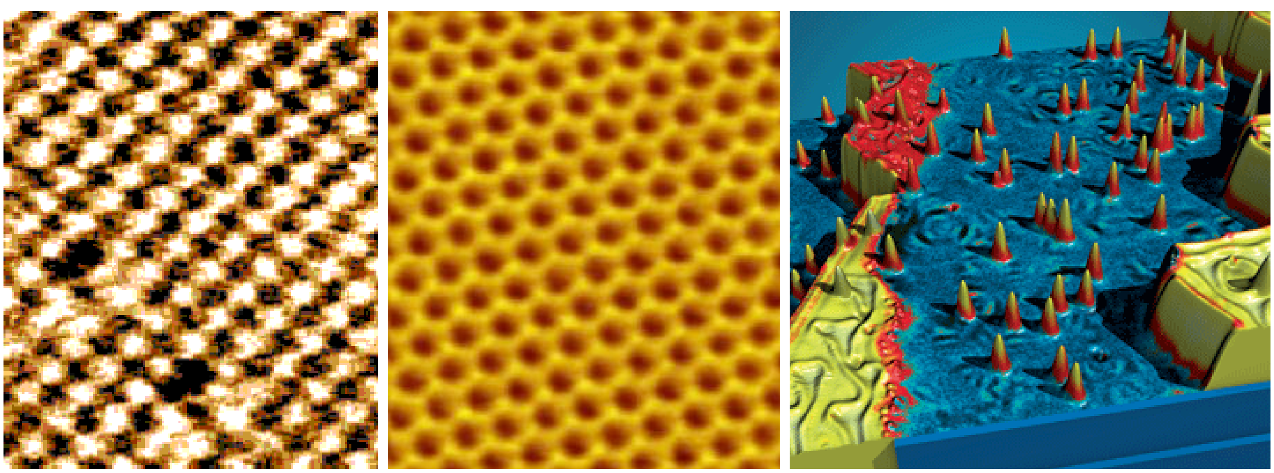
Chapter 4

Known particles

4.1 Ordinary matter

What are you made of? Blood and guts and bone and muscle is a little more accurate than the traditional mother goose rhyme. Your tissues are made of cells, which are little bags of chemicals: proteins, nucleic acids, lipids, water and other molecules. Each molecule is a specific assembly of atoms. And each atom contains an atomic nucleus surrounded by some number of electrons.

This should all sound familiar. But stop for a minute and ask how this is known. You can see cells in a microscope. But for objects smaller than cells direct observation gets more difficult. How do you know that atoms and molecules, or electrons and nuclei, exist? Is it just because someone told you so? What's the evidence?



(a) (b) (c)

Figure 4.1: Three examples of modern atomic scale imaging. Image (a) shows the surface of sodium chloride, imaged by atomic force microscopy (AFM). Note the two surface defects. Image (b) (courtesy of E. Andrei) is a scanning tunneling microscope (STM) image of a freely suspended graphene sheet — a single atomic layer of graphite. The hexagonal structure, reflecting the sp^2 hybridization of valence electrons in the carbon atoms, is obvious. Image (c) (from the cover of the April 4, 2008 issue of *Science*) shows single cobalt atoms on a platinum surface with steps, imaged with spin-polarized scanning tunneling microscopy. Blue areas show the platinum substrate; red and yellow regions in front of the steps show adsorbed cobalt monolayer stripes with magnetization up (yellow) or down (red).

The historical basis for the atomic structure of matter owes much to the development of the kinetic theory of gases, the understanding of Brownian motion, and chemistry. From a more modern perspective, two compelling types of experimental evidence for the existence of atoms can be summed up as (*i*) chemistry works, and (*ii*) individual atoms and molecules can be imaged using a variety of modern techniques, such as scanning tunneling microscopy and atomic force microscopy. A few examples of atomic scale imaging are shown in Figure 4.1 .

In the following discussion we will introduce the know particles essentially in historical order. Individual particles are characterized by their (rest) mass, their spin (*i.e.*, how they transform under ordinary spatial rotations) and their participation in the known types of interactions, which comprise the Standard Model (labeled the SM).[1] All particles participate in gravitational interactions, but foe our purposes this interaction is extremely weak and will be largely ignored in this class. Nearly all particles participate in the Weak Interactions (all except photons and gluons), which are stronger than gravity but weaker than the Electromagnetic and Strong interactions. Particles with a nonzero electric charge (plus the photon) participate in the Electromagnetic interactions. Finally the hadrons (made from quarks and gluons) participate in the Strong interactions. The relative strengths and ranges of the known "fundamental" forces are characterized in the following table.

