

Chapter 16

Matter

We've concentrated primarily on electrons throughout this course. Indeed, in our everyday life, it is the interactions of electrons that, together with photons (light), drive most of what we do. In this final chapter, we'll peer down inside the atom to see what the most fundamental particles are, and then extend our view out to bulk states comprised of large numbers of electrons.

16.1 The Standard Model of Particle Physics

Our best current understanding of Physics at the most basic level is that it is composed of a number of fundamental particles. These particles are, as best we can tell, points, much like electrons (which are in fact one of the fundamental particles). They have various properties associated with them, including mass, spin (angular momentum), electric charge, and others. It is from these fundamental particles that all of the matter we interact with is built. (However, matter built from these particles only makes up 5% of the total density of the Universe! See Section 16.7.)

Broadly, we can divide the particles into two categories: fermions and bosons. Matter is built from fermions, and the interactions between matter—the four forces—are carried by bosons.

The fermions are divided into three generations; it is only the first generation that we ever interact with on a daily basis. Each generation includes two *quarks* and two *leptons*. In the first generation, the quarks are called the “up” and “down” quarks. The two leptons are the familiar electron, and the electron neutrino. Each of the other two generations has an additional two quarks, heavier than the quarks in the first generation; and an additional two leptons, including a heavier version of the electron, and a corresponding neutrino. Additionally, for each fermion, there is a corresponding

antiparticle. For example, the anti-electron is called the “positron”. Antimatter is rare. In the very early Universe, we believe that matter and antimatter were present in equal quantities, but for some reason that is not understood matter had a *slight* advantage. A particle of antimatter, when it meets its corresponding matter particle, will mutually annihilate both, releasing their mass as energy according to the conversion $E = mc^2$. That slight advantage that matter had in the very early Universe is what’s left over to build up stars, galaxies, and us today.

Generation	Fermion	Symbol	Charge	Spin	mc^2
First	Down Quark	d	-1/3	1/2	5.05 MeV
	Up Quark	u	+2/3	1/2	2.49 MeV
	Electron	e	-1	1/2	0.511 MeV
	Electron Neutrino	ν_e	0	1/2	*
Second	Strange Quark	s	-1/3	1/2	101 MeV
	Charm Quark	c	+2/3	1/2	1.27 GeV
	Muon	μ	-1	1/2	106 MeV
	Muon Neutrino	ν_μ	0	1/2	*
Third	Bottom Quark	b	-1/3	1/2	4 GeV
	Top Quark	t	+2/3	1/2	172 GeV
	Tauon	τ	-1	1/2	1.78 GeV
	Tau Neutrino	ν_τ	0	1/2	*

Table of fermions from the standard model of particle physics. All data is from the PDG (Nakamura and Particle Data Group, 2010). Charges are in units of e , the elementary charge. *: There are three neutrinos. Although masses are not known, we have limits that the heaviest one is less than 18.2 MeV, the middle one is less than 0.19 MeV, and the lightest one is less than 1.3 eV. However, the mass eigenstates and the flavor (i.e. “type of neutrino”) eigenstates of the neutrinos are not the same, so it’s impossible to identify a given mass with a given type of neutrino.

Quarks are never observed in isolation. For the most part, they are observed in bound states called *hadrons*. The proton and neutron are two three-quark particles. There is a huge zoo of additional hadronic particles, including baryons (made of three quarks) and mesons (made up of a quark and an antiquark). The proton and the neutron are the only stable hadrons. Indeed, even the neutron is not stable unless it’s bound into an atom; a free neutron will decay to a proton, an electron, and an antineutrino in about 15 minutes. “Virtual” mesons are found inside the nucleus. Transient mesons and other sorts of baryons are made in particle accelerators, and also when cosmic rays hit the Earth’s atmosphere.

In addition to the fermions that make up matter, there are four forces through which matter interacts. The most familiar of these forces are gravity and the electromagnetic force. In our current theories of physics, gravity is described by General Relativity, and is *not* included in the Standard Model of Particle Physics. We believe

that we will one day be able to produce a working theory of quantum gravity, but we have yet to successfully do that. We expect this theory to include the graviton as a massless spin-2 boson.

