Predictions of Special Relativity

- The speed of the light is the same value for all non-accelerating observers implies
- Moving clocks run slowly implies
- Object lengths are contracted along their direction of motion implies
- Two events that are simultaneous for an observer may not be simultaneous for another observer.

More Predictions

- The speed of the light is the same value for all non-accelerating observers implies
- Speeds do not add according to our common sense implies
- Mass increases with speed implies
- $E = mc^2$

Pair Production

- Antimatter particle
  - Same as particle but opposite charge
- Produced in pairs with the particle
  - Energy supplied by a "photon" according to $E = mc^2$
- Eventually collides with a regular particle, annihilating both

General Theory of Relativity

- Equivalence Principle (aka Principle of General Relativity): accelerating observers are equivalent to gravitational fields
- There is no force due to gravity:
  - Masses distort the geometry of spacetime
  - Everything moves in "straight lines" in this non-flat geometry

Standard Hot Big Bang Model of Cosmology

- Universe created in a “Big Bang” some 14 billion years ago
  - Has been expanding since
- Question: will the expansion stop and reverse?
- Problems:
  - Dark matter and dark energy
  - The rate of expansion is increasing
  - and more …

Chaos

- Sensitive Dependence on Initial Conditions (“Butterfly Effect”)
- Trajectory never repeats
- Transition to chaos preceded by infinite bifurcations
  - Characterised by the “Feigenbaum number”
- Non-integer dimensions (“fractal”)

Order From Disorder

- Requires a system that is open
  - Example: Vivarium
- Depends critically on the “rule set”
  - Cellular Automata
- Energy sources on Earth

Conductors e.g. Metals

- Some electrons not tightly bound to the conductor
- Can leave the metal by acquiring some energy
- Energy can be supplied by:
  - Heat (“thermionic emission”)
  - Light (“photoelectric effect”)

Photoelectric Effect

- Light must have a minimum frequency
- Energy of photoelectrons proportional to the light frequency
- To explain:
  - Light is a particle ("photon")
  - Energy of photon = h x frequency of wave
    - h is very very small
- "Wave Particle duality"

Double Slit Experiment (photons or electrons)

- Interference pattern
  - Even for 1 particle at a time
  - When we don't look to see what is happening at the slits
- When we look at the slits:
  - Each particle goes through the upper or the lower slit
  - The measurement destroys the interference pattern
- Heisenberg: "The path comes into existence only when we observe it."

First Interpretation of Quantum Theory

- "Wave Function" aka "State Vector" aka "Psi Field" aka Ψ
  - Born (1930): a wave of probability
- Einstein: "God does not play dice with the universe"
- Bohr: "Quit telling God what to do!"
- Heisenberg: "The wave function represents partly a fact, and partly our knowledge of the fact."

- Line spectra for pure elements
  - Identifies the element
  - Hydrogen appears to have some regularity
- Standing Waves
  - Waves that "fit"
    - Strings
    - Drum Heads
  - Quantised

- Bohr Model for Hydrogen
  - "Allowed Orbits" characterised by an integer **n**
  - Absorbs a photon and "quantum jumps" to a higher energy higher **n** orbital
  - When in a higher energy orbital "quantum jumps" to a lower energy one, emitting a photon.
  - Totally ad hoc

de Broglie (1923)

- Electrons have a wave aspect
  - i.e. The Double Slit Experiment for electrons
- Explains Bohr Model
- Basis for Quantum Theory

Uncertainty (Indeterminacy) Principle

- Follows from de Broglie's idea
- Explains the Double Slit Experiments
- $\Delta E\ \Delta t$ also a minimum value
  - Conservation of Energy can be briefly violated
  - "Virtual Pair Production"

Bohr's Interpretations of Quantum Theory

- Complementarity
  - Opposites are complements
- Copenhagen Interpretation
  - Built on Complementarity
  - Separation of observer and observed arbitrary
    - Wheeler: no "observers" only "participators"
  - "There is no quantum world"

Electron "Spin"

- Only two states: "up" and "down"
- Beam from electron gun half up and half down
  - Which is the case for a particular electron is random
- Direction for "up" defined by the apparatus that does the measurement
- Measurement destroys any previous definition of up

Correlation Experiments

- Twins separated at birth
  - Choice of profession
  - Taste in music
- Electron pairs with total spin zero
  - If one up, the other down, and vice versa
  - Pairs are "entangled"
- Is there "local causality"?

Radioactive Decay

- Three types: Alpha, Beta, Gamma
- Half-life
- Decay of a single radioactive atom
  - Schrödinger's Cat
  - Is there a "hidden variable" influencing when the atom decays?
  - Is there a similar hidden variable influencing an electron's spin?

Bell's Theorem

- Einstein-Podolsky-Rosen (1935) → Bohm (1950's) → Bell (1964)
- Assume local hidden variables
  - Derive a result for correlations of entangled electron pairs that is wrong
  - Either there are no hidden variables or they are not local
    - "Holographic" universe?
  - Quantum Theory predicts the observed correlations

Types of Interactions

- Gravity
  - Newton
  - Einstein
- Electric
- Magnetic
  - Unified into "Electromagnetic" in 19th century
- Weak
  - Radioactive Decay
- Strong
  - Holds nucleus together

Describing Interactions

- Two Complementary Descriptions
  1. Fields
  2. Particle Exchange
- "Quantum Field Theory"
- Simplest electromagnetic interaction: an electron and a photon scatter

Antimatter Redux

- Feynman (1949): a positron is an electron going backwards in time
- Pair production and annihilation are just an extreme form of electromagnetic scattering
- Speculation: There is only one electron in the universe!
- Speculation: protons and neutrons are made of each other
  - There are no "elementary particles"

Elementary Particles

- Photon
- Electron
- Proton
- Neutron

Plus their antimatter pairs

Neutrino

- Introduced to conserve energy in radioactive decays
- Only interact via Weak and Gravitation
- Zero charge
- Very small but non-zero mass

Elementary Particles

- Photon
- Electron
- Proton
- Neutron
- Neutrino

Plus their antimatter pairs

Exchange Particles

- Electromagnetic – Photons
- Weak – W, Z

Elementary Particles

- Photon
- Electron
- Proton
- Neutron
- Neutrino
- W, Z

Plus their antimatter pairs

Exchange Particles

- Electromagnetic – Photons
- Weak – W, Z
- Strong – “Mesons”
  - Protons and Neutrons in nucleus exchange mesons

Elementary Particles

- Photon
- Electron
- Proton
- Neutron
- Neutrino
- W, Z
- Mesons

Plus their antimatter pairs

Exchange Particles

- Electromagnetic – Photons
- Weak – W, Z
- Strong – “Mesons”
  - Protons and Neutrons in nucleus exchange mesons
- Gravitation – “Graviton”
  - A Quantum Field Theory involving graviton exchange does not exist

Elementary Particles

- Photon
- Electron
- Proton
- Neutron
- Neutrino
- W, Z
- Mesons
- Graviton?

Plus their antimatter pairs

Elementary Particles

- Photon
- Electron
- ~~Proton~~
- ~~Neutron~~ Quarks
- Neutrino
- W, Z
- ~~Mesons~~ Quarks
- Graviton?
- Gluon

Plus their antimatter pairs

String Theory

- There is no such thing as String Theory (yet)
- Replaces “elementary particles” with strings
  - Vibrate with standing waves
  - 11 dimensions or more
  - Size ~ the size of the “quantum foam” of virtual pair production