Force	Relative Strength	Range
Strong	1	$\approx$ fm $= 10^{-15}$ meter
Electromagnetic	10^{-2}	"Infinite" ($\propto 1/r^2$)
Weak	10^{-6}	$\approx 10^{-3}$ fm
Gravitational	10^{-43}	"Infinite" ($\propto 1/r^2$)

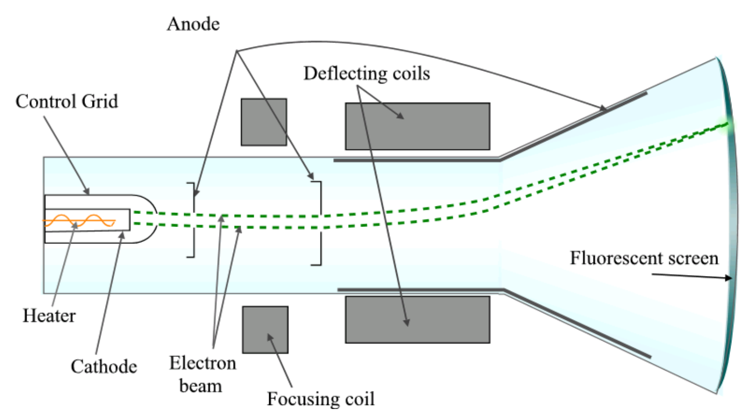


Figure 4.2: Simple sketch of cathode ray tube.

The existence of electrons has been known experimentally since the work of J.J. Thomson who, in 1897, studied the behavior of particles that pass through a cathode ray tube (which is essentially a *really old* tv) when a suitably large voltage is applied between the anode and cathode as illustrated in Figure 4.2 .

[1]We will eventually characterize this participation in terms of a variety of "charges", which themselves characterize how the particles transform under more abstract "rotations."

Thomson found that these particles have a mass to (electric) charge ratio which is *independent* of the type of material forming the cathode or the gas in the tube. Further the magnitude of this ratio is about 2000 times smaller than the corresponding mass to charge ratio of a hydrogen ion (*i.e.*, a proton). Measurement of the charge-to-mass ratio involves observing the deflection of a moving particle produced by a magnetic field (generated by the deflecting coils in Figure 4.2). The charge of a single electron can be measured using the approach of Millikan and Fletcher's famous oil drop experiment pictured in Figure 4.3. Based on refinements of such measurements, the magnitude of

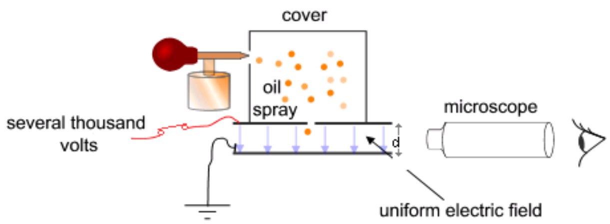


Figure 4.3: Simple sketch of Millikan and Fletcher's oil drop experiment.

the electron charge is now known to a precision of a few parts in 10^8,

$$|-e| = 1.602\ 176\ 565\ (35) \times 10^{-19}\ \mathrm{C}\,. \tag{4.1.1}$$

(The number in parentheses indicates the uncertainty in the last two digits.) In other words, a Coulomb, whose definition is based on macroscopic measurements of current plus the definition of a second, is equal in magnitude to $6.241\ 509\ 34\ (13) \times 10^{18}$ electron charges. The mass of the electron is also known to a similar precision,

$$m_e = 0.510\ 998\ 928\ (11)\ \mathrm{MeV}/c^2 = 9.109\ 382\ 91(40) \times 10^{-31}\ \mathrm{kg}\,. \tag{4.1.2}$$

One MeV ($= 10^6$ eV) is the energy acquired by an electron passing through a potential difference of one million volts. (The interested student is encouraged to become familiar with the vast amount of precision data available to you at the PDG website, which is linked at the bottom of the class web page.)

