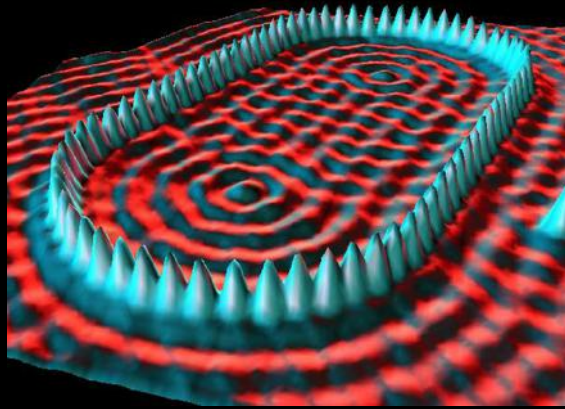


Quantum Theory



Down the Rabbit Hole...

“Curiouser and curiouser!”

- Alice in Wonderland

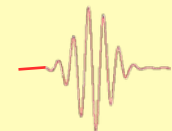
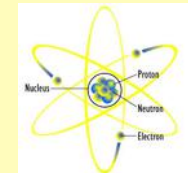
- **Newton**: given initial conditions *and* enough info, physics can *completely describe what will occur*
- *common sense* tells us that “*certainty*” exists
- *if* do NOT have enough info *then* use **probability**
(eg) predicting the weather, flipping a coin
- how do (subatomic) **particles** behave?

Quantum Theory

- in *subatomic* world, **probability** is *unavoidable*
 - **Planck, Bohr** (1900,1913)
 - **Schrodinger, Heisenberg** (1920s)
 - **Einstein** disliked **QT**'s *probabilistic description*
- A. Einstein (1926): “God does not play dice...”*

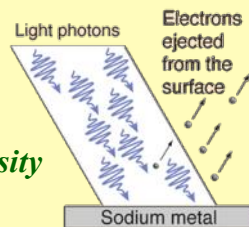
Probability Waves

- *classical physics* treats **particles** as “*points*”
- *actually behave as probability waves*
- **probability wave function** $\psi(x,t)$ is related to the *chance* of finding a **particle** at specific *position* x & *time* t
(eg) particles are really just highly localized **wave “packets”**
- **particles, waves**: different aspects of *same* thing



Photoelectric Effect

- **light** shining on a **metal surface** “**ejects**” **electrons**
- if **light is a wave**: **electron energy depends only on intensity**

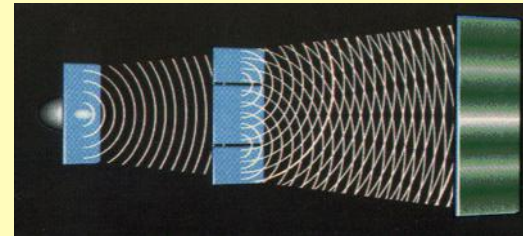


...BUT...

- light **intensity** \neq **electron energy**
- **red light** \Rightarrow **no** electrons!
- even **weak violet light** \Rightarrow **fast** electrons!
- **Einstein** proposed “**quanta**” of light: **photons** (eg) **photons** are “**particles**” of EM energy

Wave-Particle Duality

- **light** also shows **wave properties**: **interference**



Demo: laser and **interference pattern**

- **wave behaviour** leads to **interference pattern**
- **photoelectric effect** shows **light** (a “**wave**”) can behave like **particles** (“**photons**”)

Q: What if we shoot **particles** at **slits** instead?

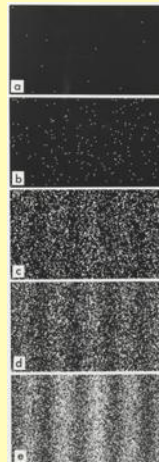
- firing **particles** at **double slit** also causes an **interference pattern**!

Q: Are they bouncing off each other?

- **same result** shooting **single particles**!

