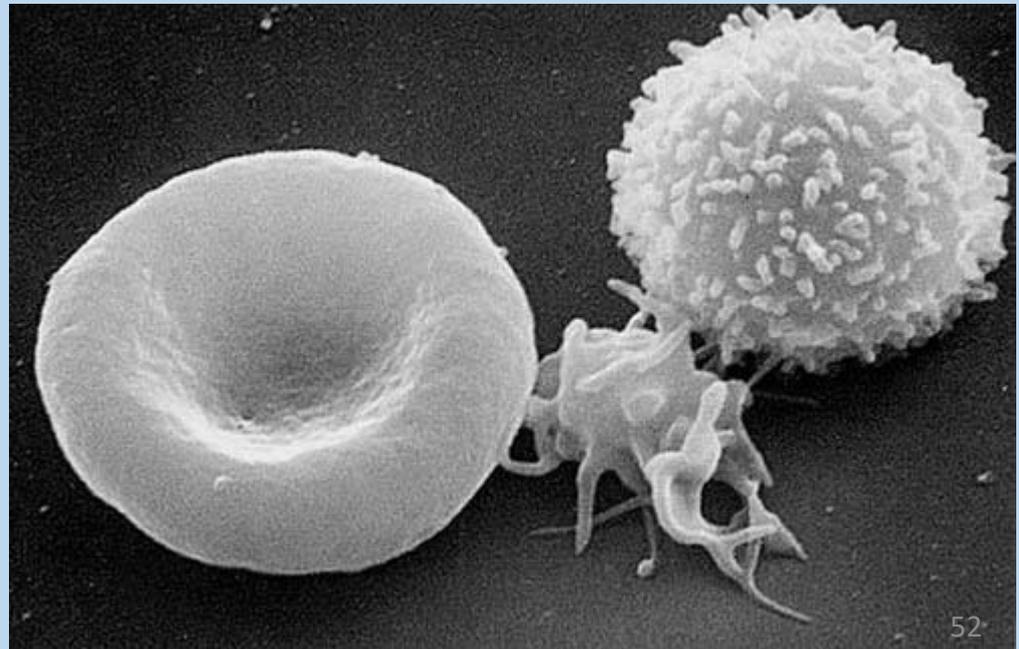
Practising with very small glass beads!

- Can be used to manipulate individual cells
- Red and white blood cells

<https://www.youtube.com/watch?v=mBE6xb0XeHM&feature=youtu.be>

White blood cell

Red blood cell



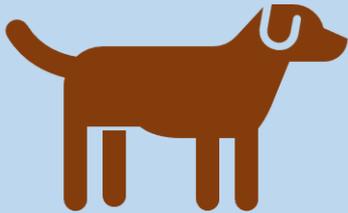
Quantum Entanglement

“Spooky Action At a Distance”

Entangled Particles

- Two quantum particles where the states are correlated
- If you measure one particle, you know what the other particle must be doing
- Even if the two particles are far apart from each other