A few angstroms (1 Å$= 10^{-10}$ m $= 5 \times 10^5$ GeV^{-1}) is the size of individual atoms, whereas nuclear sizes are naturally measured in units of the fermi (or femtometer), where 1 fm $= 10^{-15}$ m $= 5$ GeV^{-1}. Direct evidence of the size of atomic nuclei comes from scattering experiments, specifically measurements of the momentum dependence of the scattering cross section. This topic will be discussed more fully in a later chapter. For now, it suffices to note that, in order to learn about the structure of some object like an atomic nucleus, one must use some probe [such as photons (light), electrons, or other nuclei] whose wavelength is *smaller* than the size of the object of interest.

Atomic nuclei are known to be bound states of more fundamental particles, protons and neutrons (except for the lightest nucleus of hydrogen, which is just a single proton). This information again comes from scattering experiments: one can bombard nuclei with various projectiles, such as electrons or other nuclei, and observe individual protons or neutrons knocked out of the target nucleus. Just as atoms come in different types, which are usefully organized in the traditional periodic table and characterized by their differing chemical interactions, there are many different atomic nuclei distinguished by the numbers of neutrons and protons that they contain. It is conventional to label

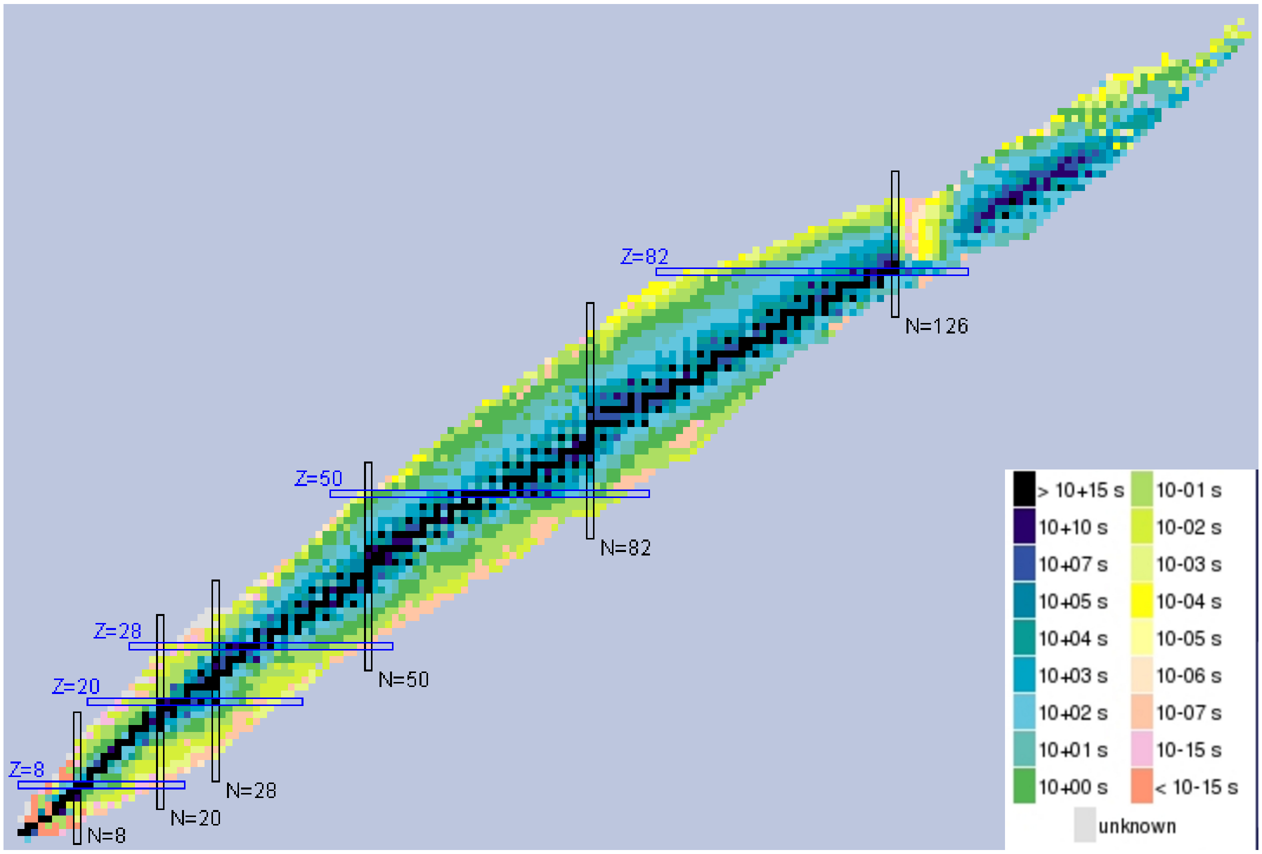


Figure 4.4: Chart of the nuclides (from the National Nuclear Data Center at Brookhaven National Laboratory). The number of protons, Z, is plotted vertically and the number of neutrons, N, horizontally. The color coding indicates the lifetime, with stable nuclei in black and lighter colors corresponding, as shown in the legend, to progressively shorter lifetimes. The rows and columns labeled with specific values of Z and N are so-called "magic" numbers where nuclei have enhanced stability.

nuclei with the atomic symbol for the corresponding element, with a preceding *superscript* indicating the atomic number A, equal to the number of protons plus neutrons, and a preceding *subscript* Z indicating the number of protons. For example, the lithium-7 nucleus, ${}^{7}_{3}\mathrm{Li}$, is a bound state of three protons and four neutrons. Figure 4.4 shows a plot of known nuclear species (or *nuclides*), color coded according to their stability (see the lifetimes in the legend). Useful interactive online versions may be found at `www.nndc.bnl.gov` and `atom.kaeri.re.kr`.[2]

Protons have charge $+e$, *precisely* equal in magnitude but opposite in sign to the electron. Note that this apparent *exact* equality (except for the sign) between the proton's electric charge and that of the electron is a very important feature of our universe. We are built from atoms with zero net charge (to a very good approximation, *i.e.* to better than one part in 10^{21}), and thus electromagnetic repulsion does *not* exclude us from sitting next to our fellow students. This situation clearly calls for some fundamental explanation. So-called "GUTS", or Grand Unified Theories, are intended to do just that

