

## Chapter 8: The Fabric of the Universe 1: Particles & Fields

Objects change position in response to forces, and light waves move from stars to our eyes. But what do the objects and waves move through? On the Earth, they move through air and water and on the surface of land and water. In the cosmos, they must pass across space and from the past into the present and future. The “fabric” of the universe – space and time – is therefore an essential aspect of the universe.

An old view considered space as an invisible lattice that does not change with time. We now know that the vacuum of space is much more interesting than that. Consider the Earth as an analogy. Atoms and molecules fill the air, and gravity pulls everything down toward the center of the planet. Similarly, particles and force fields exist throughout space, but, unlike the Earth, the space of the universe is expanding in time. Furthermore, time itself does not pass at a uniform rate everywhere.

The next several chapters present these and other ideas that make up the contemporary scientific view of the universe. We will pay special attention to how we have developed our understanding of space and time. The story involves reluctant scientists being pushed toward an exotic description of the cosmos by observational data that would demand no less. The first task, which we undertake in this chapter, is to discuss the particles and fields that occupy space.

### *The Parts of Atoms*

Before Schrödinger and his colleagues were discovering the quantum laws that describe the behavior of negatively charged electrons in atoms (see Ch. 7), others explored the positive charge that balances the negative. At the beginning of the 20th century, scientists conjectured that atoms contain uniformly distributed electrons and positive charges. In 1909 Ernest Rutherford discovered that the positive charge is instead confined to a very small nucleus in the atom. He did this by directing the positively charged “alpha rays” from radioactive atoms through very thin gold foil. He found that most of the rays passed right through, but a small fraction were deflected by a large angle (see Fig. 8-1). So, the target must be tiny but with a strong electric charge.

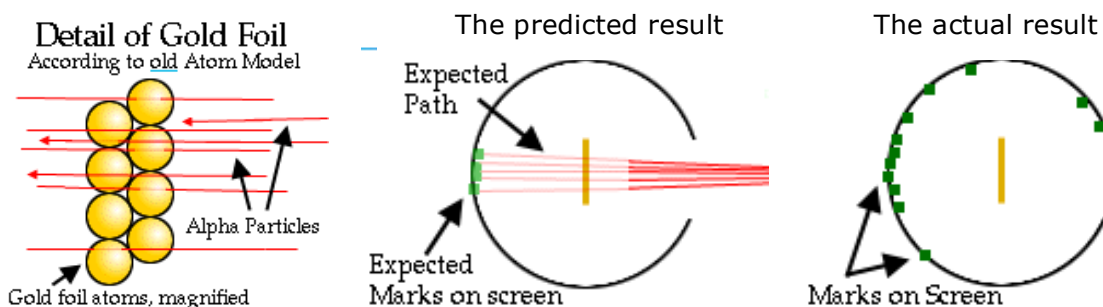


Figure 8-1. Rutherford’s scattering experiment in 1909 implied that all the positive charge in an atom is contained in a tiny core called the “nucleus.” If the positive electric charge were distributed throughout the atom, the path of the alpha rays would only bend slightly, as shown in the middle panel. The actual result, shown at right, was that most of the alpha rays followed a straight path, never having come too close to a positive charge. But a small fraction were deflected by large angles, some even in the backward direction, indicating that each of these alpha rays had encountered a tiny concentration of positive charge. [Source: [http://pdg.lbl.gov/chris/museum\\_version/rutherfords\\_result.html](http://pdg.lbl.gov/chris/museum_version/rutherfords_result.html)]

Further exploration of the nucleus indicated that it contains two types of particles: positively charged protons and slightly more massive (by 0.138%) neutrons that carry zero electric charge. The electrons that reside in “clouds” outside the nucleus (see Ch. 7) are much lighter, with mass 1/1836 times that of a

proton. All particles of a given type are interchangeable, with the same mass, electric charge, and other fixed properties. They can differ in energy, though.

The number of protons in the nucleus, called the atomic number, determines the chemical element of the atom. For example, an atom with one proton is a hydrogen atom, while one with 92 protons is a uranium atom. Atoms of the same element with different numbers of neutrons correspond to different isotopes of that element. The sum of the number of neutrons and number of protons in the nucleus is called the atomic mass. The number of neutrons has no effect on the chemical properties, but is directly related to the stability of the nucleus. Isotopes that are unstable tend to be radioactive, a characteristic that we will discuss later in this chapter.

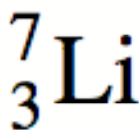
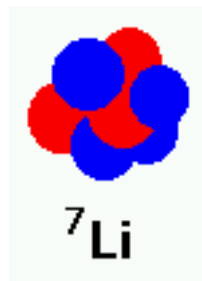
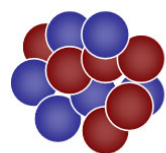
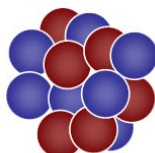


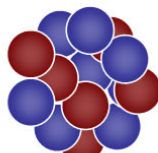
Figure 8-2. Atoms with different atomic numbers have different numbers of protons in their nuclei, so they correspond to different chemical elements. Pictured here is a lithium nucleus, with 3 protons (red) and 4 neutrons (blue). We can show the number of protons — the atomic number — by writing it as a subscript before the chemical abbreviation. The total number of nucleons — protons plus neutrons — appears as a superscript. This nucleus can also be called lithium-7: the element followed by the atomic mass.



carbon-12  
98.9%  
6 protons  
6 neutrons



carbon-13  
1.1%  
6 protons  
7 neutrons



carbon-14  
<0.1%  
6 protons  
8 neutrons

Figure 8-3. Atoms with the same atomic number can have a different number of neutrons, which affects the stability of the nucleus without changing the chemical properties significantly. Shown here are the three isotopes of carbon. The relative abundances in nature are given below the isotope name. The most common by far is carbon-12. All carbon nuclei have 6 protons. [Source: wordpress.mrreid.org]

### *Fundamental Particles: Building Blocks of Matter*

Physicists still use the same basic method as Rutherford's to explore the details of the nuclei of atoms. They bombard atoms with charged particles that they have accelerated to very high kinetic energies, and examine the outcome. Meanwhile, theorists develop models that organize the data within a framework of mathematics and predict new phenomena. The result of this effort is a long list of particles organized by a Standard Model that describes the observations in terms of a relatively small number of fundamental particles and their interactions. Here "fundamental" means that the particle is a basic unit that cannot be separated into pieces. According to the current scheme, electrons are fundamental particles, while protons and neutrons are not.

The fundamental particles belong to three classes:

1. Leptons. This class includes electrons, which we have discussed in Chapter 7. Less familiar leptons are muons and tau leptons, which are very short-lived after they are created in high-energy collisions of particles, and 3 "flavors" of neutrinos — electron, mu, and tau neutrinos.
2. Quarks. Every proton and neutron is composed of three quarks (see Fig. 8-4). There are six different "flavors" of quarks, given the odd names of "up," "down," "top," "bottom," "strange," and "charm." Depending on the flavor, each has an electric charge of  $+2/3$  or  $-1/3$  times the charge of a proton.

3. **Bosons.** Photons — particles of light — are bosons, as are particles called gluons,  $Z$  bosons, and gravitons. These have no electric charge, while  $W$  bosons can have either positive or negative electric charge.

Leptons and quarks are subject to the Pauli exclusion principle: no two leptons or quarks of the same type (e.g., two electrons or two up quarks) can have exactly the same quantum state — same energy and spin, for example — at the same location at any given time. This is what gives diversity to the different elements in the periodic table and makes chemistry possible by forcing electrons to occupy higher energy levels when the lower ones are filled. It also gives structure to the nucleus of an atom, determining which nuclei are stable and which are subject to radioactive decay.