Entangled Quantum Dogs



Asleep

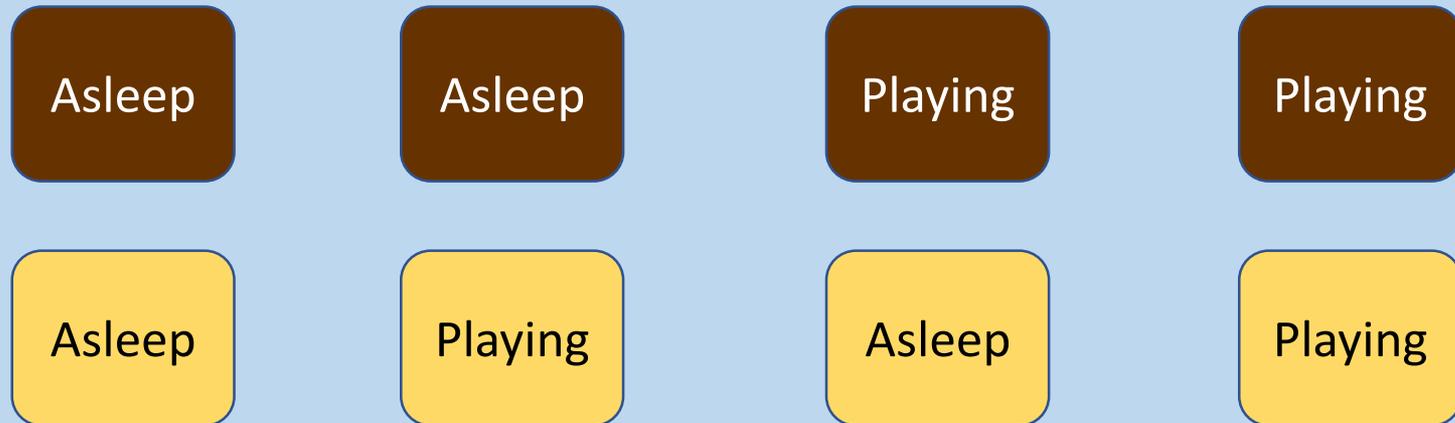
Playing

Asleep

Playing

- Each dog can be in one of two quantum states

- If the state of the puppies is completely independent then, there are 4 possible combinations



- Suppose the puppies play with each other
- The states become entangled
- They are now either both sleeping or both playing

Asleep

Playing

There are now only
two possibilities

Asleep

Playing

- If you observe one of the puppies, you can infer what the other puppy is doing without observing it directly

Asleep

Playing

Asleep

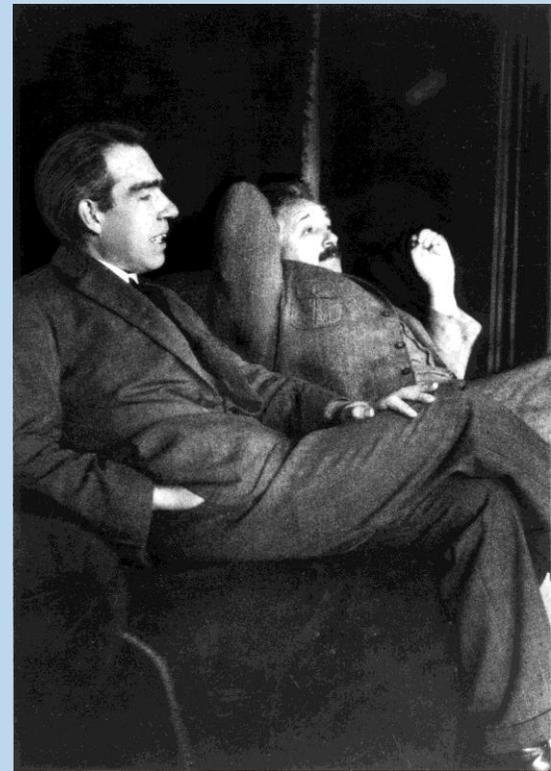
Playing

Einstein Versus Bohr

- Einstein did not like the idea of indeterminacy in quantum mechanics
- Proposed many thought experiments to try to “break” the Uncertainty Principle
- Bohr then produced an argument to refute the thought experiment

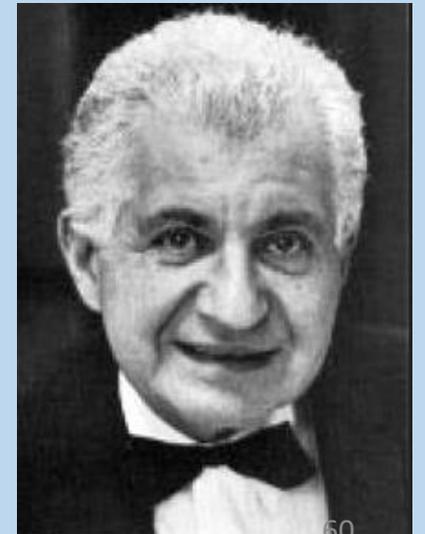
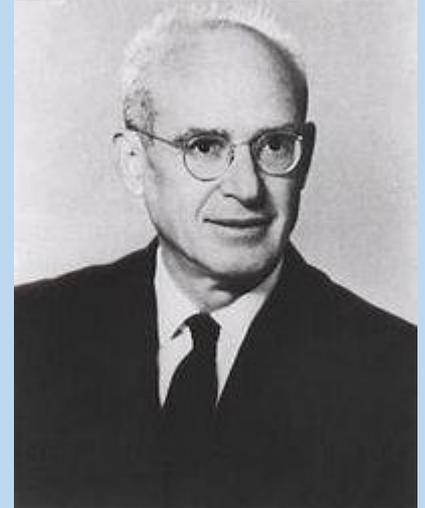
"I, at any rate, am convinced that [God] does not throw dice"
[*Jedenfalls bin ich überzeugt, daß der nicht würfelt.*]