- **particles** can behave like **waves**
- **waves** can behave like **particles**
- $\psi(x,t)$ describes **subatomic reality**

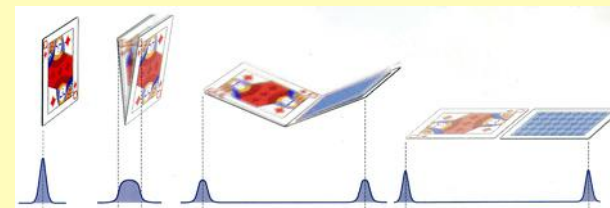
DVD: Dr. Quantum



Observation

- **probability wave functions** contain **all** possible outcomes - **there is no** definitive **state** or **reality**!

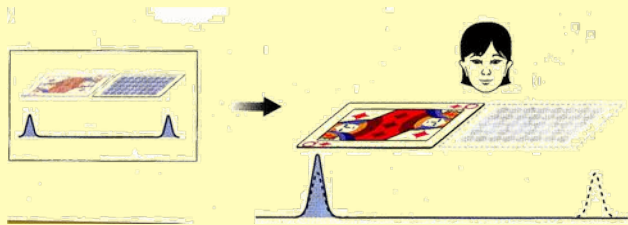
(eg) **Probability wave function** of a falling card



- **if** both “**states**” equally valid... **which is real**?

Copenhagen Interpretation

- **observation** causes **wave function** to “collapse” from a **superposition of states** to a **single reality**



(eg) implies **reality does not exist until we “look”**

Schrödinger's Cat

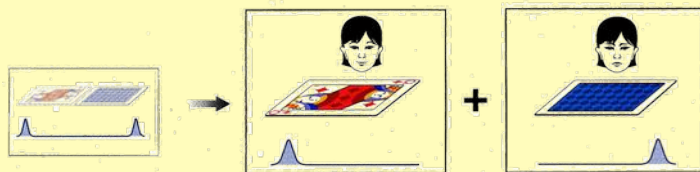


(eg) a cat, poison gas, geiger counter, some uranium & quantum theory = reality???

- **superposition of states**: using the **Copenhagen Interpretation**, the cat is both **alive & dead until we look!**

Many Worlds Interpretation

Q: Roll a die & get a 3. But chance of 1, 2, 4, 5, 6 **equally likely**; those results **should be just as real**

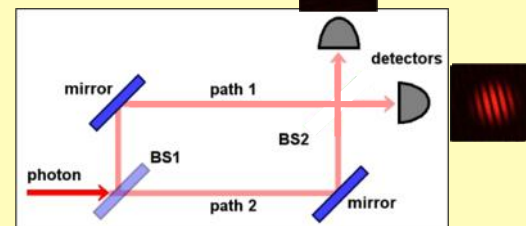


- **each possible outcome** exists in its **own reality**

Delayed Choice & Time

Q: Are past, present, and future truly separate?

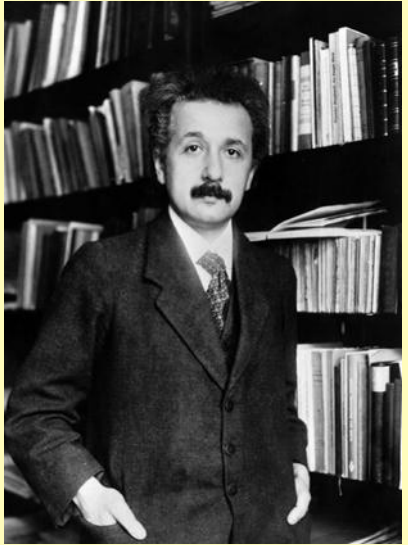
- **QT** questions this



ie. observing photon **long after** it is “split” **affects photon's behaviour back when** the “split” occurred!

"...the distinction between past, present and future is only a stubbornly persistent illusion."

- A. Einstein



CLICKER: Which of the following is correct?