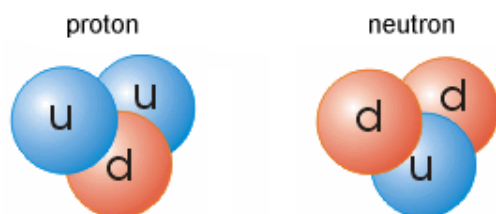


Figure 8-4. A proton is composed of three quarks, two of one type called “up,” each with  $+2/3$  electric charge, and one of another type called “down” with  $-1/3$  charge, giving a net charge of  $+1$ . A neutron is composed of 3 quarks as well, but in this case there are one up and two down quarks so that the net charge is zero. [Source: <http://www.hep.yorku.ca/yhep/quarks.html>]

Bosons are not subject to Pauli exclusion, so that more than one can occupy a single quantum state. In the case of photons, this allows us to make lasers, a concentrated beam of photons with the same wavelength traveling in the same direction in a coherent quantum state. A crucial role of certain bosons is to convey forces between matter particles.

### *Antimatter*

Most types of particle have a counterpart — its anti-particle, which has the same mass but opposite values of all other properties. For example, the anti-particle counterpart to an electron is a positron, which has the electron’s mass but a positive rather than negative electric charge. The existence of positrons was in fact predicted by Paul Dirac in 1930 when he noticed that equations describing an electron in Quantum Mechanics would be symmetric if positrons also existed. When positrons were detected in the laboratory two years later, it was a demonstration of the power of elegant mathematics in describing nature.

Particles with neutral charge have a corresponding anti-particle, which also has neutral charge. For example, the neutron has an anti-neutron, with the same mass but with other properties — e.g., spin — opposite. Other types — photons, for example — can act either as particles or anti-particles.

*Note on notation:* The symbol for an anti-particle is usually a bar over a letter. So, the letter  $p$  symbolizes a proton and  $\bar{p}$  stands for an anti-proton. For charged particles, the bar is often omitted if the sign of the charge is given. So, an anti-proton can be written either as  $\bar{p}$  or  $p^-$ . Here, in order to be clear, we will include the bar *and* the sign of the charge. For example, an anti-proton will be symbolized as  $\bar{p}^-$ . When a particle and its anti-particle counterpart collide, they may annihilate, with the mass-energy being converted to one or more other types of particle-anti-particle pairs. For example, if an electron ( $e^-$ ) and positron ( $e^+$ ) collide, they can annihilate, usually producing a pair of  $\gamma$  rays (high-energy photons). The reverse reaction can happen as well: two colliding  $\gamma$  rays (with one serving as the other’s anti-particle) can convert into an electron/positron pair (or another type of particle/anti-particle pair). In order for this to happen, the sum of the energies of the photons must exceed the energy needed to make the particle/anti-particle pair. We can symbolize such “reversible” collisions with a double-headed arrow:

$$\gamma + \gamma \leftrightarrow e^+ + e^- \quad (8-1)$$

It is therefore possible for a collision to convert one type of particle/anti-particle pair into another type. As we will see in Chapter 11, this type of event played a major role during the very first moments – within the first second – of the history of the universe.

Matter dominates over antimatter in the present-day universe. This asymmetry must have originated in the early stages of the development of the universe.

### ***The Four Fundamental Forces of Nature***

We have introduced a number of particles to nature's construction kit, so we should expect scientific rewards for this added complexity. In particular, it should allow us to explain some otherwise puzzling phenomena. One immediate reward is a description of how forces — more generally “interactions” between particles — operate. Before the 20<sup>th</sup> century, how matter in one place can affect the motion of matter in another was a mystery. The Standard Model explains this as the exchange of bosons.

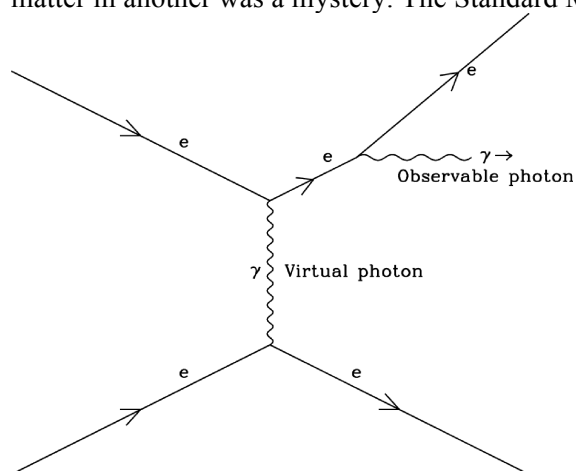


Figure 8-5. Sketch of electromagnetic repulsion between two electrons through the exchange of a virtual photon. The interaction also produces an observable photon. [Source: wikipedia.com]

The easiest force to picture is the repulsion of two negative electric charges, e.g., two electrons (see Fig. 8-5). In the interpretation of forces in the Standard Model, one of the electrons emits a photon toward the second electron. Conservation of momentum causes the first electron to recoil away from the second as the photon leaves it. The second electron, meanwhile, absorbs the photon, which knocks the second electron away from the first. The electrons end up moving away from each other, accomplishing the repulsion. Note that the photon is emitted and absorbed without ever being observed by us. We refer to such a photon as a virtual particle. A second photon that *can* be observed is emitted during the interaction. The changing directions and perhaps speeds of the electrons cause a disturbance in the electromagnetic field that produces electromagnetic waves.

It may surprise you to learn that there are only four known fundamental forces. One very familiar to us is gravity, whose related boson is the graviton, a particle that has not yet been observed. The other forces that we encounter in our ordinary lives — e.g., the sticking force of glue or the outward pushing force of a compressed spring — are really just manifestations of the electromagnetic force. The final two fundamental forces, the strong nuclear force and weak interaction, are less familiar to us.

The fundamental force of electromagnetism is the combination of electric and magnetic forces. In the 19<sup>th</sup> century, the Scottish scientist James Clerk Maxwell realized that the two forces differed only in the relative motion of the electric charges and the detector. For example, a group of stationary charges produces only an electric force; however, if the charges happen to be moving, they create an electric

current, which generates a magnetic force. Photons are the bosons that convey the electromagnetic force. Like gravity (see Ch. 4), the electromagnetic force follows an inverse square law, weakening as one divided by the square of the distance from the charge or current.

A very important fundamental force, the strong nuclear force, (or simply “strong force”), is caused by the interaction of quarks with each other via bosons called gluons. For example, a proton consists of three quarks plus gluons that bind the quarks together. The strong force acts in a manner similar to a thick rubber band, increasing in strength as the distance between the quarks is stretched. Like a rubber band that breaks if stretched beyond its limit, the strength of the force drops off dramatically beyond a certain separation between the quarks. The range of the force is only the size of the tiny nucleus of an atom; beyond this range, the strong force has essentially no effect. The super binding provided by the strong force explains why the nuclei of atoms can stay together despite the repulsion of the protons against each other from the electromagnetic force because of their similar electric charges. Neutrons, which are electrically neutral, can help keep the nucleus together, since the quarks and gluons that compose them provide additional strong force without adding any electromagnetic repulsion.

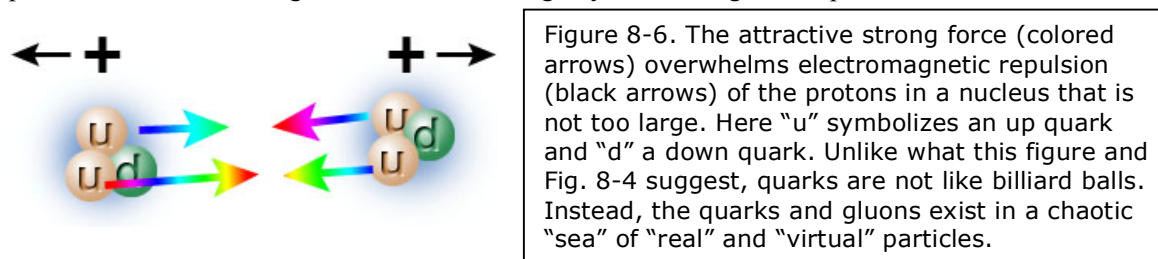


Figure 8-6. The attractive strong force (colored arrows) overwhelms electromagnetic repulsion (black arrows) of the protons in a nucleus that is not too large. Here “u” symbolizes an up quark and “d” a down quark. Unlike what this figure and Fig. 8-4 suggest, quarks are not like billiard balls. Instead, the quarks and gluons exist in a chaotic “sea” of “real” and “virtual” particles.

