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 \( \Delta E \)
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:

![Diagram showing electron and photon interaction]

• 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

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Interaction acts on</th>
<th>Exchange particle(s)</th>
<th>Relative strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>Particles with electric charge</td>
<td>Photon</td>
<td>$137^{-1}$</td>
</tr>
<tr>
<td>Weak</td>
<td>Quarks and leptons only</td>
<td>W and Z bosons</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Strong (color)</td>
<td>Quarks only</td>
<td>Gluons</td>
<td>1</td>
</tr>
<tr>
<td>Gravitational</td>
<td>Particles with mass</td>
<td>Graviton</td>
<td>$10^{-38}$</td>
</tr>
</tbody>
</table>
• 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

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

\[ \sqrt{\alpha_{EM}} \]

where \( \alpha_{EM} \approx \frac{1}{137} \)

• 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

![Diagram of photon scattering]

Amplitude $= \alpha_{EM}^2$

Weak Interaction

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

![Diagram of weak interactions]
Examples

- β\textsuperscript{−} 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
  \[
  \frac{mc^2 \times R}{c} \approx \frac{h}{4\pi}
  \]
  \[
  R \approx \frac{h}{4\pi mc}
  \]

• 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\(^2\)