Particle Interactions

Heisenberg Uncertainty Principle

- According to Heisenberg, measurements of the energy of a particle or of an energy level are subject to an uncertainty
- This uncertainty is not the result of random or systematic errors but result because of a law of nature
- The very process of measurement necessarily creates an uncertainty in the quantities being measured

- There is, however, a subtler and (for our purposes) more useful, interpretation of the energy-time Heisenberg uncertainty principle
- We know that total energy is always conserved
- Suppose that in a certain process energy conservation is violated
- For example, assume that in a certain collision the total energy after the collision is larger than the energy before the collision by an amount ΔE

- The Heisenberg uncertainty principle claims that this is in fact possible!!!
  - Provided the process does not last longer than a time interval given by

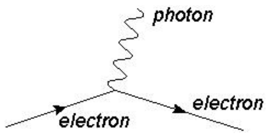
$$\Delta t \approx \frac{h}{4\pi\Delta E}$$

- In other words, energy conservation can be violated provided the time it takes for that to happen is not too long

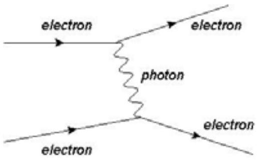
Virtual Particles

- Let us consider the possibility of a free electron emitting a photon
- This process actually violates the law of conservation of energy
- It cannot take place unless the photon that is emitted is very quickly absorbed by something else so that the energy violation (and the photon) becomes undetectable

- Because this photon violates energy conservation, it is called a virtual photon
- This process is impossible according to classical physics but is possible within quantum theory
- This process is represented by the following diagram (called a Feynman diagram)



- Consider the following diagram:



- Because the first electron emitted a photon, it changed direction a bit to conserve momentum
- Similarly, the second electron also changed direction, since it absorbed a photon

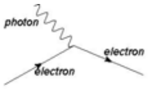
- Looked at from a large distance away, the change in direction of the two electrons can be interpreted as the result of a force or interactions between the two electrons
  - Repelling forces due to Coulomb's law
- The particle physics view is that Coulomb's law (electromagnetic force) is the exchange of a virtual photon between the electrons
  - The exchanged photon is not observable

Basic Interactions

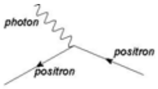
Interaction	**Interaction acts on**	**Exchange particle(s)**	**Relative strength**
Electromagnetic	Particles with electric charge	Photon	137^{-1}
Weak	Quarks and leptons only	W and Z bosons	10^{-6}
Strong (color)	Quarks only	Gluons	1
Gravitational	Particles with mass	Graviton	10^{-38}

- Since the early 1970s the electromagnetic and weak nuclear interactions have been shown to be two faces of the same interaction
  - – Electroweak interaction
- So there are really three fundamental interactions:
  - – The electroweak interaction
  - – The strong (color) interaction
  - – The gravitational interaction

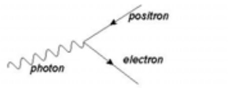
Some Interaction Vertices



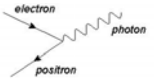
An electron absorbs a photon



A positron absorbs a photon



A photon materializes into an electron-positron pai



An electron and positron collide

Feynman Diagrams

- Feynman diagrams can be used to calculate the probability of a process actually taking place
- The vertices in the diagram represent a definite mathematical expression called the *amplitude* of the process
- The square of the amplitude gives the probability of the process actually taking place

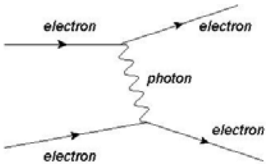
- A value called the *strength of the interaction* is applied to each vertex
- For the electromagnetic interaction, the basic vertex is assigned the value

$$\sqrt{\alpha_{EM}}$$

$$\text{where } \alpha_{EM} \approx \tfrac{1}{137}$$

- The amplitude of the diagram is the product of the values for each vertex

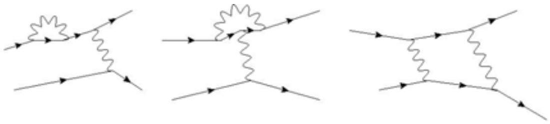
Example



- This process has two interaction vertices, so the amplitude of the diagram is proportional to

$$\sqrt{\alpha_{EM}} \times \sqrt{\alpha_{EM}} = \alpha_{EM}$$

Example



- All of these processes have four interaction vertices, so the amplitude for these is proportional to