The final fundamental force is called the weak interaction. As we will see a bit later in this chapter, it plays a role in some types of radioactivity, as well as other interactions between particles.

Each force is important over a certain distance range. Gravity influences matter on the largest scales — even across the distances between galaxies — but is extremely feeble on small scales. The most straightforward way to demonstrate this is to compare the gravitational attraction and the electromagnetic repulsion between two protons separated by a fixed distance. The calculation shows that the electromagnetic repulsion is about 36 orders of magnitude (i.e.,  $10^{36}$  times) stronger than the gravitational attraction inside an atom! So, *gravity is completely negligible when considering the forces that operate within an atom*. Electromagnetism is important on both tiny scales like inside an atom and on quite large scales, even beyond the boundaries of a galaxy. The strong and weak forces, however, only operate over extremely short ranges of the same order as the size of an atomic nucleus or smaller, roughly  $10^{-15}$  and  $10^{-18}$  m, respectively.

### ***Particles, Energy, and the Unempty Vacuum***

Table 8-1 lists all 18 fundamental fermions and bosons. These are the building blocks of every star, rock, animal, and plant in the universe. Are these particles really fundamental or are they composed of yet “more fundamental” entities? Many physicists think that there is indeed a deeper layer to the foundation of physical reality. Some are working on theories that tie together space, time, and particles more closely than does the Standard Model. In fact, we will see in Chapters 11 & 12 that the universe seems to contain at least one type of particle and a source of energy that we have not yet discovered in our laboratories. This suggests that the Standard Model is not the final word in our description of the fabric of the universe.

Fermions			electric charge	Force-carrying Bosons
Quarks	up <b>u</b> $m = 5 \text{ MeV}$	charm <b>c</b> $m = 1500 \text{ MeV}$		
	down <b>d</b> $m = 10 \text{ MeV}$	strange <b>s</b> $m = 150 \text{ MeV}$	bottom <b>b</b> $m = 5000 \text{ MeV}$	
	electron <b>e</b> $m = 0.51 \text{ MeV}$	muon <b><math>\mu</math></b> $m = 106 \text{ MeV}$	tau <b><math>\tau</math></b> $m = 1777 \text{ MeV}$	
Leptons	electron neutrino <b><math>\nu_e</math></b>	muon neutrino <b><math>\nu_\mu</math></b>	tau neutrino <b><math>\nu_\tau</math></b>	

2/3	Photons: Electromagnetic Force
-1/3	
-1	
0	W <sup>+</sup> , W <sup>-</sup> , Z <sup>0</sup> : Weak interaction
	Gluons: Strong force
	Gravitons: Gravity

Table 8-1. The 18 fundamental particles, the building blocks of matter. *Left*: Quarks and leptons (which together are called “Fermions”). *Right*: Bosons, which convey forces. Each type of particle has a corresponding anti-particle, although for some bosons (e.g., photons) the particles and anti-particles are essentially the same. The “masses” are actually values of  $mc^2$  and so are given in energy units; masses of neutrinos are not well determined yet.

### Interchangeable Energy and Mass

As part of his development of Special Relativity, which we will discuss in the next chapter, Albert Einstein realized that mass and energy must be intimately related. He proposed that they are two aspects of one unified property, mass-energy. Energy and mass can be converted into each other according to the famous equation

$$E = mc^2 \quad (8-2)$$

$E$  = energy (in J),  $m$  = rest mass (in kg),  $c$  = speed of light =  $3.0 \times 10^8$  m/s.

Referring to  $m$  as the rest mass means that the mass is measured when a particle or object is stationary.

The equivalence of mass and energy means that particles can be created from energy. Since photons are never stationary, they have no rest mass, so they can be thought of as pure energy. If two photons with enough energy collide, they can be converted into particles, usually a particle and its anti-particle (Fig. 8-7). Equation (8-1) symbolizes such a conversion. The reverse is true as well: a particle and its anti-particle can annihilate – disappear from existence – when they collide, usually producing a pair of photons.

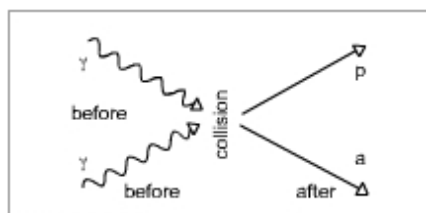


Figure 8-7. The conversion of two colliding  $\gamma$ -ray photons into a particle/anti-particle pair. The reverse of the diagram is also valid: a particle and its anti-particle can annihilate, in this case producing two  $\gamma$ -ray photons.

As we discussed in Chapter 4, total energy is conserved in physical processes. This needs to include the rest-mass energy as well as kinetic energy and all forms of potential energy. So, if we add up all the energy before an event occurs, it must equal the total energy afterward.



When we consider the energy of a particle, the usual unit of Joules is too large to be convenient. Scientists therefore prefer the electron volt (eV), where  $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$ . The energy levels of atoms (see Chapter 7) are measured in eV's. The energies of particles in the nucleus are much higher, so it is common to express their energies in millions of electron volts (MeV;  $1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J}$ ) or even a billion electron volts (GeV;  $1 \text{ GeV} = 1.6 \times 10^{-10} \text{ J}$ ). Since energy and mass are interchangeable, we can state the mass of a particle in terms of the equivalent amount of rest-mass energy. Thus the mass of a proton can be given as  $1.67 \times 10^{-27} \text{ kg}$  or in energy units as 938.272 MeV, where the latter is the value of  $mc^2$  of a proton.

### The Unempty Vacuum

Describing forces as being conveyed by virtual particles implies that these unobserved particles exist even in a vacuum as long as the vacuum contains force fields. Furthermore, we know that the fields are present everywhere. For example, there is no place in the universe that is devoid of gravity, since it is a long-range force and objects with large masses are scattered throughout space.

Where does the mass-energy for these virtual particles come from? The time-energy inequality (eq. 7-7) states that the energy of a particle cannot be known precisely over some time interval  $\Delta t$ , with the uncertainty becoming larger over shorter time intervals. This implies that enough energy to create a virtual particle can be present over a very short time. That is, virtual particles together with their anti-particle counterparts can “pop” into and out of existence on a continual basis. In a sense, they use “borrowed” energy to do this. This is an example of a concept called a quantum fluctuation.

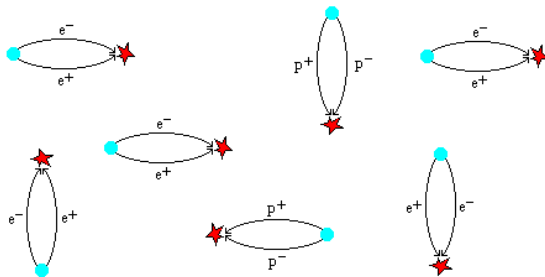


Figure 8-8. A particle/anti-particle pair can pop into existence (at the blue dots) and out of existence (at the red stars) over a very short time interval that is shorter for particles with higher rest-mass energies. [Source: <http://scienceblogs.com/startswithabang/2010/01/08/the-greatest-story-ever-told>]

If quantum fluctuations really occur, then scientists should be able to design an experiment to detect the presence of the virtual particles in an otherwise evacuated space. One such experiment, which observes a phenomenon called the Casimir effect, has actually been carried out in the laboratory. Two conducting metal plates are placed parallel to each other, separated by a very thin gap containing only a vacuum in between. The presence of the plates restricts the properties of the virtual particles that can exist in the gap; e.g., no wavelength longer than the size of the gap is allowed. This causes there to be a lower density, and therefore lower pressure, of virtual particles between the plates than outside. The difference in pressure can be measured, and has been found to agree with the predicted value. A “vacuum” is therefore not empty, but instead contains fields and virtual particles.