[2]Note that most tables of nuclides, including the one at `atom.kaeri.re.kr`, list *atomic* masses, not nuclear masses, the distinction being that the atomic mass is the mass of the neutral atom. In other words, the atomic mass includes the rest mass of all the electrons plus the mass of the nucleus, as well as the (negative) atomic binding energy.

by postulating a "grand" underlying symmetry that relates quarks and leptons. This "relationship" can then explain the exact equality of the magnitudes of the electric charges of electrons and protons. The existence of such an underlying symmetry, even if badly broken at the energy scales we are used to, would lead to interactions allowing the proton to decay (slowly, see below) into leptons. The search goes on, but for now proton decay had not been observed and we have not real explanation of why there is a single fundamental unit of electric charge.

The mass of a proton is measured to be

$$m_p = 0.938\ 272\ 046(21)\ \mathrm{GeV}/c^2\,. \tag{4.1.3}$$

This is about 2000 times larger than the mass of an electron. Neutrons, which are neutral (zero electric charge) particles, are slightly heavier than protons,

$$m_n = 0.939\ 565\ 379(21)\ \mathrm{GeV}/c^2\,. \tag{4.1.4}$$

Neutrons, protons, and electrons are all spin 1/2 particles, where spin is measured in terms of the fundamental quantum of spin, $\hbar$. Looking ahead, it is essential (and we will discuss and use this at several points) to recall that one way to classify particles is in terms of whether their spin is one-half integer (as here) or integer valued (in units of $\hbar$). The former are labeled "fermions" and the later "bosons". One way to think about the difference between these classes of particles is how they transform under rotations. The familiar behavior (*i.e.*, behaving like you do) is that of bosons. After a rotation of 360 degrees, or 2π radians, about any axis a boson is *un*changed (*i.e.*, comes back to where it started). Less familiar is the behavior of a fermion under such a rotation; it does not come back to where it started but instead differs by a minus sign (*i.e.*, its phase has changed by π radians). Of course, we are sensitive to such phases only in the context of quantum mechanics. Thus the intrinsic difference between these two varieties of particles becomes absolutely clear in the context of quantum field theory (QFT) where we must define operators to represent these particles (and the fields that describe them). For fermions these operators must *anti*-commute ($\{A, B\} = AB + BA = 0$ or $AB = -BA$), while for bosons the corresponding operators must commute ($[C, D] = CD - DC = 0$ or $CD = DC$). Thus, when we build states out of identical fermions, the states must be *anti*-symmetric under the interchange of any pair of fermions. This immediately leads to the Pauli Exclusion principle - *no* two identical fermions can reside in the *same* state, since such a situation would necessarily be symmetric. On the other hand, a state constructed of identical bosons must be symmetric under the interchange of any two of the bosons. Thus bosons are "happy" to be in the same state as that guarantees symmetry (and lasers really do produce beams of coherent photons, all in the same state). You will often see this connection between spin and the interchange symmetry referred to as the Spin-Statistics Theorem.