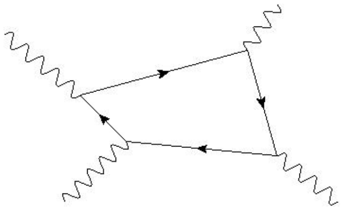
$$\sqrt{\alpha_{EM}} \times \sqrt{\alpha_{EM}} \times \sqrt{\alpha_{EM}} \times \sqrt{\alpha_{EM}} = \alpha_{EM}^2$$

Building Feynman Diagrams

- Using the basic interaction vertex for the electromagnetic interaction, we can build up complicated processes
- All we need are the following ingredients:
  - – The basic interaction vertex
  - – Lines with arrows to represent electrons and positrons
  - – Wavy lines to represent photons

Example

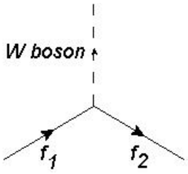
- Photon scattering off another photon

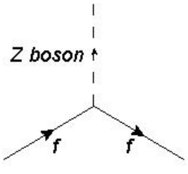


$$\text{Amplitude} = \alpha_{EM}^2$$

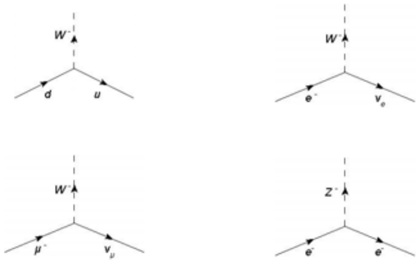
Weak Interaction

- Weak interactions involve the W and Z bosons along with two fermions

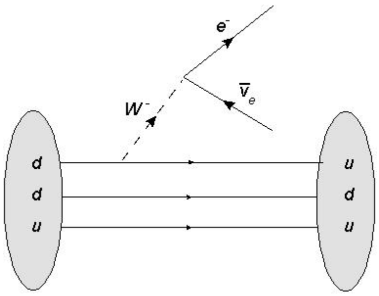




Examples

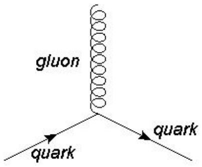


- β^- decay

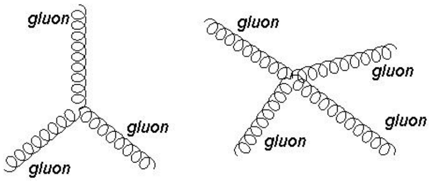


Strong (color) Interaction

- Strong (color) interaction is complex
- One vertex is similar to the electromagnetic interaction
  - Except that it involves quarks and gluons

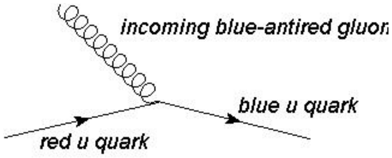


- There are also interactions that just involve gluons



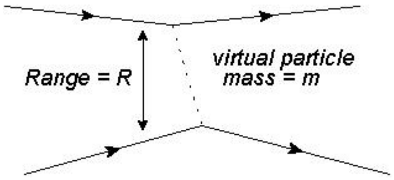
Example

- A red u quark becomes a blue u quark



Range of Interaction

- Consider the following interaction in which two particles interact by the exchange of some particle with mass *m*



- The fastest that the virtual particle can travel is the speed of light, *c*
- The time to reach the other particle will be $\frac{R}{c}$
- The energy exchanged will be mc^2
- Taking the uncertainties to be of the order of the values we have by the Heisenberg uncertainty principle

$$mc^2 \times \frac{R}{c} \approx \frac{h}{4\pi}$$

$$R \approx \frac{h}{4\pi mc}$$

- This explains why the electromagnetic force has an infinite range
  - Mass of photon is zero, therefore the range is infinite
- This also explains why the weak reaction has a short range
  - W and Z bosons have a large mass
  - W has a mass of about 80 GeVc^{-2}