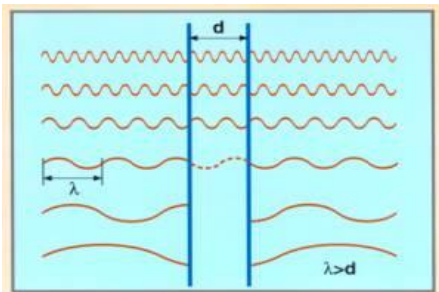


Figure 8-9. The Casimir effect: two metal plates placed extremely close to each other exclude virtual particles with wavelengths longer than the gap between the plates. This lowers the pressure in the gap, so the plates feel a force toward each other. This experiment supports the idea that unobserved virtual particles exist throughout space.

### ***Unification of the Forces***

Scientists yearn to simplify their models of the universe. This desire drives them to search for unifying principles. This concept follows the example of Newton, who combined gravity on the Earth and throughout the cosmos. In the 1860s, Maxwell successfully unified electricity and magnetism. He recognized that the two phenomena are actually just different aspects of the same force.

The 1960s saw the first modern unification, which combined the electromagnetic force with the weak interaction into the “electroweak” interaction. Weak “charges” are closely related to electromagnetic charges and the weak-interaction bosons are similar in some ways to photons, which transmit the electromagnetic force. For example, a  $Z^0$  boson that transmits the weak interaction can produce an interference pattern with a nearby photon. In fact, at extremely short distances the weak interaction is comparable in strength to the electromagnetic force. The apparent difference in the strengths of the two forces in our current, cold world is due to the huge difference in mass between the  $W$  and  $Z$  bosons (roughly 100 times the proton’s mass) and the massless photon. However, in an environment so hot that the average energies of particles exceed the rest-mass energies of the  $W/Z$  bosons, there is a symmetry that causes the distinction between the two forces to vanish. Such conditions existed in the early universe (see Ch. 11).

Theoretical physicists have proposed a similar unification of the strong force with the electroweak interaction. As in the electroweak interaction, the basic idea is that at sufficiently high energies the three forces act the same. The mathematical unification of gravity with the other three forces has not yet been accomplished, and there is no accepted model that incorporates gravity into quantum theory. One promising model, called “string theory,” involves one-dimensional entities called “strings,” either open-ended or in the form of closed loops. These exist in multi-dimensional space, the 4 dimensions of space-time (discussed in Chapter 9) plus 6 or 7 others. According to this model, all particles correspond to different vibration states of the strings. Dimensions other than the four that we experience in macroscopic space-time are “folded” such that they are apparent only over extremely short length scales, much shorter than the size of the nucleus of an atom. We would then not notice them in our macroscopic world, just as your foot doesn’t respond to little cracks in the sidewalk that are much smaller than your shoe.

A major question is the origin of the property we call “mass.” Why do various particles have such widely different masses? Why, for example, is the top quark 200 times heavier than the proton, and 400,000 times more massive than the electron? The electroweak unification theory suggested that another particle, the Higgs boson, is responsible for determining the masses of all the particles. The main mission of the world’s largest particle accelerator, the Large Hadron Collider (LHC) in Geneva, was to try to discover the Higgs boson. In 2012 two teams of experimenters announced that they had indeed found strong evidence for a particle with Higgs-like behavior at an energy of 125 GeV. The properties of the particle appear to be consistent with those predicted for the Higgs boson, so the discovery is regarded as another major triumph of unified field theories.

### ***Conversion from One Element into Another: Radioactivity and Nuclear Fission and Fusion***

Now that we know about the parts of atoms, we can ask whether it is possible to convert one element into another by adding or subtracting some of their contents. Newton and other reputable scientists tried such “alchemy” experiments, but they always failed. We now know that the reason for their lack of success is that chemical reactions supply far too little energy to remove or change a proton in the nucleus of an atom. It is the number of protons that determines the element. Nevertheless, the transmutation of elements is in fact possible through nuclear reactions, which occur in nature as well as in modern laboratories. The processes that cause this to happen follow very specific rules.



Most elements found in nature have stable nuclei; however, many elements have isotopes that are unstable. These eventually decay into other, lighter types of nuclei, emitting a photon or particle as they do. This phenomenon is called radioactivity. Some nuclei can also split into two lighter nuclei, either as a spontaneous process or as the result of being struck by some other particle. This process is called nuclear fission.

Nuclei can also combine in a process called nuclear fusion. These are usually fairly light nuclei so that the new nucleus does not have too high an atomic number and atomic mass. Otherwise, the fusion reaction would not be energetically favorable, with “favorable” meaning that the new nucleus represents a lower – and therefore more stable – energy state than the sum of the energy states of the two original nuclei.

Nuclear fusion is of central importance when we discuss the energy source of stars, which we will study in Chapter 13. All of the processes we are about to discuss – fusion, radioactivity, and fission – are responsible for the wide variety of chemical elements and isotopes found in nature.



Figure 8-10. A tower of building blocks becomes unstable as it becomes taller. Adding a second tower of blocks next to it increases the stability, as long as the second tower is not much taller than the first. Similarly, the nucleus of an atom containing many protons needs more support than their strong force can provide. The strong force from neutrons provides that support, analogous to the 2<sup>nd</sup> tower of blocks. [Source: <http://images.chron.com/blogs/momhouston/re-called%20blocks.jpg>]

### *Unstable Nuclei*

Why would a nucleus be unstable? Consider a tower of toy building blocks. Even if a child builds the tower on a hard, flat floor, it becomes less and less stable as more blocks are added. This is partly because the potential energy of the top blocks is high relative to the floor, so a lower energy state of multiple shorter towers or individual blocks scattered on the floor is a “preferred,” more stable state of the system. The other reason is that the highest blocks are not well connected to the lowest ones. In the case of blocks, this is because the surfaces are not perfectly smooth and flat and they do not line up exactly in the vertical direction because of imperfect stacking. In the nucleus of an atom, the electromagnetic repulsion of the protons counters the attraction of the strong force between protons on opposite sides of a large nucleus. Adding neutrons helps, since their extra strong force is like building a second tower of wider, more stable blocks next to the first tower, providing strength to the structure. But if the second tower is too high, the stability of the entire structure will be lower.

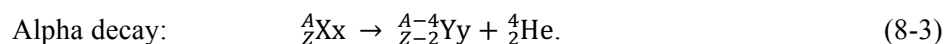
Consider a relatively large nucleus filled with many protons and neutrons. There is still more negative binding energy from the strong force than positive energy of electromagnetic repulsion, so the nucleus remains intact for some time. But, according to Quantum Mechanics, there is a small probability at any given time that one or more components of the nucleus will momentarily have enough energy to be ejected. (This is often called “tunneling” through a potential-energy barrier). This event will increase the magnitude of the binding energy of the nucleus that remains. Since the binding energy is negative, the final energy state is lower than when the nucleus was larger. The average time that it takes for this to happen — from less than a second to billions of years — depends on the number of protons and neutrons.

### Radioactivity

“Radioactivity” is a general term for the emission of particles by a nucleus as it drops to a lower, more stable energy state. The particles were initially called “rays” or “radiation,” which led to the “radio” in “radioactivity” — there is no relation to radio waves. They were given the three first letters in the Greek alphabet,  $\alpha$ ,  $\beta$ , and  $\gamma$ . Physicists later identified these as ( $\alpha$ ) the nuclei of helium atoms, ( $\beta$ ) electrons or positrons, and ( $\gamma$ ) high-energy photons. We consider each of the types of decays in turn.

1. Alpha decays: In this process, the original nucleus becomes a lighter nucleus while also producing the nucleus of a helium atom (which contains 2 protons + 2 neutrons). For example, after an average time of 4.5 billion years, uranium-238 ( $^{238}_{92}\text{U}$ ) will eject a helium nucleus and become thorium-234 ( $^{234}_{90}\text{Th}$ ), which has two fewer protons and two fewer neutrons.