Protons and neutrons are collectively referred to as *nucleons*. Recall that the masses of the neutron and proton are *very* similar (see Eqs. 4.1.3 and 4.1.4), suggesting that these two particles should be related somehow (by a slightly broken symmetry?). Nucleons are known to have internal structure: they may be regarded as bound states of three quarks. We will later be discussing quarks, and their possible bound states, in much greater detail. For now, we simply note that the observational evidence for quarks is necessarily somewhat indirect. It turns out that scattering experiments with nucleons *cannot* liberate free quarks. Why is that? Good question and we will have more on this point later. This apparent disconnect between the degrees of freedom in the theory (the quarks) and the degrees of freedom observed in the lab (the hadrons) has constituted one of the major intellectual challenges in particle physics. The previous experience has always been that you could "take things apart", molecules → atoms, atoms → electrons and nuclei, nuclei → neutrons and protons. When we try to take protons apart, we find more protons, plus pions and kaons, but no isolated quarks! On the spatial resolution scales larger than a fermi, we believe that quarks are *always* "confined" inside hadrons. We need to become comfortable with this new set of rules.

Interestingly, the "internal gear wheels" story currently ends here. No evidence for internal structure within quarks, or electrons, has yet been found. If quarks and leptons are discovered someday to be composite objects, bound states of some not-yet-known more fundamental constituents, then the length scale on which this binding occurs must be at least three orders of magnitude smaller than the femtometer (fm) scale of nucleons. This limit on the length scale is set by the corresponding energy scale (TeV) of the experimental measurements at both the Tevatron and the LHC, which, until now, have not exhibited any internal structure for quarks or leptons..

4.2 Stability of particles

Are protons, or electrons, or hydrogen atoms stable? Or can they spontaneously decay? In other words, if one of these particles (or atoms) is completely isolated, in a vacuum, can it eventually, spontaneously fall apart? It is important to recognize that this is a "bad" question. It is fundamentally unanswerable — because feasible experiments must necessarily last only a finite length of time. If there is no known evidence that a certain type of particle *can* decay, then the question one should ask is what *limits* can be placed on the stability of the particle.

For protons and electrons, we have no evidence whatsoever that these particles are unstable, and experimental bounds on the lifetimes of these particles, if they do decay, are very long,

$$\text{proton lifetime } \tau_p > 2.1 \times 10^{29} \text{ yr}, \tag{4.2.1}$$

$$\text{electron lifetime } \tau_e > 4.6 \times 10^{26} \text{ yr}. \tag{4.2.2}$$

We should be impressed with these limits, considering that they vastly exceed the age of the Earth (a mere 4.5 billion years) and the Universe (over 13 billion years). Suppose, hypothetically, that protons do decay with a lifetime of 10^{30} years. How could one ever know? The direct approach of watching one particle for 10^{30} years is obviously impractical. But if you can watch many identical particles simultaneously, and detect if (and when) a single one of them decays, then extremely long lifetimes can be measured.[3] A cubic meter of water contains 2.7×10^{29} protons (and the same number of electrons). So if $\tau_p = 10^{30}$ yrs, then within a tank holding 100 cubic meters of water, 27 protons (on average) will decay every year. The challenge is in designing and operating an experiment which can detect the decay of individual protons within a large quantity of material. While the development of such detectors (essentially instrumented large tanks of water) has not yet led to the observation of proton decay, it has resulted in detectors capable of detecting the neutrinos from our sun and from supernovas elsewhere in the galaxy. This is, in fact, a very nice story of the synergies that drive science. The initial push was to detect proton decay (yielding only a limit until now), but the technology developed contributed to the very exciting (and unexpected) discovery that neutrinos are not massless!

