PHY140Y

37 Particle Physics

37.1 Overview

- Elementary Particles
- Quarks and Leptons
- The Fundamental Forces
- Open Questions in Particle Physics

37.2 Elementary Particles

The discovery of the neutron in the early 1930's led to a picture of our world that incorporated three "elementary particles," the proton, neutron and electron. With these building blocks, all the various elements could be constructed. One had four fundamental interactions: gravity which appeared to be revolutionized by Einstein's successful theory of relativity, electromagnetism, the strong force holding the nucleus together, and something that became known as the weak force, that was responsible for β deccay. This picture was very tidy, and terribly wrong, as physicist soon discovered.

Perhaps the first cracks in this picture arose from the discovery of the μ^- lepton. First observed in the 1930's, it seemed to be something like an electron, but much more massive and unstable. It has a mass of 106 MeV/c^2, and decayed almost exclusively into electrons and something else. Today, we know that the muon decays via

$$\mu^- \rightarrow e^- + \bar{\nu_e} + \nu_\mu, \tag{1}$$

where I have introduced another new particle, the muon neutrino (ν_μ). The μ^- (which has an antiparticle labelled the μ^+) has a lifetime of 2.2×10^{-6} s. It's role was simply not understood.

A few years after, a new particle was discovered in high energy collisions of protons, the pi meson. It comes in three different charge modes, π^+, π^- and π^0, and has a mass of 138.6 MeV/c^2 for the $\pi^\pm$ and 135.0 MeV/c^2 for the π^0.

The discovery of the electron neutrino at about the same time further deepened the mystery about what role these new particles really played. Physicists began looking for traces of additional new particles, and soon discovered them in studies of cosmic ray collisions with protons. By the late 1950's, a literal zoo of particles had been discovered. Examples of some of its denizens were

- the K mesons K^+, K^- and K° with masses of almost 500 MeV/c^2,
- the ρ η and ϕ mesons, that decayed into pairs or triplets of π or K meson,

- The Δ and N^* baryons that appeared to be cousins of the proton and neutron, being slightly heavier but decaying to a neutron or proton and additional π mesons.

The large number of these elementary particles by the early 1960's forced physicists to look for patterns in the properties and behaviour of these particles, hoping to find some straight-forward explanation for why they existed. They found that on the basis of the decay properties of the particles, they could identify three different groups:

1. the **leptons**, which consisted of the electron, muon and associated neutrinos,
2. the **baryons**, which consisted of the proton and neutron and heavier unstable particles that decayed to either a proton or a neutron, and
3. the **mesons**, which had the property that they always decayed to final states that consisted only of lower mass mesons such as π's and K's.

One conservation law with the strong force appeared to be at play: The total number of baryons had to remain constant (counting a baryon as +1 and an antibaryon as −1). Mesons had baryon number 0. Thus, the decays

$$\Delta^+ \rightarrow p\pi^0 \text{ and } \rho^+ \rightarrow \pi^+\pi^0\pi^0 \tag{2}$$

were allowed, but a decay like

$$N^{*+} \rightarrow \pi^+\pi^0 \tag{3}$$

was not. I should note that this principle was only true of the strong force. Decays mediated by the weak force (the β decay of the neutron is a good example) did not respect this conservation law.

These observations and the related taxonomy helped organize the particles, but it didn't reveal any insights till the advent of the quark model.

37.3 Quarks and Leptons

37.3.1 The Original Quark Model

In the early 1960's, a model was proposed that gave a simple explanation for the mesons and baryons. This model, proposed by Gell-Mann and Zweig, viewed the mesons and baryons (together, these were called **hadrons**) as consisting of smaller particles called quarks. In their model, they had to have three different kinds of quarks:

- the "up" quark, u,
- the "down" quark, d, and
- the "strange" quark, s.

