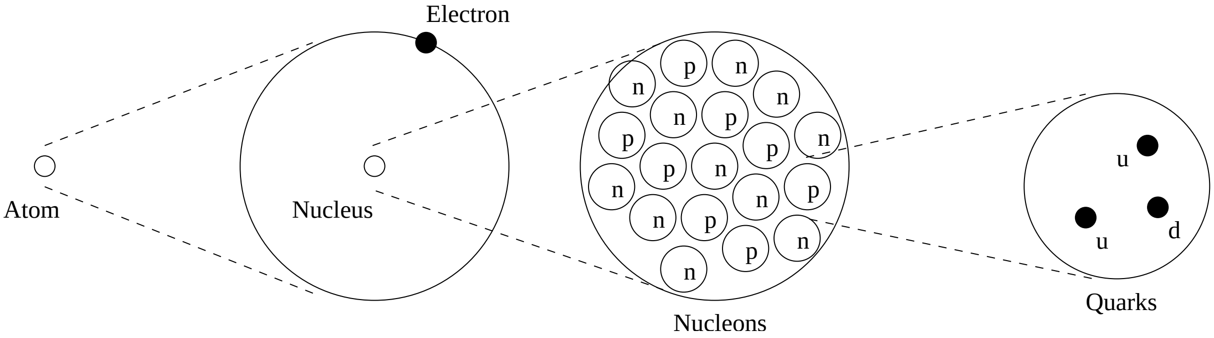
Nuclear and Particle Physics - Lecture 1
Overview

1 Introduction

These lectures will cover particle and nuclear physics. Although historically, nuclei were discovered before particles, I will present the material in the opposite order, as the properties of nuclei are best understood in the context of the particles and forces which comprise them.

We are going to look at the most fundamental particles in nature. For centuries, it was thought that atoms (from the Greek *atomos* meaning "not divisible") were the most basic constituents of matter. Unlike the ancient Greeks, you all know atoms are not fundamental but are made of electrons orbiting around a nucleus. The electrons we believe *are* fundamental (although maybe someone giving this course in the 22nd century will start by saying "In the last century, physicists believed electrons were fundamental but of course now we know...".) However, the nuclei we already know are not fundamental. Nuclei are made of protons and neutrons and even these are not fundamental; they in turn are made of "quarks". Specifically, there are three quarks in a proton or neutron; protons contain two u-type quarks and one d-type, while neutrons contain one u-type and two d-type quarks. In the same way as for electrons, we currently believe quarks are not made of anything else.



There is another fundamental particle which occurs in nature and this is called the "neutrino". This is not found as a part of atoms because the force it feels is so weak that it is not bound. However, other than the force, its properties are very similar to the electrons and quarks.

To be clear, by fundamental, I mean the particles have no size (they are infinitely small), have no substructure (they are not made of anything else) and cannot be excited or broken up. Obviously, all these things can only be experimentally shown to be true to some limit.

For the particle physics part of the course, I will present what is known as the "Standard Model" (SM). This theory has been developed over the last ~ 30 years and has been extremely successful. In fact, almost no experimental measurement is in quantitative disagreement with its predictions; the one exception are the recent data indicating neutrinos have mass, since the basic SM assumes neutrinos are massless. However, even this can be easily accomodated by a straightforward extension to the model.

In the SM, all the "matter" particles, meaning the ones discussed above, are spin 1/2 and hence fermions. In contrast, all the three forces which we shall consider, namely the electromagnetic (EM), strong and weak forces, are due to particles with spin 1 which are bosons. There is one other particle in the SM which falls into neither category; this is the Higgs boson, which has spin 0, and it is responsible for the "drag" on particles, even when in vacuum. This drag we see as mass. The Higgs is the only SM particle not yet observed and there is therefore a large effort going into finding it.

The SM does *not* include the fourth known force, gravity. In practical terms, this is fine because it has a negligible effect on any particle physics experiment, since the gravitational force between particles is so much weaker than even the weak force. However, on a theoretical level, a quantised theory of gravity seems to be extremely difficult and is one of the Holy Grails of theoretical physics right now. It is, however, known that the quantised gravity particle would have to have spin 2, making it significantly different from the other forces. We will ignor gravity from now on.

2 The matter particles

The spin 1/2 matter particles are organised into "families", also known as "generations".