We can generalize from this example. We use the symbol  $^A_Z\text{Xx}$  to represent some element Xx with atomic number  $Z$  and atomic mass  $A$ . The atomic number is simply the number of protons in the nucleus of the atom; it defines which element the atom belongs to. The atomic mass is the sum of the number of protons and number of neutrons. Together, protons and neutrons are called “nucleons.” We use  $^4_2\text{He}$  to represent the alpha particle, since it is a helium nucleus. We use Yy to represent the resultant “daughter” product (lighter element) of the decay. Then we can write the general equation of an alpha decay as



Notice how the sum of the superscripts on the right-hand side equals the value of the superscript on the left-hand side, and the same for the subscripts. This is because the number of nucleons – protons plus neutrons – is conserved in a nuclear reaction such as a radioactive decay. We also know that the total energy of the Yy and He nuclei must equal the rest-mass energy that the Xx nucleus had before the decay:

$$m(^{A-4}_{Z-2}\text{Yy})c^2 + m(^4_2\text{He})c^2 + \text{kinetic energy} = m(^A_Z\text{Xx})c^2 \quad (8-4)$$

$m()$  = mass of nucleus in the parentheses (in kg),  $c$  = speed of light =  $3.0 \times 10^8$  m/s, Yy represents the “daughter” nucleus created by the process, Xx represents the original nucleus,  $Z$  = atomic number = number of protons of original nucleus,  $A$  = atomic mass = number of nucleons of original nucleus. The binding energy of the nucleus is included in the rest-mass energy, so we do not need to include it separately.

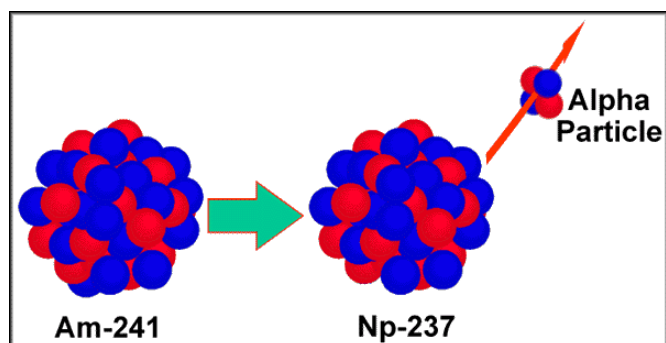
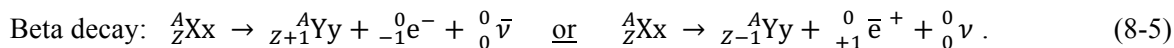


Figure 8-11. An alpha decay. A nucleus of an element with a high atomic number ejects a helium nucleus and becomes the nucleus of a lighter element. In the example illustrated here, Americium-241 ( $^{241}_{95}\text{Am}$ ) is converted into Neptunium-237 ( $^{237}_{93}\text{Np}$ ) plus a helium nucleus ( $^4_2\text{He}$ ), also called an “alpha particle.” [Source: [newcastle-schools.org.uk/nsn/chemistry/Radioactivity](http://newcastle-schools.org.uk/nsn/chemistry/Radioactivity)]

2. Beta decays: In this reaction, an atom releases either an electron or a positron, plus an anti-neutrino or a neutrino. In the first process, the weak interaction causes a neutron to turn into a proton in the nucleus, which increases the atomic number by one. In the second type of beta decay, a proton in the nucleus

becomes a neutron, so the atomic number decreases by one. The final proton or neutron remains in the nucleus. When writing the reaction equation, we use the same symbols as before, plus  $e^-$  to signify an electron,  $e^+$  for a positron,  $\nu$  for a neutrino, and  $\bar{\nu}$  for an anti-neutrino. The equation of a beta decay is then



Xx represents the original nucleus, Yy represents the “daughter” nucleus created by the process,  $Z$  = number of positive charges,  $A$  = atomic mass = number of nucleons,  $e^-$  represents an electron,  $e^+$  is a positron (anti-electron),  $\nu$  is a neutrino, and  $\bar{\nu}$  is an anti-neutrino.

Note that the atomic mass does not change, since no nucleon was ejected from the nucleus, and that the atomic number  $Z$  is now the number of positive charges, since protons are no longer the only positively charged particles involved. The opposite of a beta decay can happen as well. An electron that penetrates the nucleus of an atom can combine with a proton to make a neutron and a neutrino. The atomic number then decreases by one. This is called electron capture. The reaction equation for this is:

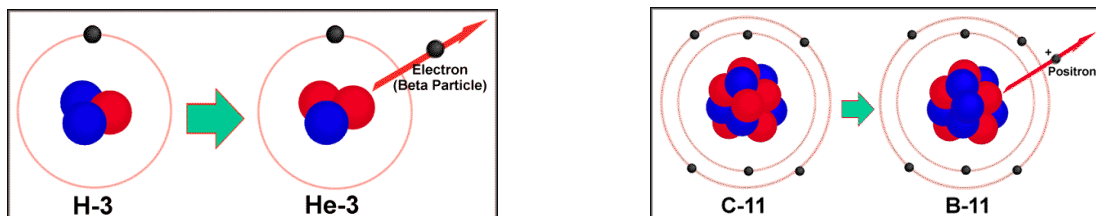
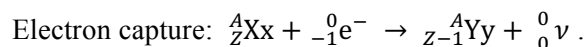


Figure 8-12. The two varieties of beta decay. Protons are the red circles and neutrons are blue. *Left:* a nucleus with too many neutrons (here, tritium,  ${}^3_1\text{H}$ , an isotope of hydrogen) ejects an electron (and an anti-neutrino, not pictured) to become the nucleus of an element with a higher atomic number by one (a light isotope of helium,  ${}^3_2\text{He}$ , in this example). *Right:* a nucleus (in this case a light isotope of carbon,  ${}^{11}_6\text{C}$ ) with too few neutrons ejects a positron (and a neutrino), becoming the nucleus of an element with a lower atomic number by one (in this case an isotope of boron,  ${}^{11}_5\text{B}$ ). [Source: [lhs.lps.org/staff/sputnam/chem\\_notes](https://lhs.lps.org/staff/sputnam/chem_notes)]

3. The third type of radioactive decay is not as important to our discussion. Gamma rays ( $\gamma$  rays — high-energy photons) are emitted from a nucleus. This happens when the only change is a relaxation of the nucleus to a lower, and therefore more stable, energy state.

### Stable Nuclei

Radioactive decays all release energy in the form of a photon ( $\gamma$  ray) or kinetic energy of the “daughter” products. In other words, the reactions are all energetically favorable, since the nucleus is in a lower energy state after the decay than before. As we explained above with the help of the building block analogy, the energy of a nucleus can become too high if there are either too many protons relative to the number of neutrons or vice versa.

If there are too many neutrons in comparison to protons, then the highest-energy neutrons will tend to beta-decay (first half of eq. 8-5) to turn into a proton, which will occupy a lower energy state than did the now-decayed neutron. Likewise, if there are too few neutrons compared to protons, then the nucleus will undergo the second type of beta decay (2nd half of eq. 8-5) in which a proton in a high energy state

becomes a neutron. In both cases, the energy lost by the nucleus goes into the particles that are created and released.

This tendency for nuclei to decay if they are in too high an energy state means that there is a small range in the number of neutrons that will result in a stable nucleus of any given element. Figure 8-13 shows this “valley of stability” (dark streak); the light shaded area signifies isotopes that are radioactive, while the blank area corresponds to combinations of numbers of protons and neutrons that have never been observed because they would have energies too high for such a nucleus to form at all.