Albert Einstein, Letter to Max Born



Einstein-Podolsky-Rosen Paradox

- Often called the EPR-Paradox
- In the 1935, Einstein, with Boris Podolsky and Nathan Rosen suggested that Quantum Mechanics was incomplete
- Information to determine the absolute state of any particle must be available, but cannot be described by the existing quantum mechanics



Alice and Bob Problems

- Traditionally the particles are Alice (A) and Bob (B)



If you measure the state of A



EPR Theory says you must be able to predict exactly what state B is
This breaks the Uncertainty Principle

Alice



Bob

Graham

Katie

Local Variables

- A local variable problem means that if A and B are a distance apart, information about the state of A can only move at or less than the speed of light to get to B



If you measure the state of A

EPR Theory says you must be able to predict exactly what state B is

Non-Local System

- Bohr could not find a classical argument to beat the EPR paradox
- There isn't one!
- Quantum Mechanics is a Non-Local System



State of A is unknown until measured

Once measured, A is in a known state, and perturbs the state of B, even though B has not been observed itself

- The EPR paper did not mention “Entanglement” itself, this term was coined by Schrödinger as “*Verschränkung*”

Verschränkung *Ver•schrän•kung* f , -, -en **Collins**

a (=das *Verschränktsein*) **fold**

b (=das *Verschränken*) **crossing over**

[+von Armen] **folding**

[+von Beinen] **crossing**

[+von Händen] **clasp**

Translation German - English Collins Dictionary

Einstein referred to the entanglement as
“*spukhafte Fernwirkung*”
“*Spooky action at a distance*”

Local Hidden Variable Problem

- The model that Einstein, Podolsky and Rosen proposed is called a **Local Hidden Variable** problem
- The experimenter is not aware of all the variables, but they do affect the results

- Local means that action at a distance can only take place at the speed of light or less (It takes time for the measurements to affect things at a distance)

Bell's Theorem

- The British Physicist John Bell produced a mathematical theorem which could be tested experimentally
- It predicted what results must happen IF the Einstein-Podolsky-Rosen model was correct.
- Bell shared Einstein's misgivings about the probabilistic nature of quantum mechanics



John Stewart Bell
1928-1990

Bertlmann's Socks

- Bell used the fact that his friend and colleague Reinhold Bertlmann used to always wear odd socks to illustrate quantum entanglement

Les Implications Conceptuelles de la Physique Quantique

J. Phys. Colloques 42 (1981) C2-41-C2-62

DOI: 10.1051/jphyscol:1981202

BERTLMANN'S SOCKS AND THE NATURE OF REALITY

J.S. Bell

CERN, CH-1211, Geneve 23, Suisse



How Do You Create Entangled Particles?

- Most of the experiments are done with photons, because it is relatively easy to produce pairs of entangled photons
- It is also possible to entangle atoms together
- All processes are local – either the atoms OR the photons produced have to be close together

<https://www.forbes.com/sites/chadorzel/2017/02/28/how-do-you-create-quantum-entanglement/#6a7fc5bf1732>

Entanglement From Birth

- Calcium ions in an excited state.
- They can't decay by emitting a single photon
- They have to emit two photons (one green, one violet)