The electromagnetic force is the best understood of the four forces. It unifies the electrostatic force and the magnetic force. The photon is the particle that carries the electromagnetic force; we see it as light. Radio waves, infrared radiation, ultraviolet radiation, x-rays, and gamma rays are all forms of light at wavelengths different from those our eye can detect. All of these are made up of photons, the quanta of the electromagnetic field. It is the electromagnetic force that forms the potential in which electrons move in atoms, and it is that interaction that governs the interactions between atoms.

Because the photon and the (presumed) graviton are massless, both gravity and electromagnetism are long-range forces. In contrast, the other two forces are short ranged. The strong nuclear force is the force that binds quarks together into protons and neutrons, and that ultimately binds protons and neutrons together into nuclei. The bosons that carry the strong nuclear force are called gluons. They may be massless, although a moderate mass isn't ruled out. However, other properties of the strong force limit it to a short-range force. The weak nuclear force is, as its name suggests, much weaker than the strong nuclear force, and has only a secondary effect in nuclei. The charge carriers of the weak force are indeed massive, limiting it to a short range force. The weak force is the *only* force other than gravity that interacts with *all* of the particles in the standard model. Neutrinos, in particular, only interact via the weak force, making them extremely hard to detect. The weak force is responsible for much radioactive decay; it is a result of the weak force, for instance, that a free neutron will decay into a proton, an electron, and an antineutrino. The bosons that carry the weak force are called "intermediate vector bosons." Their name is the same as their symbol. There are three, the W^+ , W^- , and Z^0 bosons.

Force	Boson	Symbol	Charge	Spin	Mass
Electromagnetic	Photon	γ	0	1	0
Strong	Gluon	g	0	1	0?
Weak	W^+ Boson	W^+	+1	1	80 GeV
	W^- Boson	W^-	-1	1	80 GeV
	Z Boson	Z^0	0	1	91 GeV

Table of bosons in the standard model of particle physics. All charges are in units of e , the elementary charge. Not included is the hypothesized graviton, which would be a massless, chargeless, spin-2 boson.

16.2 Nuclei and Atoms

Quarks bind together to make protons and neutrons. A proton is composed of two up quarks and a down quark, and a neutron is composed of two down quarks and an up quark. Together, protons and neutrons are called nucleons. Nucleons can themselves bind together to make nuclei. These nuclei are always positively charged, with the total charge depending on the total number of protons. Nuclei are so called because they sit at the nucleus of atoms; an atom is a nucleus that has gathered negative electrons into the various electron states (i.e. orbitals) allowed by the electric potential created by its positive charge. The smallest nucleus is the Hydrogen nucleus, composed of but a single proton; it is about 10^{-15} m across. The largest stable nuclei have a more than 200 nucleons in them. Nuclei with more nucleons than that tend to be unstable, and spontaneously fission into smaller nuclei.

The *binding energy*— that is, the potential energy that results from combining nucleons together to make nuclei— is an appreciable fraction (1% or so) of the mass energy of the nucleons. The nucleus with the greatest binding energy per nucleon is Iron-56, which makes it (in a sense) the most stable nucleus. You can get energy out by fusing lighter elements together until you get to Iron-56; after that, it costs energy to build up heavier elements.

Of course, in nature, most materials are mostly electrically neutral, at least on Earth. It turns out that most of the baryonic material in space is in the form of plasma (mostly ionized Hydrogen, i.e. free protons and free electrons) filling the void between galaxies inside galaxy clusters. On Earth, though, for the most part if there's a free electron, it will be captured by the first nucleus that comes by with an extra positive charge. Hence, in our everyday experience, all things are composed of atoms. We organize our understanding of the various different types of atoms via the Periodic Table, as was discussed at length in Chapter 15.