	Generation			Charge	Feels the force of		
	1^{st}	2^{nd}	3^{rd}	Units of e	Strong	EM	Weak
U-Type Quarks (×3 colours)	u	c	t	$+2/3$	Y	Y	Y
D-Type Quarks (×3 colours)	d	s	b	$-1/3$	Y	Y	Y
Charged Leptons	e	μ	τ	-1	N	Y	Y
Neutral Leptons (Neutrinos)	ν_e	ν_μ	ν_τ	0	N	N	Y

Table 1: The Matter Particles; Spin 1/2

The first column under "Generation" contains the matter particles we have already met; the next two columns are the further generations which are heavier copies. There seems to be no difference in the properties of any of the particles of the same type between different generations except for their masses; e.g.

$$m_e = 9.11 \times 10^{-31}\ \mathrm{kg}, \qquad m_\mu = 1.88 \times 10^{-28}\ \mathrm{kg}, \qquad m_\tau = 3.17 \times 10^{-27}\ \mathrm{kg}$$

The principle of universality postulates that all the other properties (e.g. charge) are equal and, of course, this means experimentally we need to check this principle is correct.

All the spin 1/2 particles obey the same quantum mechanics wave equation, namely the Dirac equation, which is beyond the level of this course. For every one of the above particles, there is a corresponding antiparticle with an identical mass but opposite charge (and opposite other quantum numbers also). The existence of these antiparticles is predicted by the Dirac equation; they are thought of as (at some level) particles going backwards in time.

The matter particles do *not* interact with each other, which might sound like a strange statement to say about a pair of electrons, which we know repel each other. In fact, the matter particles interact with the force fields only and the electron pair only appear to repel each other; they are actually both pressing against the EM fields which then apply the force to the other electron.

3 The force particles

The electromagnetic force is well known and is responsible for light, electricity, magnetism, atomic structure, etc. The strong force holds the protons and neutrons together in the nucleus and is clearly stronger than the electromagnetic repulsion of the positively charged protons, hence being called strong. The weak force is less obvious at the macroscopic level for the simple reason that it is less strong, but is responsible for the critical first step of the reactions which power the sun as well as causing beta decay of nuclei.

The force fields themselves are also quantised and so have associated particles. All three forces have spin 1 particles and there are no generations for the forces.

Force	Name	Symbol	Number	EM charge
Strong	Gluons	g	8	0
EM	Photon	γ	1	0
Weak	W and Z	$W^\pm$, Z^0	3	±1, 0

Table 2: The Force Particles; Spin 1

In contrast to the matter particles, each force particle has a different wave equation and it is this fact which gives each force a different characteristic. The EM force particle, the photon, has a wave equation which comes from Maxwell's equations. The strong and weak force equations are more complicated, not least because they carry the strong and weak force charges themselves, i.e. they "self-interact". This would be equivalent to the photon being charged and makes things much more difficult.

The W^+ and W^- are antiparticles of each other. However, the photon and Z have no distinct antiparticle, as they are their own antiparticles. Like the weak bosons, the gluons are a mixture; of the eight, there are three particle-antiparticle pairs and the other two are their own antiparticles.

4 The Higgs particle

The final piece of the SM is the Higgs particle, which is spin 0 and has no charge. Without this particle, the SM would be inconsistent, as all the matter and force particles would need to be massless. However, it is a purely theoretical construct at present as it remains to be confirmed experimentally.

Name	Symbol	Number	Charge
Higgs	H	1	0

Table 3: The Higgs Particle; Spin 0

5 Composite particles and hadrons

The above list all the known (and for the Higgs, hypothesised) fundamental particles. By fundamental, we mean they do not appear to be made out of any other particles, to the extent that we can measure. However, of the matter particles, only the leptons (e, μ, τ and their neutrinos) are actually observed as *free* particles. The quarks are never seen singly, but always occur in bound states, which are called hadrons. To most macroscopic experiments, these hadrons act as if they were pointlike and so are also called particles, or more accurately, composite particles.

