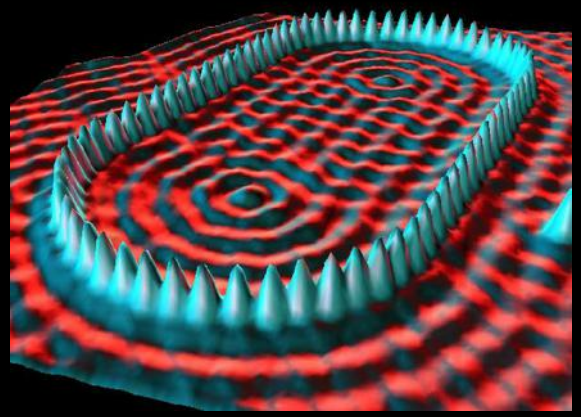
Quantum Theory



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*** we do NOT have enough info: use ***probability***

(eg) *predicting the weather, flipping a coin*

- how do (subatomic) ***particles*** behave?

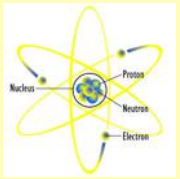
Quantum Theory

- 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…*"

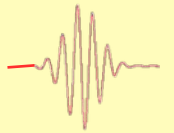
Probability Waves

- *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***

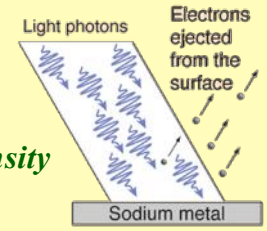
(eg) particles are really just highly localized ***wave "packets"***



- *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*** ≠ ***electron energy***

• ***red light*** ⇒ ***no*** electrons!

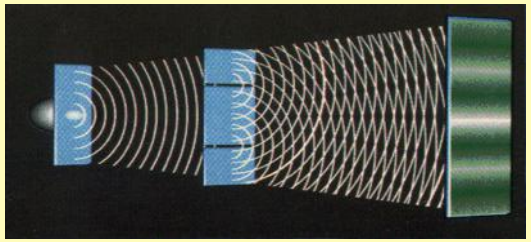
• *even* ***weak violet light*** ⇒ ***fast*** electrons!

• ***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?*

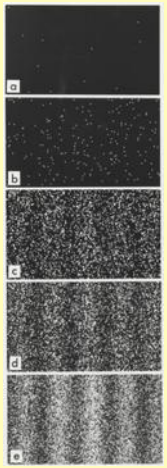
• ***same result*** shooting ***single particles!***

• ***particles*** **can** behave like ***waves***

• ***waves*** **can** behave like ***particles***

• ***ψ(x,t)*** describes ***subatomic reality***

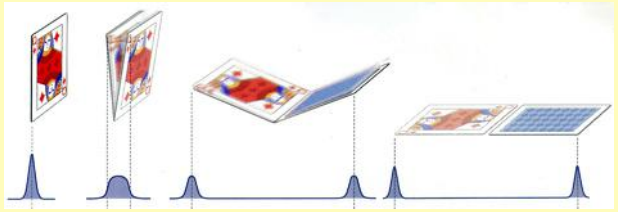
DVD: Dr. Quantum



Observation

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

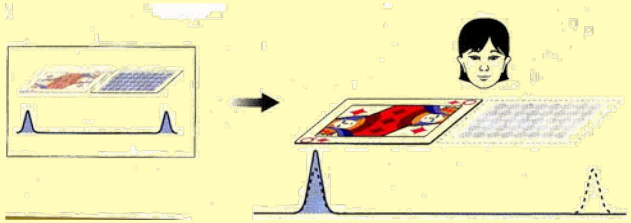
(eg) Probability wave function of a falling card