Quark	Mass (MeV/c^2)	Charge	Baryon Number
u	~ 5	$+2/3$	$+1/3$
d	~ 5	$-1/3$	$+1/3$
s	~ 300	$-1/3$	$+1/3$

Table 1: The properties of the light quarks.

In addition, they had to assume that each quark had an anti-particle equivalent, labelled $\bar{u}$, $\bar{d}$ and $\bar{s}$. These quarks had some unusual properties, some of which are detailed in Tab. 1. Gell-Mann and Zweig assumed that the same force that holds protons and neutrons together, the strong force, held the quarks together as well.

The mesons are composed of a quark-antiquark pair. Thus, a π^+ is in fact a $u\bar{d}$ system. Similarily, a K^0 is a $d\bar{s}$ combination. The fact that the quark masses did not come even close to adding up to the masses of the observed particles was presumed to arise from the effects of the strong interaction. In this model, a three quark system makes up a baryon. Thus, the proton is a uud system, while the neutron is a dud system. This picture successfully described all the known baryons at the time.

It also led to a new view of the weak interaction. In the quark model, the β decay of a neutron to a proton now could be viewed as arising from the transformation of a d quark to a u quark, releasing at the same time an $e^-\bar{\nu}_e$ pair. Although simplistic, if could be reconciled with the decay of a muon, where a similar process occurs (the μ^- transforms to a ν_μ, releasing at the same time an $e^-\bar{\nu}_e$ pair). Even the lifetimes of these decays could be reconciled.

However, the introduction of this model raised a number of new questions. For example, if quarks are real, why can't we see a free quark? Why are the only observable particles quark-antiquark pairs or three quark pairs? What is really behind the strong force? What is this mysterious weak interaction? Are quarks even real, or is the quark model just an accidental "accounting" scheme? These questions persisted for at least 15 years. During that time, new elementary particles continued to be discovered — even one that was predicted by the quark model, the Ω baryon which consists entirely of strange quarks (sss).

37.3.2 The Discovery of the Heavy Quarks

In 1974, the first of a series of remarkable discoveries where made. In studying very high energy collisions between protons and in the study of high energy e^+ and e^- collisions, two teams independently discovered a new particle, that was quickly identified as a massive meson. Known as the J/ψ particle, this meson had a mass of 3.1 GeV/c^2 and decayed either into pairs of leptons and antileptons or quarks and antiquarks. Very quickly thereafter, a series of similar mesons were discovered at somewhat higher masses.

This discovery was exactly what one would expect if a heavy quark with a mass of around 1.6 GeV/c^2 existed. Dubbed the charm quark (c), this object fit fairly neatly as a partner to the strange quark, which it appeared to decay to at least 2/3 of the time (along with the creation

Quark	Mass (MeV/c^2)	Charge	Baryon Number	Year of Discovery
u	~ 5	$+2/3$	$+1/3$	1962
d	~ 5	$-1/3$	$+1/3$	1962
c	$1,600$	$+2/3$	$+1/3$	1974
s	~ 300	$-1/3$	$+1/3$	1962
t	$175,000$	$+2/3$	$+1/3$	1995
b	$4,700$	$-1/3$	$+1/3$	1977

Table 2: The properties of the all six known quarks.

of additional quarks or leptons). The J/ψ meson was identified as a $c\bar{c}$ pair, as were the heavier mesons with similar properties. These heavier mesons were identified as the radial excitations of the $c\bar{c}$ ground state, in analogy with the radial excitations of the hydrogen atom that result in nS states (n=$2, 3, \ldots$). The charm quark also appeared to have a charge of $+2/3$. Finally, it's decay into the strange quark appeared to be a weak decay, due to the relatively long lifetime for the decay (amost 10^{-12} s).

In 1977, the discovery of a much more massive meson was announced, the Υ, which had a mass of almost 10 GeV/c^2. It was almost immediately interpreted as the bound state of a new type of quark, labelled b, and alternatively called the "bottom" or "beauty" quark. Based on its decay properties, it was identified as having a charge $-1/3$.

