# Physics 4213/5213
# Lecture 1

## 1 Introduction

There are four known forces: gravity, electricity and magnetism (E&M), the weak force, and the strong force. Each is responsible for interactions between particles which are mediated by the exchange of quantum carriers. The current situation is summarized in the table below:

| Force | Intermediate Quanta | Status now | Possible Ideas |
|---|---|---|---|
| gravity | graviton | classical | string th. |
| E&M | photon | SM (electro-weak th.) | supersym. |
| Weak | $W^{\pm}, Z^0$ | SM (electro-weak th.) | supersym. |
| Strong | 8 gluons | SM (QCD) | supersym. |

The goal of particle physics is to unify all forces in a single theory (The Theory of Everything). The Standard Model (SM) combines E&M and the weak and stong forces. Gravity has to be added as a quantum field theory. Possible ways to do this are under investigation including string theory and supersymmetry. String theory treats particles an excitations of quantum strings instead of point entities. Supersymmetry postulates the existence of a symmetry between fermions and bosons such that for every fermion there is a super-partner boson and vice versa. Only future research can determine if these ideas will be successful.

## 2 Interactions

The modern view of interactions is elegantly described by Feynman diagrams. (See Fig. 1.) The strength of the interaction (i.e. force) is proportional to the “charge” which enters at each vertex. Several types of charge exist. You are familiar with the electric charge but there is also a “color” charge for the strong interaction and a “weak” charge for the weak interaction. Intermediate quanta are exchanged between particles as indicated in the Feynman diagram. More complicated diagrams (i.e. with loops, etc.) describe the interaction at higher order in a perturbation expansion. The intermediate bosons (bosons are particles with integral spin) which carry the forces have the properties given in Table 1. All of these particles have been observed except for the graviton. The gluons are not observed as free particles but their effects can be observed indirectly.

| **Quanta** | **spin** | **mass** | **range** | **source** |
|---|---|---|---|---|
| graviton | 2 | 0 | $\infty$ | mass |
| photon | 1 | 0 | $\infty$ | elec. charge |
| $W^{\pm}, Z^0$ | 1 | 80, 91 GeV/$c^2$ | $10^{-18}m$ | weak charge |
| gluons | 1 | 0 | $\leq 10^{-15}m$ | color charge |

Table 1: Properties of the intermediate quanta.

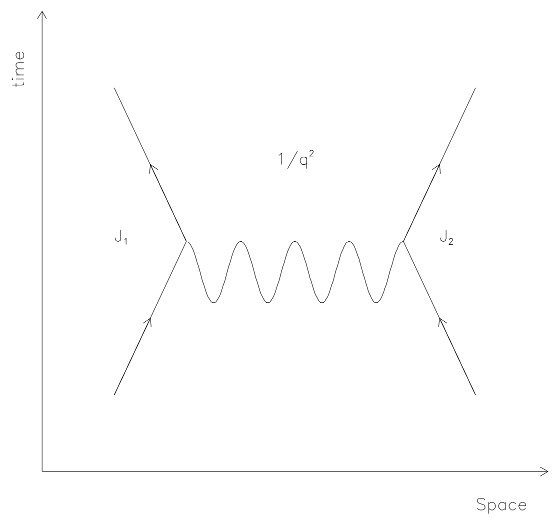


Figure 1: Feynman diagram for $e^- + e^- \to e^- + e^-$.

| **quark** | **free mass** (MeV/c$^2$) | **constituent mass** (MeV/c$^2$) |
|---:|---:|---:|
| d | 15 | 330 |
| u | 7 | 330 |
| s | 200 | 500 |
| c | 1,300 | 1,500 |
| b | 4,800 | 5,000 |
| t | 174,000 | ∼174,000 |

Table 2: Masses of the quarks.

# 3 Fermions

Fermions are particles with half-integral spin. Particles that interact under the strong force are made up of constituents called **quarks**. The fermions which do not interact strongly are called **leptons**. Quarks and leptons come in three “families” or “generations” with six different lepton “flavors” and six different quark “flavors”.

$$\begin{matrix} \begin{pmatrix} u \\ d \end{pmatrix} & \begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \\ \begin{pmatrix} c \\ s \end{pmatrix} & \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \\ \begin{pmatrix} t \\ b \end{pmatrix} & \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix} \end{matrix}. \tag{1}$$

The neutrino’s (on the bottom right) have zero electric charge and very small (if any) masses. Cosmological arguments imply that the sum of all neutrino masses is less than 100 eV/c$^2$. The quarks (on the left) are never seen as free particles because the strong (color) force becomes stronger as the quarks separate. We say that the quarks (and gluons) carry color and are confined in colorless bound states. Each flavor of quark comes in three colors; red, blue and green . These bound states interact stongly and are called “hadrons”. So now we see that matter is built up of quarks and leptons. Forces are mediated by the intermediate bosons. The strong force is described by a field theory called Quantum Chromodynamics (QCD) and is responsible for binding quarks into hadrons. The residual color force outside color neutral hadrons is the nuclear force which binds stable hadrons into nuclei. This is analogous to the electrically charged nuclei and electrons which are bound by the E&M force (QED) into atoms. The residual E&M force (mediated by photons) binds atoms into molecules.