16.3 Molecules

Atoms can bond together. Sometimes, if one atom is able to completely steal an electron from another atom (as is the case with Chlorine and Sodium atoms, where a Sodium atom will donate an electron to a Chlorine atom), the resulting ions will then stick together as a result of the electrostatic attraction between their opposite net charge.

More common, however, are molecules made from what is called covalent bonds. The electrons in the outer (unfilled) shell of an atom are known as “valence” electrons. Depending on the electronic configuration of an atom, it will have one or more effective valence electrons. In a molecule, the valence electrons are no longer associated

with a single atom, but instead are shared between the electrons. In terms of the quantum mechanics involved, you wouldn't find a solution to Schrödinger's Equation for just the potential of one atom. Rather, you create a joint potential for the two atoms (including the effects of inner-shell electrons), and determine a solution for the system as a whole. The result is an electron wave function that indicates the electron probability cloud is shared between two or (for more complicated molecules) more of the atoms that composes the molecule. Just as nuclei have a binding energy, molecules have a binding energy, meaning that it is a lower energy state for these atoms to bind together and share an electron than it is for them to stay separate. Although this binding energy is typically a billionth of the mass energy of atoms, it is enough to create the vast majority of energy producing processes (e.g. burning gas to power a car) that we are familiar with in our everyday lives.

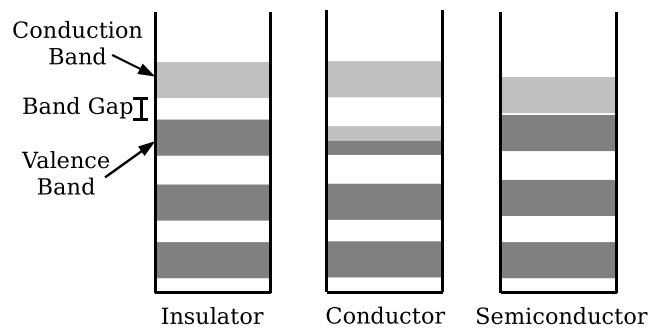
Finding these solutions to multi-atom potentials is an extremely difficult problem, and cannot be solved analytically (as the Hydrogen atom may be). Describing the quantum mechanical state and electron orbitals of any molecule more complicated than something like H_2 generally involves both heavy-duty numerical calculations on computers and heavy-duty quantum chemists.

16.4 Solids

Roughly speaking, a solid is when a large collection of molecules are held together and fixed in place. They aren't completely still, unless a solid is at absolute zero temperature. (And that's not possible, as a result of Heisenberg's Uncertainty Principle.) Most solids are at a higher temperature; the solids you interact with every day are approximately at room temperature, about 20°C or 290 K. At such a temperature, the molecules are vibrating about, each with about 1/40 eV of kinetic energy in that vibration. Solids are held together different ways. Some solids form crystals, where every atom is bonded one way or another to neighboring atoms. Other solids do not strictly have covalent or ionic bonds holding everything together, but are held together by intermolecular forces resulting from the attraction of one electron cloud to a neighboring nucleus and the like.

In some particularly interesting solids, valence electrons don't end up just being shared between neighboring atoms in molecules, but are rather associated with the solid as a whole. These solids *may* be conductors, if there are quantum states available for electrons to move about. When the valence electrons are associated with the solid as a whole, you can approximate the potential in which they move as a three-dimensional square well the size of the solid. Of course, this isn't exactly true, as there will be localized potential wells where each atom in the solid is. However, it is reasonable to approximate the solid as a fixed lattice, with valence electrons potentially free to move through it.

If you associate the valence electrons with the solid as a whole, you then need to think about the states available to those electrons. Since we are talking about a chunk of material that may have a huge number of atoms (e.g. about 10^{22} atoms if we're talking a mere 1g sample of Copper), we're also talking about a huge number of valence electrons, and a huge number of available states. Depending on how you model it, you can think of the states as resulting from the lattice, or as resulting from the effective square well potential in which the electrons move. The nature of the underlying lattice *does* matter. Typically, the states available to the valence electrons come in bands of energy, with gaps between the bands; this is one way in which a simple square well does not reflect the nature of the potential (where the distribution of states would be continuous). Three examples of solids with bands and band gaps are shown below. Each diagram is an energy level diagram. In a shaded band, there are *many* electron states stacked one on top of the other. Because electrons are fermions, however, each individual state may only have two electrons (two, not one, because of electron spin).