- (a) probability is at the core of quantum mechanics
- (b) multiple, parallel universes do really exist
- (c) time runs from past to present to future
- (d) only certain particles behave like waves

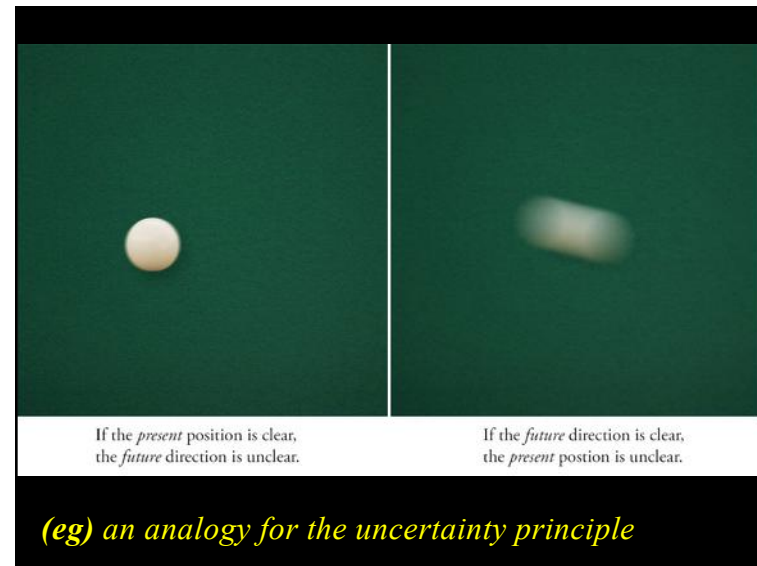
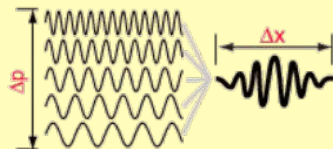
Uncertainty Principle

• **classical physics:** with good enough instruments & technique, anything *can be perfectly determined*

• **quantum:** **uncertainty** is **unavoidable**; knowing some aspects well *means* knowing others poorly

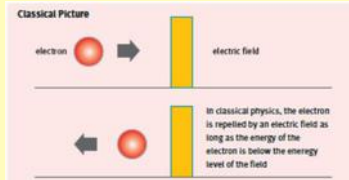
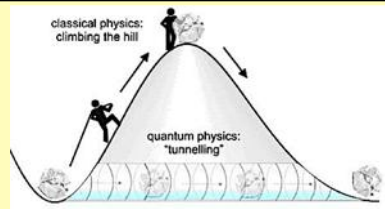
(eg) if **speed** well known, **position** poorly known

$\psi(x, t)$
Precisely determined momentum

A single, continuous wave packet moving to the right. The wave has a constant wavelength and amplitude, representing a state of precisely determined momentum.

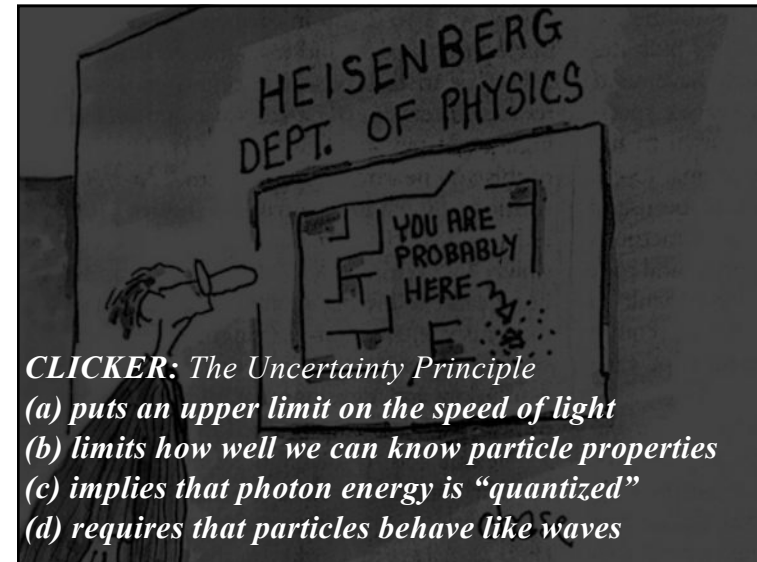
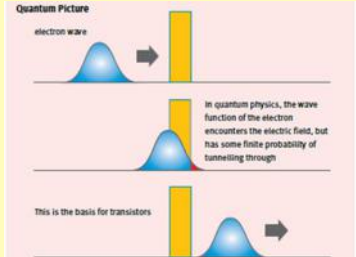
(eg) UP makes events possible... even when common sense says they should not occur