Detailed studies of the hadrons with bottom and charm quarks seemed to indicate that this was not the total story. In particular, the properties of the b quark were analogous with the d and s quarks, leading to the expectation that the bottom quark had to have a partner. These theoretical speculations, however, could not identify what the detailed properties of this new partner might be, although since it hadn't yet been observed, it was assumed to be quite massive. It was even given a name: denoted by t, it was alternatively called "top" or "truth."

Searches for the top quark were made through the 1980's and early 1990's, with each unsuccessful search progressively implying that the top quark had to be particularly massive. In 1994, initial evidence was presented for the existence of the top quark, but it wasn't until 1995 when two groups simultaneously announced that they had observed the production of top and anti-top quarks in the annihilation of extremely energetic protons and antiprotons. The mass of this new quark was surprisingly high – approximately 175 GeV/c^2, or about the mass of a gold nucleus. But it clearly was the partner to the b quark, as its primary decay mode was to this quark.

This now left us with a quark model that had doubled in size. There were now six types, or "flavours," of quarks, with rather different masses. I summarize in Tab. 2 some of the salient properties of all six.

37.3.3 The Leptons

During this period of activity in the quark sector, the leptons were not completely ignored. In fact, in 1978, a third charged lepton was discovered, the tau lepton or τ^-. It was discovered in

Quark	Mass (MeV/c^2)	Charge	Lepton Number
e^-	0.005	-1	$1, 0, 0$
ν_e	0	0	$1, 0, 0$
μ^-	106	-1	$0, 1, 0$
ν_μ	0	0	$0, 1, 0$
τ^-	$1,700$	-1	$0, 0, 1$
ν_τ	0	0	$0, 0, 1$

Table 3: The properties of the all six known leptons. There are three separate lepton conservation laws, one requiring total electron number to be conserved, one requiring total muon number to be conserved, and one requiring total tau lepton number to be conserved. These three quantum numbers are listed in the right-most column.

electron-positron annihilations (the positron is just another name for an antielectron), and within about 10^{-12} s decayed either into a μ^- or an e^- with two neutrinos.

Why two neutrinos? In order to preserve the pattern established with the electron and muon, the τ^- had to have associated with it it's own neutrino. Thus, when any charged lepton decays, it actually is being transformed into its corresponding neutrino releasing at the same time a number of additional particles. The weak force is responsible for this behaviour, something we will discuss in more detail in the next section.

Three separate conservation laws emerged from the studies of the leptons. Regardless of the type of interaction, it appeared that the sum of the number of electrons and electron neutrinos had to be conserved, that the sum of the number of muons and muon neutrinos had to be conserved, and the sum of the number of tau leptons and tau lepton neutrinos had to be conserved. In making this sum, antiparticle states had to be subtracted. These three conservation laws could be summarized by assigning to each lepton an electron lepton number, a muon lepton number and a tau lepton number, and then requiring that in any interaction, the total initial and final state lepton numbers had to be equal. Thus, the processes

$$e^+e^- \to \tau^+\tau^- \text{ and } \tau^- \to \mu^-\bar{\nu_\mu}\nu_\tau \tag{4}$$

were allowed, but processes like

$$J/\psi \to e^-\mu^+ \text{ and } K^0 \to \pi^+e^- \tag{5}$$

were not.

The properties of the know leptons are summarized in Tab. 3.

37.4 The Fundamental Forces

At the same time that the quarks and leptons were getting sorted out, significant steps were taken in our understanding of the forces that held together these particles.

At this point, it is customary to simply ignore the force of gravity. It remains an unsolved problem, so as we usually do with problems that are too hard, we set them aside until we have the fortitude to tackle them again.

This leaves us with three forces to grapple with, the electromagnetic force, the weak force and the strong force. Let me address them in that order.