Electron energy states in the band gap model of solids. Increasing energy is upwards on all three diagrams. Dark gray bands indicate bands of many energy states that are filled. Light Gray bands indicate bands of many empty energy states.

In the figure on the left, the top filled band is called the *valence band*. Again, this band, and the band below it, represent a huge number of closely spaced energy states for valence electrons. The energy of the top filled state (assuming the solid as a whole is in its lowest overall energy state) is called the *Fermi energy*. These states are *not* places where the electron can be, in the sense of places in space. Electrons in higher states have more energy than electrons in lower states, so they are in fact moving around. However, they're not moving around in a way that would allow electrons to flow in a coordinated fashion from one side of the solid to another. Rather, they're moving around in the same way that an electron in a higher orbital of an atom that has some kinetic energy associated with it. The electron is still tied to the solid, and stuck in the energy state it's in. But, that state is not localized to one nucleus; it's

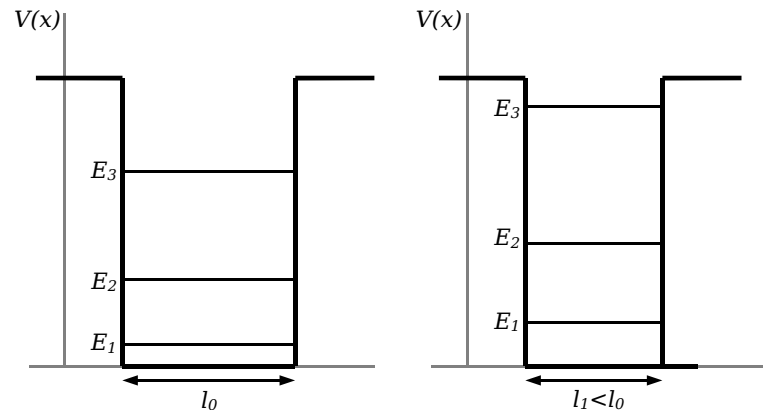
associated with the insulator as a whole. That there are no empty states nearby is why nothing can change that would allow for electric conduction.

The first empty band above the filled band is the *conduction band*. If you want to conduct electricity— that is, allow charge to move through the solid— you need to be able to get electrons out of the states where they're fixed, and into states that have empty states nearby. If there is a band gap between the valence band and the conduction band, this is not very easy; it takes a lot of energy to get an electron out of the state where it normally is and into a state where there are many neighboring states, allowing it to move in a coordinated way through the solid. The conduction band is the band where there are lots of empty states that the electron can make transitions between (or occupy in a superposition of states) so as to allow it to move through the solid and thereby carry electric current. (Electric current ultimately is just the transfer of net electron charge from one side of the conductor to the other.) *Every* material will ultimately carry electron current, if you apply enough potential to it. However, the wider the band gap, the more energy it takes to liberate an electron from the valence band and into the conduction band, thereby allowing it to move freely. If there is a wide gap, we would consider the material an insulator.

In the middle figure above, the material is a conductor. Here, the Fermi energy is in the *middle* of a band of available energy states. As such, electrons in the top filled states have many nearby states available to them. They may freely change states, and thus are able to go into states that can correspond to electrons transferring charge through the material.

The rightmost figure above is a semiconductor. Here, there is a band gap between the valence and conduction bands, but that band gap is quite small. Because of thermal excitations— electrons bumped about by the vibrating atoms resulting from the non-zero temperature— a tiny fraction of the electrons will in fact be up in the conduction band. However, the conductivity of this material remains small, because not very many electrons are up there. (The conductivity will go up with temperature, however, as more electrons statistically get bumped up into the conduction band.) The typical band gap in a semiconductor is around 1–2 eV, which is a lot larger than the 1/40 eV that is the average energy available to one particle at room temperature. By *doping* a semiconductor— that is, adding impurities— you can either add additional valence electrons inside the band gap at an energy just below the conduction band, or additional valence states at an energy inside the band gap just above the valence band. By putting such doped semiconductors together, you can create devices with interesting electrical properties, such as diodes and transistors.