- quantum tunneling



- real effect which makes fusion easier in stars

- limits useful minimum size in computer chips



Standard Model

- Democritus (400 BCE) proposed "atoms"
- atoms *not* "fundamental"
- electron "discovered" 1897
- proton "discovered" 1919
- neutron "discovered" 1932
- 1960's: dozens of particles were known – fundamental?
- standard model accounts for particles but incomplete; e.g. gravity?

	Leptons		Quarks	
I	e^- Electron	ν_e Electron neutrino	d Down quark	u Up quark
II	μ^- Muon	ν_μ Muon neutrino	s Strange quark	c Charm quark
III	τ^- Tau particle	ν_τ Tau neutrino	b Bottom quark	t Top quark
Force carriers	W W boson	Z Z boson	g Gluon	γ Photon

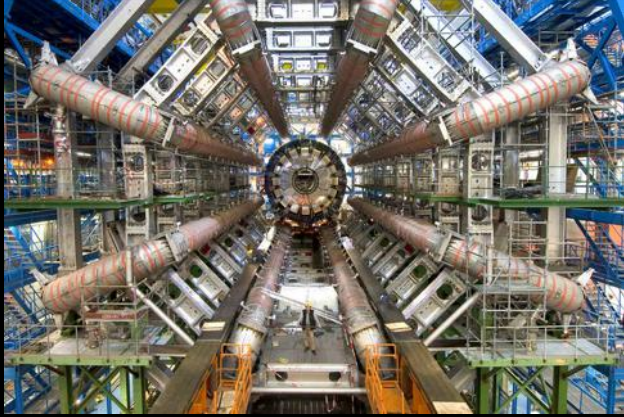
Atom Smashing

Q: How do we learn about all of these particles?

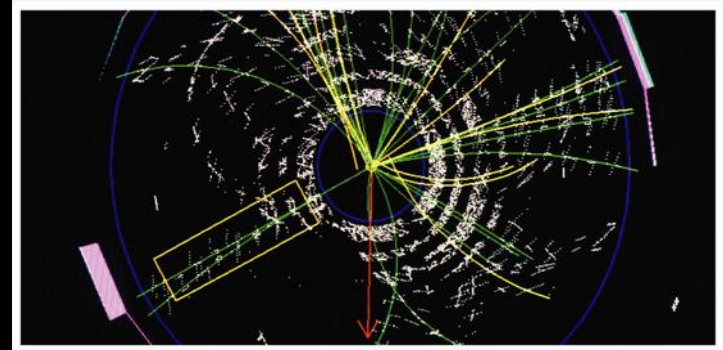
- particle accelerators generate high particle energies so "interesting things" can occur

- CERN/LHC produces energies of TeV (10^{12} eV)
- highly focused, like shortly after Big Bang

(eg) higher, more concentrated than average atom energies (\sim eV), but total energy less than flying bug



- Illinois' Fermilab *particle accelerator* (C ~ 6 km)
- CERN's *LHC* is larger (C ~ 27 km)



- particle trails following a collision event

(Super)String “Theory”

- a “*simple*”, *elegant view* of our universe
- *fundamental building blocks* of *all* particles are tiny, vibrating “*strings*” or “*loops*” of energy



- *good*: *SST* could *unify GR* and *Quantum*
- *bad*: requires *11 dimensions* (“*M-Theory*”)
- *Is it right?* So far, *no* concrete tests...

Q: "Is it physics or philosophy?"



Review: Quantum

- *different rules* apply in the “*world of the small*”
- *quantum world* inherently *probabilistic*
- *particle-wave duality* is a reality, (*eg photons*)
- *Uncertainty Principle* limits ability to “*know*”
- *Standard Model* very successful but complex
- *quantum* & *relativity* don't “*mesh*” - *other ideas?*