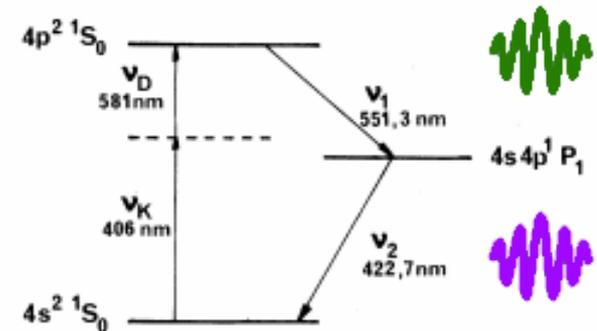


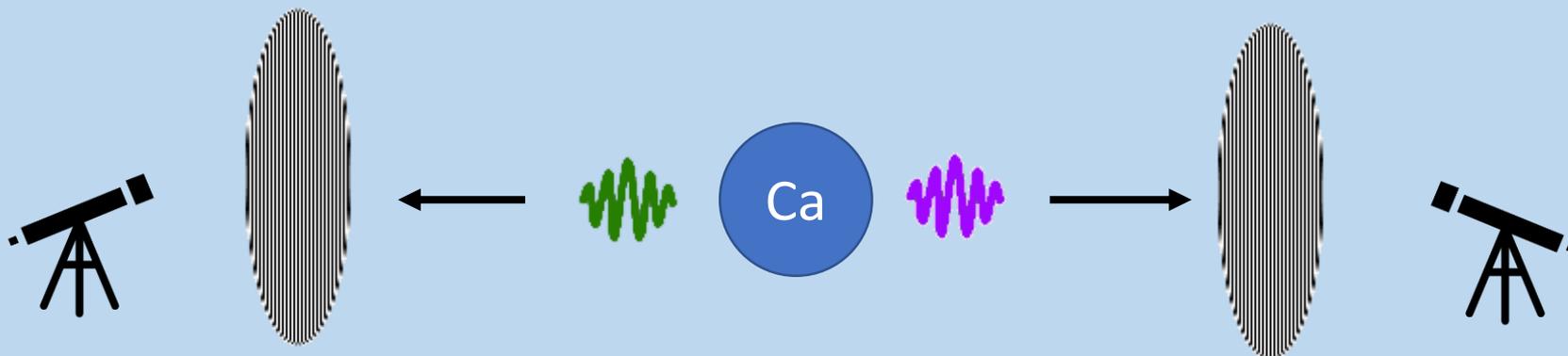
FIG. 1. Relevant levels of calcium. The atoms, selectively pumped to the upper level by the nonlinear absorption of ν_K and ν_D , emits the photons ν_1 and ν_2 correlated in polarization.

Experimental Tests of Realistic Local Theories via Bell's Theorem

Alain Aspect, Philippe Grangier, and Gérard Roger
Institut d'Optique Théorique et Appliquée, Université Paris-Sud, F-91406 Orsay, France

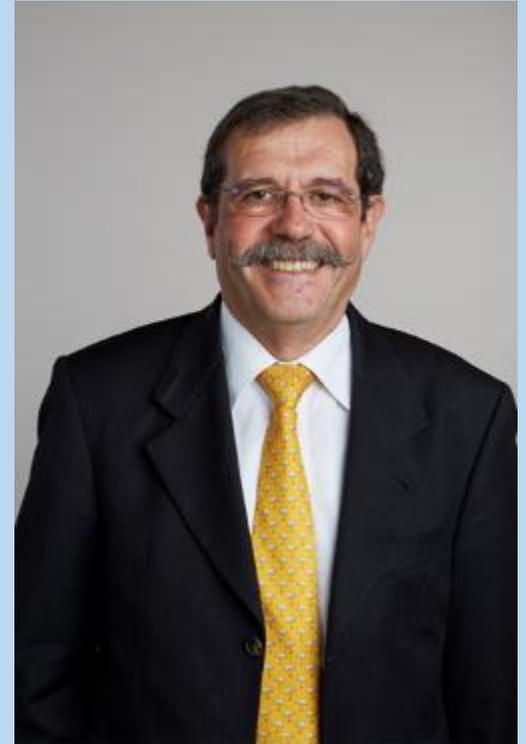
(Received 30 March 1981)

- The two photons are emitted in random directions
- If the second photons is emitted in **exactly** the opposite direction, it has to be emitted with opposite polarization to the first
- This is the “entanglement”
- This is obviously low yield because most of the photon pairs aren’t in exactly opposite directions



The Aspect Experiments

- Aspect's team did three crucial experiments measuring the correlation of entangled states
- They concluded (convincingly) that the Local Hidden Variable model was wrong
- EPR was wrong!
- “Spooky action at a distance does occur”



Alain Aspect (France) (1947-)