One thing that is interesting about solids is what happens when you try to compress the solid. In a square well, if you decrease the width of the well the energy of all the states increases:



If you think about squeezing a solid, what this means is that you’re pushing the states occupied by the valence electrons to higher energy levels, and therefore you must be putting energy into the solid. The need to exert energy on a solid when squeezing will manifest as a pressure (force per area) that resists the force trying to squeeze the solid. While you might think that it is the atoms and molecules themselves resisting being pushed closer together that makes a solid resist being compressed, this is not the whole case. In fact, this additional energy put into the valence electrons—which, remember, are not associated with individual electrons, but with the solid as a whole—contributes significantly to the restorative pressure of a compressed solid. This pressure is called *Fermi degeneracy pressure*. In this circumstance, “degeneracy” is a technical term referring to electrons all being packed into states as tightly as they can. The Fermi degeneracy pressure that resists the compression of a solid is a direct result of those states rising to higher energies as a result of the compression.

16.5 Liquids, Gasses, and Plasmas

If you put enough energy into a solid, eventually it will melt. At this point, the atoms and molecules in the solid are no longer held together in the crystal, lattice, or other structure. Instead, they have enough energy to break whatever bonds (covalent, ionic, or otherwise) holding them together, and now they can flow past each other. The atoms and molecules are still largely packed together as closely as they can go, and there still are bonds of a sort holding the broadly together, but no longer are they fixed in place. Such a state would be called a liquid.

If you raise the temperature of a liquid enough (to the “boiling point”), and continue to add energy, you can break the residual forces holding the liquid together, and give each molecule enough energy that it starts to bounce about freely. Add enough energy, and the liquid becomes a gas. At this point, each molecule or atom of the gas moves around freely. Molecules do very regularly collide with each other, but they’re not in constant interaction any more as is the case with a liquid.

Indeed, if you investigate the momentum and kinetic energy states available to molecules in a gas, the states are mostly empty. Unlike the valence electrons in a solid, which mostly fill up the lowest states available to them, there are many, many empty lower energy states for every gas molecule. As such, it's easy to change the energy of a gas molecule by a very small fraction of its current energy, as there are so many empty states about. At this point, you can approximate the available energy states as a continuum, and the gas molecules behave like classical particles. A traditional gas is described by the *Maxwell Boltzmann* distribution, which specifies the fraction of gas molecules that will be moving at any velocity given the temperature of the gas and the mass of each molecule. This description applies to the air around us, to the gas between the stars, and to the gas in atmospheres of stars.

Solid, liquid, and gas are the standard “three states of matter.” If you ionize a gas— that is, if you tear an electron off of a substantial fraction of the gas atoms— it becomes a plasma, the fourth state of matter. Because the individual particles in a plasma are electrically charged (either positive ions or negative electrons), electric and magnetic fields can greatly influence the behavior of a plasma. There are a few ways to create a plasma. One is just to raise the temperature of the gas high enough so that the average kinetic energy of any particle is high enough that collisions will tend to ionize gas molecules. Another is to shine ionizing radiation— generally ultraviolet or x-ray radiation— on the gas. Interstellar gas around young massive stars is typically mostly ionized as a result of the radiation from those stars, even though the temperature of the gas itself isn't high enough to maintain that ionization. A final way to ionize gas is to run high energy particles through it. For instance, if you can shoot an electron beam through dilute gas, it will tend to ionize the gas it passes through. This is how plasma discharge tubes are created.