37.4.1 The Electroweak Force

The force of electromagnetism classically was considered to have an infinite range, since it satisfied a r^{-2} distance dependence. From a quantum mechanical point of view, we identified the photon as the force carrier of electromagnetism, a picture that worked extremely well in describing the interactions of charged particles. In the mid to late 1940's, the theory of quantum electrodynamics (QED as it became known) was developed by Feynman and others that proved to give us an excellent description of this force.

In the language of QED, the photon mediates the electromagnetic interaction by being exchanged between two charged particles. Thus, one can write down "Feynman" diagrams that illustrate this sort of interchange, as shown in Fig. 1a). At the same time, studies of the β decay process and similar processes (like μ decay) seemed to indicate that there may be a similar sort of process at the root of these weak interactions.

In the late 1960's and early 1970's, physicists developed a theory of the weak force that involved the interchange of a massive force carrier, known as the intermediate vector boson (IVB). This IVB came in three different charge flavours, which have the names W^+, Z^0 and W^-. In the language of IVB exchange, μ decay was now a process where

$$\mu^- \to W^- \nu_\mu \text{ and } W^- \to e^- \bar{\nu}_e. \tag{6}$$

In this sense, the IVB acted like the photon, but it could couple leptons of different flavours. This process was extended to the quark sector, where one now described the β decay of the neutron as arising from the quark decay

$$d \to W^- u \text{ and } W^- \to e^- \bar{\nu}_e. \tag{7}$$

In both cases, we see that by exchanging the IVB, the particle turns into its quark or lepton partner. This behaviour of the weak force suggested that we should really think of the quarks and leptons as coming in pairs, or "doublets." Thus we really should write the quarks and leptons as

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \tag{8}$$

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}, \tag{9}$$

where the weak force causes transitions between particles in the same doublet.

The Feynman diagram for this such a transition is shown in Fig. 1b). The parallels between the weak and electromagnetic forces was only broken by the fact that the IVB's were very massive

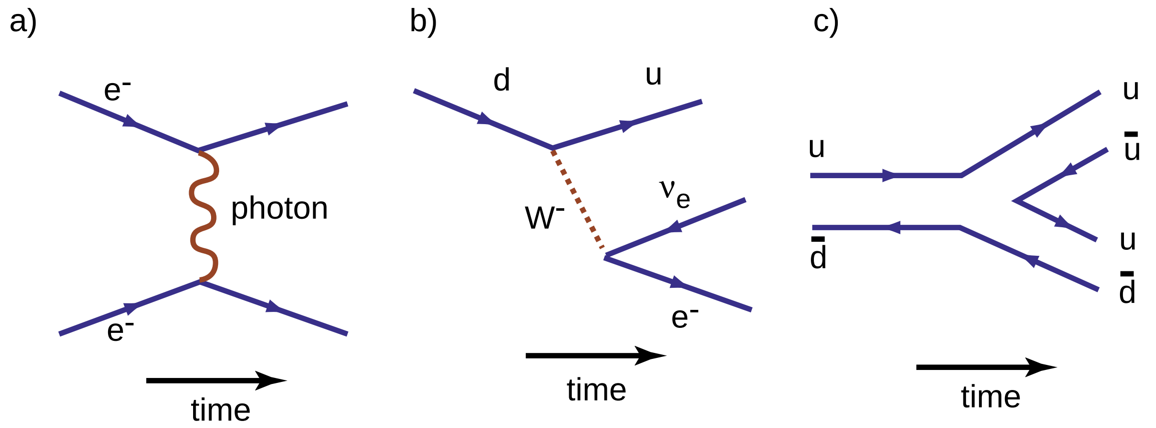

Figure 1: a) The Feynman diagram for the scattering of one electron off another. The time axis is in the horizontal direction, while we can take the vertical direction to represent in some sense the separation of the particles in space. The lines with arrows that point forward represent a particle while the lines with arrows pointing backward in time represent antiparticles. b) The Feynman diagram for the transtion of the d quark into a u quark, the process responsible for β decay of a nucleus. c) The decay of a ρ meson via the strong force (the gluons are not shown).