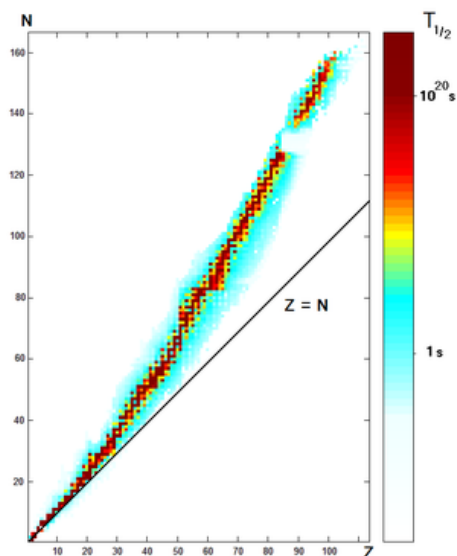


Figure 8-13. Graph plotting the number of neutrons in the nucleus  $N=A-Z$  vs. the number of protons (= the atomic number  $Z$ ). The small squares indicate nuclei that can exist long enough for an observation of them to occur. The deep red squares correspond to the most stable nuclei. The average decay time for the nuclei is given on the right-hand scale, which is in powers of 10. Any time longer than about  $4 \times 10^{17}$  s is longer than the age of the universe. The diagonal line corresponds to the case in which the number of neutrons equals the number of protons in the nucleus.  
[Source: <http://www.nationmaster.com/encyclopedia/atom>]

### Half-life of an Unstable Nucleus

The decay of an unstable nucleus occurs at a random time that follows the probability laws of Quantum Mechanics. Although we cannot predict exactly when a given unstable nucleus will decay, we can predict the time — called the half-life,  $t_{1/2}$  — at which point half of the nuclei in a sample will have decayed into lighter “daughter” nuclei. The half-life of an isotope can be determined by observing decays in the laboratory.

This means that we can use radioactive decay as a clock for determining the age of materials. In many cases the daughter nucleus is extremely rare in nature, so essentially all the nuclei of this isotope are products of the decay. The ratio of daughter to parent nuclei found in a sample then determines what fraction of the collection of parent nuclei have decayed. If the ratio is 1:1, for example, then half the original parent nuclei have decayed and the age of the material must equal the half-life. (If the daughter particle is also unstable, the analysis is more complicated, but the principle is the same.)

We can formulate this concept with some equations. The fraction of the parent nuclei that have not yet decayed is

$$F(\text{remaining}) = \frac{1}{2^q}, \quad (8-6)$$

where  $q$  is the number of half-lives that have passed since the material formed,  $q = t/t_{1/2}$ . Figure 8-14 represents equation 8-6 in graphical form. The equation for  $q$  is

$$q = \frac{\ln f(\text{remaining})}{\ln 2} = -1.44 \ln F(\text{remaining}). \quad (8-7)$$

(Here “ln” symbolizes the natural logarithm function.) The age of the material is then given by

$$\text{age} = t = q t_{1/2}. \quad (8-8)$$

It is easiest to consider examples in which  $q$  is an integer. For example, after one half-life  $q=1$ , and half of the parent nuclei remain. After two half-lives  $q=2$ , so  $(1/2)^2=1/4$  remain. And after three half-lives  $q=3$ , and  $(1/2)^3=1/8$  remain.

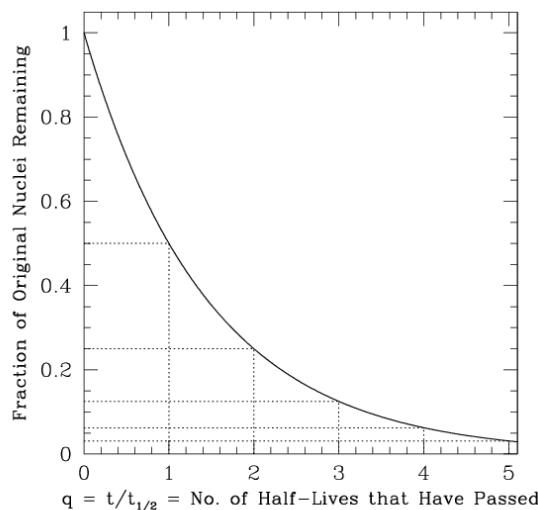


Figure 8-14. The decrease in the number of radioactive nuclei that remain after a given number of half-lives have passed, symbolized by  $q$ . Dotted lines are drawn for integer values of  $q$ .

### Nuclear Fusion

Nuclear fusion is the union of two nuclei to form a heavier nucleus. For example, two hydrogen nuclei (each of which is just a proton) can combine to form a deuterium nucleus (an isotope of hydrogen containing a proton plus a neutron), emitting a positron and a neutrino in the process:



This reaction can occur because the deuterium nucleus has less mass-energy than the combination of the original two hydrogen nuclei. The rest of the energy ends up going to the (massless) photon, the neutrino, and the kinetic energy of the deuterium nucleus.

Since positively charged nuclei repel each other until they come so close that the strong force takes over, nuclear fusion will occur only at very high temperatures (millions of Kelvins). Under such conditions, the nuclei can approach each other so fast that the repulsion is not strong enough to keep them from colliding, and fusion occurs. Once this happens, energy is released as long as the final nucleus has a lower energy state than the sum of the energies of the two original nuclei. Iron, with 26 protons, is the heaviest nucleus that can be made with fusion reactions that release energy. This fact plays an important role in the deaths of stars much more massive than the Sun, as we will see in Chapter 13.

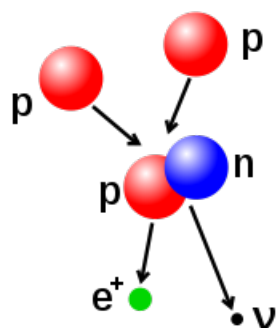


Figure 8-15. Nuclear fusion reaction in which two colliding hydrogen nuclei (which are just protons) combine to form a deuterium nucleus, an isotope of hydrogen with one proton and one neutron. The process also creates a positron ( $e^+$ ) and a neutrino ( $\nu$ ).  
[Source: <http://www.nationmaster.com/encyclopedia/atom>]

### Summary

Since the time when Ernest Rutherford's group discovered the nucleus in the early 1900's, scientists have unveiled an amazingly rich structure to this tiny kernel of the atom. The positive charges are carried by protons, which exist alongside electrically neutral neutrons, attracted to each other by the short-ranged strong nuclear force.

All the natural forces known in the universe are aspects of four fundamental forces: gravity, electromagnetism, the strong force, and the weak interaction. Gravity is important over long ranges, but is negligible for individual atoms. Electromagnetism is both long- and short-ranged. The strong and weak interactions act only over extremely short distances,  $10^{-15}$  m and  $10^{-18}$  m, respectively.

The Standard Model of particle physics provides a coherent picture of the underlying building blocks of matter in terms of three classes of fundamental particles: quarks, leptons, and force-carrying bosons. The model has been extremely successful in terms of its ability to make predictions that experiments have verified. There are still challenges, such as the incorporation of gravity with the other forces into a unified field theory, and explaining the values of the masses of the various members of nature's "particle zoo." Some progress is being made in this direction through string theory, and a few physicists have even been so bold as to claim that soon there will be a successful "Theory of Everything." The history of science, however, shows us that such expectations have generally been misdirected and that nature holds surprises for us beyond our current imagination.

Each particle has an anti-particle counterpart. These have identical masses, but some other properties — electric charge, for example — have equal but opposite values. A collision of two high-energy  $\gamma$ -ray photons can create a particle-anti-particle pair. Conversely, the collision of a particle with its anti-particles annihilates the two, creating (for example) two  $\gamma$ -ray photons in the process. Because of the time-energy inequality, enough energy can appear — even in a vacuum — to create a particle-anti-particle pair for a very short time. Such "virtual particles" are constantly popping in and out of existence.

Not all nuclei are stable. An excess of protons or neutrons leaves a nucleus susceptible to radioactive decay, in which the nucleus relaxes to a lower (more deeply negative) energy state while emitting one or more particles. Some of these decays — ejection of a helium nucleus in an alpha decay, ejection of an electron and an anti-neutrino or a positron plus a neutrino in a beta decay, or the capture of an electron by a nucleus — convert the nucleus to one of a different element. The occurrence of these decays follows the probability laws of Quantum Mechanics. The fraction of radioactive atoms that have decayed in an object indicates the age of the item.



Nuclei can combine through nuclear fusion, which occurs most readily between nuclei with low atomic numbers (small numbers of protons) inside the cores of stars (to be discussed in Ch. 13). In general, nuclear fusion of light elements and nuclear fission (splitting apart) of heavy elements convert mass to energy.

In Chapter 11, we will explore the nature of the universe and find that the theory of particle physics plays a major role in the early history of the cosmos.