16.5.1 Quantum Gasses

It *is* possible to create a fundamentally quantum gas, however. If you can lower the temperature of a gas enough while allowing it to stay as a gas e.g. by keeping it at a low enough density that it does not condense into a liquid or solidify), you can get to the point that a substantial fraction of the gas is occupying the lowest states available to it. At this point, the gas is no longer adequately described by classical physics. If the gas is composed of fermions (i.e. each molecule has net half-integral spin), you will have what's called a “Fermi gas”, that is analogous in many ways to the valence electrons in a solid. If, on the other hand, the gas is composed of bosons, and you can lower its temperature enough, it's possible to create a “Bos-Einstein condensate”, where a substantial fraction of the gas molecules all drop into the *same* state (something that would be impossible for atoms). At this point, you can see coherent quantum phenomena for the whole gas, such as interference, because of all the molecules or atoms that are in the same state. A Bos-Einstein condensate was

first created in 1995 (Anderson et al., 1995); this work received the Nobel Prize in physics in 2009.

16.6 Planets, Stars, Galaxies, and Clusters

Once you get past the sizes of everyday solids, liquids and gasses, you enter the realm of astronomical objects. In our Solar System, such objects range from lowly asteroids, through dwarf planets such as Pluto or Ceres, through rocky planets such as the Earth or Mars, on up through the gas giants such as Saturn or Jupiter. However, the vast majority of the mass of our Solar System is in the Sun, the star about which everything else orbits. The Sun is a ball of gas, 300,000 times the mass of the Earth. It is composed of about 74% Hydrogen, about 24% Helium, and 2% everything else. This is a very different composition from the Earth, which is composed mostly of heavier elements. However, the composition of the Sun is more typical of the composition of the Universe as a whole— indeed, the Sun has a greater than average fraction of heavy elements!

Stars collect together into galaxies, gravitationally bound systems of millions, billions, or even trillions of stars. Galaxies themselves collect together into groups and clusters, which may themselves have thousands of galaxies. The groups and clusters we can identify are part of a filamentary structure that fills the Universe. Most galaxy groups and clusters are found in this filamentary web, with vast voids between them. On the largest scales, the universe is homogeneous. That is, if you look at one spot in the universe about a billion or so light-years across, it looks pretty much the same as another, with galaxy clusters on filaments surrounding voids.

16.7 Dark Matter and Dark Energy

All of the matter discussed so far in this chapter only makes up 5% of the energy density of the Universe. (We can talk about mass density and energy density interchangeably, as mass is a form of energy. The amount of energy E in mass m can be found through the famous conversion $E = mc^2$.) Several different lines of evidence have shown us that most of the mass in galaxy clusters is not the luminous mass we can observe. Indeed, this mass can't be baryonic at all. Dark Matter is the name given to this mass; it's not dark the way dust is, which absorbs light is. It neither absorbs nor emits light; it only interacts with light gravitationally (and has been observed partly through the gravitational lensing effect). Dark Matter interacts only via gravity and, perhaps, the Weak Force. In this way, it is similar to neutrinos. We have not identified a particle that can make up Dark Matter. We're very sure that

it's there, and we're very sure that it makes up most of galaxies and galaxy clusters, but we don't know exactly what it is.

Dark Matter, however, itself only makes up about 20-25% of the energy density of the Universe. In the late 1990's, astronomers discovered that the expansion of the Universe is *accelerating*; this discovery was awarded the Nobel Prize in Physics in 2011. This is not something you would expect from regular matter or from Dark Matter. With matter (including Dark Matter), as well as normal forms of energy such as radiation (light), the gravitational effect is attractive. The result would be to tend to slow down the expansion of the Universe. For the Universe to be accelerating, there must be something else in it. Dark Energy is the name given to this unknown substance that evidently makes up about 75% of the energy density of the Universe and that has a negative gravitational effect. Dark Energy is even more unknown than Dark Matter, and indeed some believe that it doesn't really exist as a substance, but is a pointer to our theories of gravity breaking down. Many believe that the most likely candidate for Dark Energy is vacuum energy (see Section 11.4.2), but for now nature of Dark Energy remains one of the primary outstanding unanswered questions in both astronomy and fundamental physics.