particles. The $W^{\pm}$ bosons have a mass of 81 GeV/c^2 while the Z^0 has a mass of 91 GeV/c^2. This apparent discrepancy was overcome by the development of a theory in the early 1970's that could explain all four force carriers as representative of a single force, known as the **electroweak force**. The fact that the photon was massless and the IVB's were massive was explained by a process called "spontaneous symmetry breaking," where a fifth particle known as the Higgs boson entered the picture and preferentially made the IVB's massive, leaving the photon massless. This theory predicted that if you looked at these interactions at high enough energies, they would in fact be effectively identical interactions.

In this way, we were able to unify the electromagnetic and weak forces, a major breakthrough in our understanding of elementary particles.

37.4.2 The Strong Force

The strong force responsible for causing quarks to bind and form hadrons was the subject of intense theoretical and experimental studies. It was clear that on one hand the force was very strong, as it kept together the nucleus. It also was very short range, because once outside the nucleus, its effects rapidly dropped off. Finally, it had to be such that it only allowed $q\bar{q}'$ and $qq'q''$ systems to be tightly bound states, with all other quark combinations being unstable. A theory was developed in the late 1960's and early 1970's that appeared to have these features.

Known as quantum chromodynamics (or QCD), it postulated that quarks had yet another property that was whimsically called "colour." Each quark could come in one of three colours, say "red," "green," or "blue." A set of force carriers called gluons could be exchanged between coloured objects, just like the photon could be exchanged between objects that had electric charge. The theory required there to be eight types of gluons, which each type causing the transformation of the colour of the quark. These gluons were massless objects.

The properties of this colour force were such that only "colourless" combinations of quarks were allowed to exist. This naturally led to the explanation that only mesons and baryons could be constructed from the quarks. It also explained why one never saw a free quark – it would now be a coloured object, and the energies required to allow that to happen would be enormous.

So, now one could understand the proton and neutron as being bags of quarks held together through the exchange of gluons. The strong decay of a meson like a ρ^+ (thought to be an excited $u\bar{d}$ state) could now take place through a Feynman diagram as shown in Fig. 1c), where the exchange of gluons allowed a $u\bar{u}$ state to be created to form the daughter π^+ and π^0 mesons. I should emphasize that the properties of the strong force did not allow transitions between different flavours of quarks – only the weak force could do that. And the strong force only acted on quarks.

37.4.3 Towards a Unified Theory

With these developments, we saw that we now had theories of the strong and electroweak forces that were founded on quantum mechanics and had very similar properties. The more recent theoretical work has been centred on uncovering whether there is a common framework in which to describe both the electroweak and strong forces, thereby unifying them in much the same way that we unified the electromagnetic and weak force.

The evidence for such a unified picture remains elusive. There are some hints that as one looks at interactions at higher and higher energies, the properties of these forces may converge. However, the evidence for this still remains weak and there are many open theoretical questions.

37.5 Open Questions in Particle Physics

Let me conclude this very brief overview of particle physics by mentioning where big "open" questions remain:

- What is mass? We still have no idea why the quarks and leptons have the masses that they do.
- Why only three generations of quarks and leptons? What is magical about three?
- How does gravity really work? We have no theory that describes gravity in a way that is consistent with quantum mechanics.

Besides these fundamental questions, there remain many open issues today at a more detailed level. I will mention only one of these, to give you a flavour of their nature.

We still really don't understand neutrinos at all. When we try to measure the rate of neutrinos from the sun, we find that we seem to be missing about half of them! This is a serious problem. We would like to believe that they are massless, but in fact recent measurements seem to indicate that they may have a mass, even though it is a small one. There are in fact a number of major experiments underway to try to measure their properties, with one of them taking place in a mine 2 km underground in Sudbury, the Sudbury Neutrino Observatory. I suspect that we may hear more about this in the next few years.