### ***Glossary***

**Nucleus:** The tiny core of an atom, containing all of its positive charge.

**Particle:** A tiny, distinct bit of matter or energy. A particle of a given type is interchangeable with another particle of the same type. Examples: electrons, photons, neutrons, quarks

**Nucleon:** A particle found in the nucleus of an atom. Usually refers to a proton or neutron. The number of nucleons is given the symbol  $A$ .

**Proton (symbol  $p$  or  $p^+$ ):** A particle with positive electric charge. Its charge is equal and opposite to that of an electron but its mass is 1836 times higher. A proton is composed of 3 quarks bound to each other through interactions involving gluons.

**Neutron (symbol  $n$ ):** An electrically neutral particle. Its mass is slightly higher than that of a proton. A neutron is composed of 3 quarks bound to each other through the action of gluons.

**Electron (symbol  $e$  or  $e^-$ ):** A fundamental particle of the lepton family of the fermion class, with negative electric charge, that is an important component of an atom.

**Photon (symbol  $\gamma$ ):** Unit of light (see Ch. 5). A fundamental particle of the boson class. Photons convey the electromagnetic force. A photon has zero rest-mass.

**Fermion:** A class of particle that includes leptons and quarks. Examples: electrons, quarks, protons, neutrons, neutrinos

**Pauli exclusion principle:** Law expressing that no two fermions can share the exact same quantum state. Allows the possibility of building complex structures through addition of fermions.

**Boson:** A class of particle. All force-carrying particles are fundamental bosons. Examples: photons, gluons, gravitons

**Lepton:** A family of matter particles that includes six fundamental particles and their anti-particle counterparts. Examples: electrons, muons, neutrinos

**Quark:** A family of matter particles that includes six fundamental particles (up, down, top, bottom, charm, and strange quarks) with electrical charges of  $+2/3$  or  $-1/3$  times that of a proton.

**Gluon:** Fundamental, massless particle of the boson class that conveys the strong force.

**$W$  and  $Z$  bosons:** Fundamental particles of the boson class that convey the weak interaction. Their masses are very high compared to those of protons.

**Higgs boson:** Hypothesized fundamental particle that interacts with other particles to determine their masses. A new particle with properties matching those predicted for the Higgs boson was discovered in 2012 in experiments with the Large Hadron Collider.

**Graviton:** Fundamental, massless particle of the boson class that conveys the gravitational force. (Not yet detected – a single graviton interacts with matter too weakly to detect with current techniques.)

**Standard Model of particle physics:** Theoretical scientific framework designed to describe the composition of matter and the transmission of forces.

**Fundamental particle:** A basic unit of matter or energy that cannot be broken down into smaller units. There are 18 types of known fundamental particles, plus their anti-particle counterparts.

**Elementary particle:** A fundamental particle.

**Fundamental force:** One of four basic interactions between particles found in nature. Includes gravity, electromagnetism, the strong force, and the weak interaction.

**Electromagnetism:** A fundamental force that affects electrically charged particles. Important on both long and short ranges. Transmitted by photons. This one force combines the phenomena we call electricity and magnetism.

**Strong (nuclear) force/interaction:** A fundamental force that attracts quarks to each other. Very short-ranged, transmitted by gluons.

**Weak interaction:** A fundamental force that plays a role in radioactive decays. Very short-ranged, transmitted by  $W$  and  $Z$  bosons.

**Anti-particle (denoted by a bar over a letter):** The “partner” of a particle with the same mass but opposite electric charge. When a particle and its anti-particle meet, they can annihilate, creating one or more particle/anti-particle pairs of another type. (See eq. 8-1 for an example.) Examples: positrons (anti-particles of electrons), anti-protons, anti-neutrinos

**Positron (symbol:  $\bar{e}^+$ ):** Anti-particle of an electron.

**Neutrino (symbol:  $\nu$ ):** A very low-mass, electrically neutral fundamental particle belonging to the lepton family. Comes in 3 “flavors” – electron, mu, and tau neutrinos.

**Virtual particle:** A boson (e.g., photon) or other particle that disappears before it can be observed. For example, according to the Standard Model, a virtual boson is both emitted and absorbed during an interaction that causes a force to be transmitted.

**Mass-energy:** Following Einstein’s equation  $E=mc^2$ , mass and energy are two forms of the same characteristic of matter. Here  $m$  is the rest mass, *i.e.*, the mass measured when the particle is not moving.

**Rest mass (symbol:  $m$ ):** Mass as measured when an object or particle is stationary. This is the common definition of mass.

**Conservation of energy:** A physical law stating that the total energy of a system remains constant. For example, in a radioactive decay, the mass-energy of the initial nucleus equals the sum of the mass-energy of the nuclei and particles that remain after the decay.

**Quantum fluctuation:** Name given to variations in the energy of a small region of space over a very short time interval, as allowed by the time-energy inequality (expression 7-7).

**Unification of forces:** Attempt to describe the fundamental forces of nature in the same mathematical form. The forces then act the same when the energy per particle involved is very high.

**Higgs boson:** a proposed particle that interacts with other particles to give them the property of mass. It has not yet been detected.

**Atomic number (symbol:  $Z$ ):** The number of protons in the nucleus of an atom. The atomic number specifies the element.

**Atomic mass (symbol:  $A$ ):** The total number of nucleons – protons plus neutrons – in the nucleus of an atom. The atomic mass specifies the isotope of the atom.

**Element:** A name given to similar atoms. All atoms of an element have the same atomic number.

**Isotope:** A term that differentiates among the atoms of a given element according to the number of neutrons in the nucleus.

**Decay:** Conversion of a particle or atom into other particles or atoms.

**Radioactivity (or radioactive decay):** Emission of particles from the nucleus of an atom.

**Alpha ray (symbol:  $\alpha$  or  ${}^4_2\text{He}$ ):** A helium nucleus that is emitted during a radioactive alpha decay. (See eq. 8-3.)

**Alpha decay:** Conversion of an atom into one with two fewer protons and two fewer neutrons. An alpha ray (helium nucleus) is ejected from the nucleus by this process. (See eq. 8-3.)

**Beta decay:** Conversion of an atom into one with a higher or lower atomic number. A neutron decays into a proton or a proton into a neutron. An electron and anti-neutrino or a positron and neutrino are emitted. (See eq. 8-5.)

**Electron capture:** the combining of an electron with a nucleus to convert one of the protons into a neutron. Decreases the atomic number by one without changing the atomic mass.

**Nuclear fission:** The splitting apart of the nucleus of an atom into less massive pieces, each with lower atomic number.

**Half-life (symbol:  $t_{1/2}$ ):** The interval of time over which an unstable nucleus has a 50% probability of decaying. For a sample containing many unstable nuclei, half of them will have decayed during one half-life. (See eqs. 8-6 and 8-7.)

**Nuclear fusion:** Process by which two nuclei combine to form a nucleus with a higher number of nucleons. Important in the conversion of mass to energy in a star.