• ***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"***

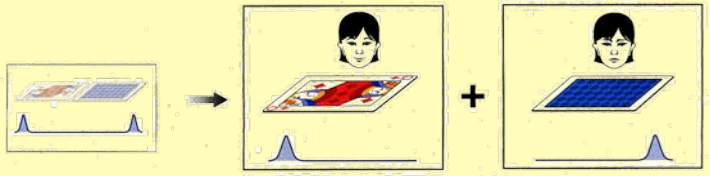
Schrödinger's Cat

(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***

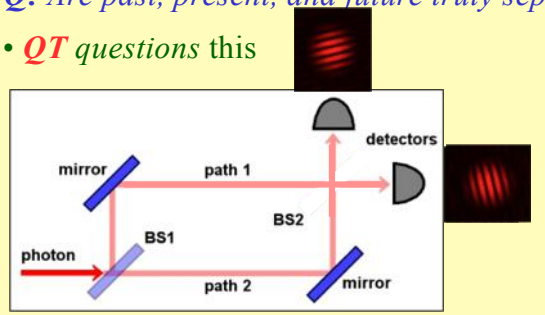


• **each** *possible outcome* exists in its ***own reality***

Delayed Choice & Time

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

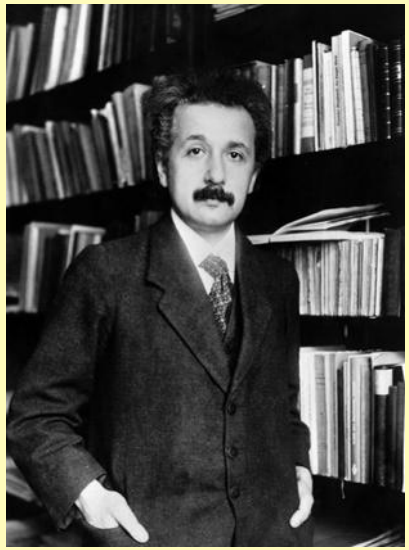
• ***QT*** *questions* this



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



Uncertainty Principle

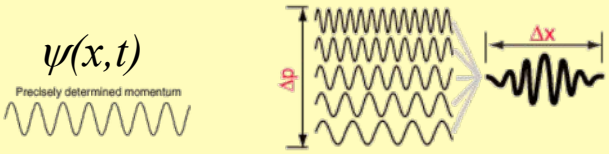
• ***classical physics***: with good enough instruments ***&*** technique, anything ***can be perfectly determined***

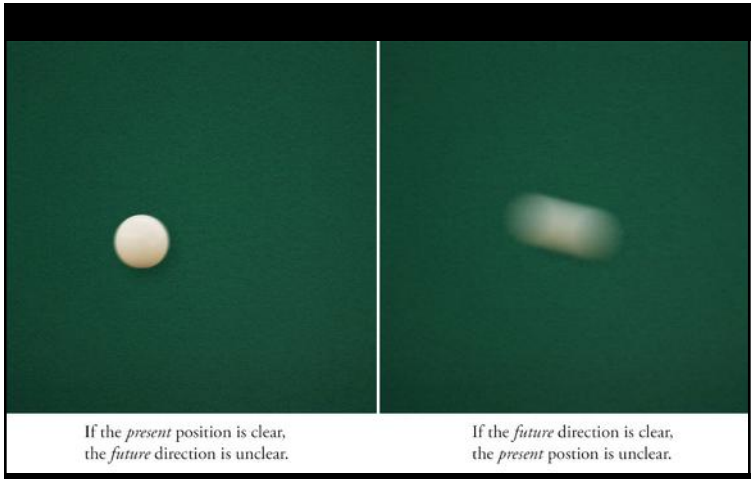
• ***quantum***: ***uncertainty*** *is* ***unavoidable;*** knowing some aspects well ***means*** knowing others poorly

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

$\psi(x,t)$

Precisely determined momentum

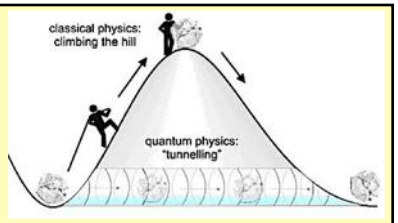


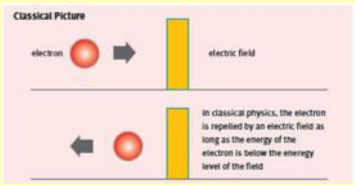


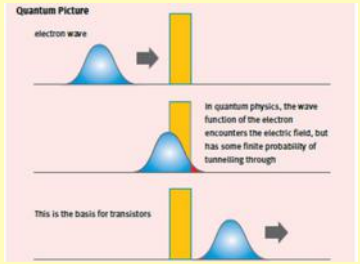
(eg) *an analogy for the uncertainty principle*