The Standard Model predicts the existence of an as yet undiscovered particle called the Higgs which is responsible for giving all particles their mass. There are 21 parameters in the Standard Model which have to be determined by experiment and these include the lepton and quark masses. Since the quarks do not appear as free particles, it is hard to define their mass. A “free-quark” mass comes from field theory and a “constituent-quark” mass comes from the mass of bound state hadrons (see Table 2). The lepton masses are given in Table 3.

| **lepton** | **mass (MeV/c$^2$)** |
|---:|---:|
| e | 0.51 |
| $\mu$ | 105.7 |
| $\tau$ | 1777 |

Table 3: Lepton masses.

# 4 Antimatter

Each particle has an antiparticle which has opposite values of electric charge, color charge, flavor; but has the same spin and mass. For example the anti-electron is the positron, and $\overline{d_{red}}$ is the antiparticle of the $d_{red}$ quark, etc. Some neutral particles are their own antiparticle such as the photon and the $\pi^0$.

# 5 Units

Before starting on the path toward understanding particle physics, the units that will be used throughout are introduced. Since particle physics involves both relativity and quantum mechanics, the speed of light $c$ =2.998$\times 10^8$ m/s and Planck's constant $\hbar$ =1.055$\times 10^{-34}$ J-s will appear in most calculations. For simplicity these values will be taken as $\hbar = c = 1$ for all formulas and when a number needs to be calculated they will be put back in such that the units come out correct.

The units for energy are given in electron volts (eV), where 1 eV is the energy gained by an electron (or any particle with the charge of the electron) when accelerated by an electric potential of 1 V. Now keep in mind that momentum is given by $p = E/c$ and mass by $m = E/c^2$—$c$ is the speed of light. If the speed of light is set equal to one ($c = 1$), then the energy, momentum and mass are all given in the same units.

Finally the electric charge, which will usually be referred to as the coupling constant and gives the strength of the interaction, is given in terms of a dimensionless number. This number is defined as the Coulomb repulsion energy between two electrons that are one Compton wavelength apart divided by the rest mass energy of the electron:

$$\alpha_{\rm em} = \frac{e^2}{4\pi\epsilon_0(\hbar/mc)}\frac{1}{mc^2} = \frac{e^2}{4\pi\epsilon_0\hbar c} = \frac{e^2}{4\pi} = \frac{1}{137}, \tag{2}$$

where the last equality comes from using Lorentz-Heaviside units and setting $\hbar = c = 1$. For each interaction a dimensionless coupling strength is introduced.

| Interaction | Symbol | Value |
|---|---|---|
| Electromagnetic | $\alpha_{\rm em}$ | $\approx 1/137$ |
| Weak | $\alpha_{\rm w}$ | $\approx 1/29$ |
| Strong | $\alpha_{\rm s}$ | 1 to 0.1 |

Table 4: List of the coupling constants for particle interactions

# 6 Particle Classification

In the current edition of the *Particle Data Group Tables* there are several hundred particles listed. Obviously all these cannot all be elementary particles—at this point the quarks will be ignored, they will slowly be shown to be needed as the course progresses. In order to make any head way in understanding the particle spectrum, the particles are classified according to their various properties. One obvious classifications scheme would be to separate them into Fermions and Bosons. This turns out to not be immediately useful, but separating out those that have strong interactions from those that do not has some value. Those particles that have strong interactions are referred to as hadrons, while those that do not are labeled as leptons. The hadrons are further broken down into fermions (baryons) and bosons (mesons). Examples of baryons are the proton, neutron, $\Delta$, $\Lambda$, etc. Examples of mesons are $\pi$, $\rho$, $K$, $D$, etc. The only leptons known were already given in equation 1.

In order to see the role of baryons and meson, consider the world before about 1960. At this point in time, atoms were known to be composed of protons and neutrons in a compact dense nucleus surrounded by electrons. The electrons are kept in orbits about the nucleus by the opposite electrical charges of the electron and proton. When this is viewed in the context of quantum field theory, the attraction is due to the exchange of massless photons. The fact that the photon is massless comes from the uncertainty principle and the fact that the range of the electromagnetic interaction is infinite:

$$\Delta E \times \Delta t = \Delta E \times \frac{\Delta x}{c} \approx \hbar \tag{3}$$

$$\Longrightarrow \Delta E \approx \frac{\hbar c}{\Delta x} = 0. \tag{4}$$

To bind the protons and neutrons together in the nucleus, a new force had to exist, otherwise the repulsive force of the protons on each other would cause the nucleus to break apart. This force was thought to be short in range and much stronger than the repulsive electrostatic force. The range was thought to be of the order of the size of the proton, which from scattering experiments was known to be about $r_0 \approx 10^{-15}\,\mathrm{m}$. Using the same arguments as in equation 4, the mass of the intermediate particle is found to be $m \approx 197\,\mathrm{MeV}$ and further this particle has to be a boson—this is due to the fact all know transitions in angular momentum change by integral amounts. The exchange particle is the $\pi$-meson or pion; $m_\pi \approx 135\,\mathrm{MeV}$. The mesons were considered the carriers of the strong force, while the baryons made up matter. *This is no longer considered the case.*

It should be pointed out, that the arguments just given above should be treated as approximations. They are not precise and are being used only to get an estimate of what is possible.