An example are the pions, π^+, π^- and π^0, which are known to be the quark-antiquark states $u\overline{d}$, $d\overline{u}$ and a combination of $u\overline{u}$ and $d\overline{d}$, explicitly $(u\overline{u}-d\overline{d})/\sqrt{2}$. All such quark-antiquark states are called mesons. The antimesons are formed by swapping quarks for antiquarks and vice versa, so the π^+ and π^- are antiparticles of each other, while the π^0 is its own antiparticle. Because mesons have one quark and one antiquark, both of which are spin 1/2, then no matter what their orbital angular momentum, their total spin is always even; hence all mesons are bosons.

There are also three-quark bound states, such as the proton, p, which is uud (and hence charge +1) and the neutron, n, which is udd (and hence charge 0). The antiparticles of these are simply the states with all quarks replaced by antiquarks, e.g., the antiproton, $\overline{p}$, which is $\overline{u}\overline{u}\overline{d}$ (charge −1) and the antineutron, $\overline{n}$, which is $\overline{u}\overline{d}\overline{d}$ (charge 0; but note the antineutron and neutron are different particles). As these states all have three spin 1/2 quarks, they all have half-integer spin and so are all fermions.

6 Nuclei

Protons and neutrons can actually bind together through the strong force strongly enough to form bound states. These can alternatively be thought of as bound states of 6, 9, 12... quarks. These bound states form the nuclei of atoms and the sum of the proton charges is what holds the outer atomic electrons in their orbits using the EM force.

Obviously, a nucleus can be described by the number of protons (often called the atomic number) and usually denoted by Z, and the number of neutrons, denoted by N. The total number of protons and neutrons (collectively called nucleons) is denoted by the atomic mass number A which is by definition $Z + N$. The usual symbol for a nucleus is the chemical symbol preceded by a superscript of A and a subscript of Z. E.g. the most common isotope of lead (chemical symbol Pb, $Z = 82$) has $N = 126$ and hence $A = Z + N = 208$ and so is written as $^{208}_{82}\mathrm{Pb}$. The simplest nucleus, that of hydrogen which has just a single proton, can be written as $^{1}_{1}\mathrm{H}$, although this is the same thing as p. Other simple nuclei are the deuteron, d, which is $^{2}_{1}\mathrm{H}$, i.e. made of one proton and one neutron, and the helium nucleus, $^{4}_{2}\mathrm{He}$, i.e. made of two protons and two neutrons, which for historical reasons is often called an alpha particle, α.

In principle, antiprotons and antineutrons would form antinuclei with effectively identical levels. Of course, these would be negatively charged and so could not attract electrons into bound orbits. However, antielectrons, also called positrons, would have stable orbits around such antinuclei, making antiatoms. In practice, antiprotons and antineutrons have been made although no bound states of larger antinuclei have been formed in a controlled way. There have been antihydrogen atoms made from the antiprotons with positrons, although only thousands were made in total. We are a long way from building anything large out of antimatter.

7 Units

Finally, a brief word on units. As is common in many branches of physics, the areas of particle and nuclear physics use convenient units which are not SI units.

It is common to measure energies in units of electron volts, eV, which is the energy acquired by a charge e in moving through 1V, i.e. 1.602×10^{-19} J. In fact, in nuclear and particle physics, more common units are its higher magnitudes of keV (10^3 eV), MeV (10^6 eV), GeV (10^9 eV) or even TeV (10^{12} eV).

Since $E = mc^2$, then $m = E/c^2$ so masses are often given in units of MeV/c^2; e.g. the electron mass of 9.11×10^{-31} kg can also be written as $(9.11 \times 10^{-31}) \times (2.998 \times 10^8)^2/1.602 \times 10^{-19} = 5.11 \times 10^5$ eV/c^2 = 0.511 MeV/c^2. Similarly, the proton mass of 1.67×10^{-27} kg is 938.4 MeV/c^2. One other mass unit commonly used in nuclear physics is the atomic mass unit, which is defined to be 1/12 of the mass of a $^{12}_{6}\mathrm{C}$ atom and is 931.5 MeV/c^2. As we will see in the next lecture, in a similar way, momentum can be given in MeV/c.

Particles and nuclei are small, so short distance scales are common. A frequently used unit is the femtometre or fermi, 1 fm = 10^{-15} m. Areas are often given in barns, where 1 barn = 10^{-28} m^2 = 100 fm^2.

Note in particular, some text books will use “natural units”, in which the fundamental constants are defined to be $\hbar = c = \epsilon_0 = 1$ so they do not appear in any equations. We will not use this convention, but be careful when looking things up.