## Questions for Discussion

- A. What property of bosons prevents them from being good building blocks of matter?
- B. What would happen if you shook hands with a twin made completely out of antimatter?
- C. How do we know that there are not portions of the Earth that are made of anti-matter rather than matter? How could we check whether other planets or other parts of the universe might be made of anti-matter?
- D. What would be the advantages and disadvantages of using matter/anti-matter annihilation to propel a spacecraft?
- E. If gravity is completely unimportant on the microscopic atomic scale, why is it so important on the macroscopic scale of everyday life?
- F. If a force is caused by a virtual particle, how fast can the force be transmitted? For example, if you connect a powerful battery a wire coil to make an electric circuit, how fast would the outer boundary of the new force field move?
- G. Explain how two forces that act quite differently in a typical laboratory on the Earth could act the same in a setting where the temperature is extremely hot.
- H. Can you think of a way to detect a single particle created during a quantum fluctuation so that it becomes “real” rather than virtual?
- I. How do neutrons help to make a nucleus stable? How can they cause a nucleus to be unstable?
- J. The masses of nuclei can be measured in different units. One system that is used is called Unified Atomic Mass Units (amu), where 1 amu is equivalent to a rest-mass energy of 931.494 MeV, where  $1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J}$ . In this system, the mass of an atom of  $^{12}_6\text{C}$ , the isotope of carbon with 6 protons and 6 neutrons, is defined to be exactly 12.00000 amu. The mass of a free neutron is measured to be 1.008665 amu, and the mass of a free proton is measured to be 1.007276 amu. Subtract the mass of the  $^{12}_6\text{C}$  nucleus from the sum of the masses of its constituents, and explain why this is greater than zero. That is, why is the mass of the nucleus less than the sum of the masses of its parts?
- K. Electron capture is the reverse process of the beta decay given in the first half of equation 8-5. The text does not mention positron capture, the reverse of the second half of equation 8-5. Why would this process be much less common?
- L. Reasoning from analogy with atomic spectra, discuss the possible origin of the  $\gamma$  rays that are emitted in some radioactive decays.
- M. A free neutron (a neutron outside a nucleus) decays with a half-life of 887 seconds through the beta decay process. But neutrons that are inside a stable nucleus generally do not decay. Can you think of a reason why this is the case?
- N. Why can't we use the nuclear processes of radioactivity, fission, or fusion to realize the ancient goal of the alchemists to become very rich by converting mercury into silver or lead into gold?

## Sample Problems on Nuclei and Particles

1. A free neutron is created at rest in a physics laboratory. About 15 minutes later, it decays into a proton, an electron, and an electron anti-neutrino. What is the maximum possible energy of the electron if the mass-energy of the anti-neutrino can be neglected? The rest-mass energy of a neutron is 939.565 MeV, that of a proton is 938.272 MeV, and that of an electron is 0.510999 MeV.

Answer: Since energy is conserved, the rest-mass energy of the neutron will be converted into rest-mass plus kinetic energy of the proton, electron, and antineutrino. The electron will have maximum energy if the energy of the proton and antineutrino are minimized. If we ignore the mass-energy of the anti-neutrino, its minimum energy is close to zero, while the minimum energy possible for the proton is its rest-mass energy, 938.272 MeV.

We can express the conservation of energy as  $E_{\text{initial}} = E_{\text{final}}$ , where  $E_{\text{initial}}$  is the energy of the neutron and  $E_{\text{final}}$  is the sum of the energies of the proton ( $p^+$ ), electron ( $e^-$ ), and anti-neutrino ( $\bar{\nu}$ ). Since the neutron started at rest,  $E_{\text{initial}} = 939.565 \text{ MeV}$ . So, we have

$$E_{\text{initial}} = E_{\text{final}} = E_{\text{min}}(\bar{\nu}) + E_{\text{min}}(p^+) + E_{\text{max}}(e^-)$$

$$E_{\text{max}}(e^-) = E_{\text{initial}} - E_{\text{min}}(\bar{\nu}) - E_{\text{min}}(p^+) = 939.565 \text{ MeV} - 0 - 938.272 \text{ MeV} = \underline{1.293 \text{ MeV}}.$$

Since this is greater than the rest-mass energy of an electron, the electron will possess a substantial amount of kinetic energy. (If the answer were less than the rest-mass energy of an electron, the decay would not be possible.)

2. A uranium-235 ( $^{235}_{92}\text{U}$ ) nucleus undergoes an alpha decay. What is the final nucleus that is created? Use both ways of symbolizing the nucleus, as done above for uranium-235,  $^{235}_{92}\text{U}$ .

Answer:

From eq. (8-3),  $^A_Z\text{Xx} \rightarrow ^{A-4}_{Z-2}\text{Yy} + ^4_2\text{He}$ , where  $^A_Z\text{Xx}$  is  $^{235}_{92}\text{U}$ .

So,  $235 - 4 = 231$  and  $92 - 2 = 90$  and the final result is  $^{231}_{90}\text{Th}$ , thorium-231

3. A nuclear reactor creates 8 g of plutonium-238 ( $^{238}_{94}\text{Pu}$ ), which undergoes an alpha decay with a half-life of 89 yr. If the 8 g of plutonium-238 is stored in a lead box, how long will it take for the box to contain only 1 g of plutonium-238?

Answer: The key to this problem is to determine the number of half-lives that are needed to reduce the 8 g to 1 g. After this time, equal to the age  $t$ , 1/8 of the sample will remain. We need to convert this to a power of  $1/2$ . Fortunately, this is easy: We know that  $1/8$  is  $(1/2)^3$ . So, following eq. 8-6 and the discussion preceding it, we can see that  $q=3$  half-lives must pass. Since one half-life is 89 yr, we can use eq. 8-8 to obtain:  $t = qt_{1/2} = (3)(89 \text{ yr}) = \underline{270 \text{ yr}}$  (rounded to two significant digits).

## Homework Problems

1. In energy units, the rest-mass energy of a proton is 938.272 MeV, that of a neutron is 939.565 MeV, and that of an electron is 0.510999 MeV. A free neutron (a neutron outside a nucleus), originally at rest, decays through the beta decay process, producing a proton, an electron, and an electron anti-neutrino. Calculate the maximum total energy that the anti-neutrino can have.

2. A thorium-230 ( $^{230}_{90}\text{Th}$ ) nucleus undergoes an alpha decay. Determine the final nucleus that is created. Use both ways of symbolizing the nucleus, as done above for thorium-230,  $^{230}_{90}\text{Th}$ .
3. A thorium-234 ( $^{234}_{90}\text{Th}$ ) nucleus undergoes a beta decay in which an electron and anti-neutrino are emitted. Determine the final nucleus that is created. Use both ways of symbolizing the nucleus, as done above for thorium -234,  $^{234}_{90}\text{Th}$ .
4. A sodium-22 ( $^{22}_{11}\text{Na}$ ) nucleus undergoes a beta decay in which a positron and neutrino are emitted. Determine the final nucleus that is created. Use both ways of symbolizing the nucleus, as done above for sodium-22,  $^{22}_{11}\text{Na}$ .
5. A beryllium-7 ( $^7_4\text{Be}$ ) nucleus undergoes an electron capture in which a neutrino is emitted. Determine the final nucleus that is created. Use both ways of symbolizing the nucleus, as done above for beryllium-7,  $^7_4\text{Be}$ .
6. A carbon-14 nucleus ( $^{14}_6\text{C}$ ) undergoes a beta decay with a half-life of 5730 yr. An ancient artifact has 1/16 the original number of  $^{14}_6\text{C}$  atoms.
  - a. Determine the age of the artifact.
  - b. Determine the fraction of the original number of  $^{14}_6\text{C}$  atoms that will remain as  $^{14}_6\text{C}$  atoms when the artifact is twice as old as it is now.

### **Homework Questions Requiring Logic**

*Explain how you arrive at your response to each question.*

7. A new particle is discovered in experiments involving high-energy particles. It has a very short average lifetime, after which it decays into an electron, a positron, and two  $\gamma$  rays. The rest-mass energy of an electron or a positron is 0.511 MeV. The sum of the energies of the two  $\gamma$  rays always exceeds 1 MeV. Determine the minimum rest-mass energy (in MeV) of the new particle.
8. An electron that passes by another electron will produce a photon, and the two electrons will still remain. But a  $\gamma$ -ray photon passing by an electron cannot produce only a single electron without also producing a positron. Why is the first process possible and the second process impossible?
9. Look at the periodic table of chemical elements in Appendix B. The most stable nucleus of gold (symbol: Au) has an atomic number of 79 and an atomic mass of 197 ( $^{197}_{79}\text{Au}$ ).
  - a. What isotope of what element can make this gold nucleus with an alpha decay?
  - b. What isotope of what element can make this gold nucleus with an electron-emitting beta decay?
  - c. What isotope of what element can make this gold nucleus with a positron-emitting beta decay?
10. Imagine that you had a test tube containing four identical radioactive atoms with a half-life of 1 hour that you have just produced with a nuclear reactor. What is the probability that none of the nuclei of the atoms will have decayed after one hour? [*Hint: As a close analogy, think of the probability that four coins that you flip will all fall with the head side up.*]