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

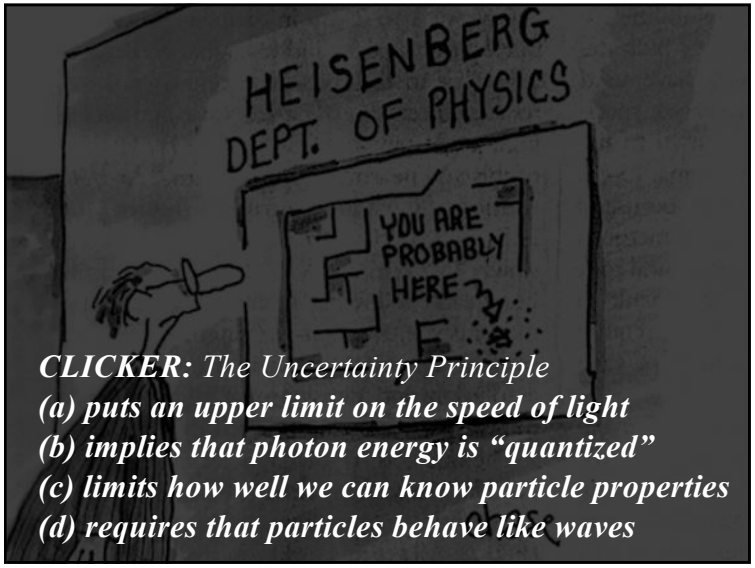
- *quantum tunneling*







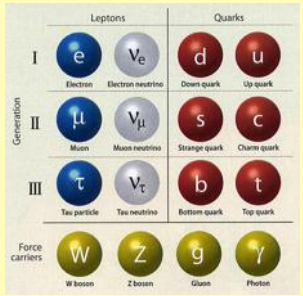
- ***real effect*** which makes ***fusion*** *easier* in stars
- limits *useful minimum size* in ***computer chips***



CLICKER: *The Uncertainty Principle*
(a) puts an upper limit on the speed of light
(b) implies that photon energy is "quantized"
(c) limits how well we can know particle properties
(d) requires that particles behave like waves

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?***



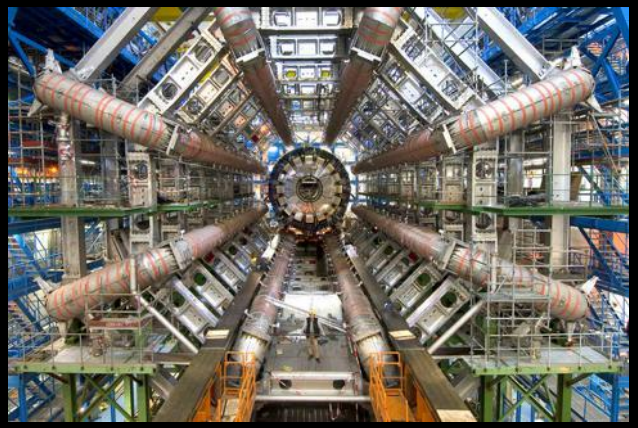
Atom Smashing

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

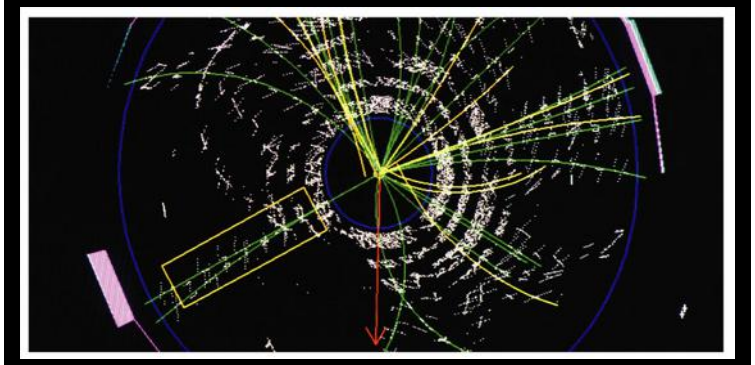
- ***particle accelerators*** generate high particle energies so "*interesting things*" can occur

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

(eg) *higher, more concentrated* than average atom energies (~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

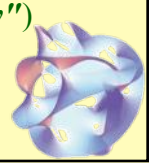
• *fundamental building blocks* of ***all*** particles are tiny, vibrating "***strings***" or "***loops***" of energy


• ***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?***