[3]The lifetime τ of an unstable particle is, by definition, the time interval (in its rest frame) for which the probability of the particle decaying is $1/e$. If you start with N_0 identical particles, then the mean number of particles which will *remain* after time t is given by $N(t) = N_0\, e^{-t/\tau}$. If $N_0 \gg 1$ then, on average, one particle will have decayed by the time $t_1 = \tau/N_0$, since $N(t_1) \approx N_0 - 1$.

Next consider neutrons, the other basic constituents of nuclei besides protons. Unlike protons, an isolated neutron is known to be unstable, with a lifetime of about 15 minutes. The products of the decay are a proton, an electron, and a less familiar particle called an *electron antineutrino*, denoted $\bar{\nu}_e$. This decay is represented symbolically as

$$n \longrightarrow p + e^- + \bar{\nu}_e \,. \tag{4.2.3}$$

This decay process is referred to as a *beta decay*,[4] and is a consequence of interactions known as *weak interactions*, which will be discussed more fully in a later chapter. Neutrinos are nearly massless, spin-1/2 particles which interact extremely weakly with ordinary matter and as a result are very difficult to detect. They come in several different types (distinguished by the charged lepton with which they are correlated by the weak interaction), and exhibit interesting quantum-mechanical phenomena which we will also examine later.

Although a single free neutron is unstable, when neutrons bind with protons to form nuclei the resulting bound states are, in many cases, effectively stable (meaning that their lifetimes, if finite, are in excess of billions of years). Such stable nuclei include deuterium ($^2_1$H) which is a bound state of one proton with one neutron,[5] helium-3 ($^3_2$He) which contains two protons and one neutron, helium-4 ($^4_2$He) consisting of two protons and two neutrons, and many progressively heavier nuclei (recall Figure 4.4) up to bismuth-209 ($^{209}_{83}$Bi) which is the heaviest (known) nucleus that is essentially stable.[6]

4.3 Nuclear decays

In addition to (apparently) stable bound states, there are many more unstable nuclei with lifetimes that range from very long, billions of years, down to very short, less than femtoseconds. Stable nuclei have roughly the same number of protons and neutrons (or in heavier nuclei, slightly more neutrons than protons, recall Fig. 4.4). Many nuclei with an excess of neutrons, relative to the number of protons, undergo beta decay. This converts a neutron within the nucleus into a proton, while emitting an electron and an antineutrino. For example,

$$\begin{array}{cclc} & \beta \text{ decay} & & \text{lifetime} \\ {}^3_1\text{H} & \longrightarrow & {}^3_2\text{He} + e^- + \bar{\nu}_e & 17.8 \text{ yr}\,, \\ {}^6_2\text{He} & \longrightarrow & {}^6_3\text{Li} + e^- + \bar{\nu}_e & 1.16 \text{ s}\,, \\ {}^{10}_4\text{Be} & \longrightarrow & {}^{10}_5\text{B} + e^- + \bar{\nu}_e & 2.18 \text{ Myr}\,, \\ {}^{14}_5\text{B} & \longrightarrow & {}^{14}_6\text{C} + e^- + \bar{\nu}_e & 18.0 \text{ ms}\,. \end{array}$$

[4] This is a historical name which dates from the early 1900s, when three distinct types of radioactive decay, called α, β, and γ, had been identified. The different decay types were distinguished by the degree to which the particles emitted in the decay could penetrate ordinary matter. Alpha decays produce particles with very little penetrating power which were later identified as helium-4 nuclei. Gamma decays produce extremely penetrating particles, later identified to be high energy photons ("gamma rays"). Beta decays produce particles which penetrate farther than alphas, but less than gammas. These were subsequently identified to be electrons.

[5] Recall the notation for nuclei: the symbol ^A_ZSy denotes the nucleus of the element "Sy" with A nucleons, of which Z are protons.

[6] In fact, bismuth-209 has recently been found to alpha decay with a lifetime of 2×10^{19} yr.

Some nuclei with an excess of protons, relative to the number of neutrons, can convert a proton into a neutron by capturing an electron from the cloud of electrons surrounding the nucleus, and then emitting a neutrino which carries off the excess energy,

$$\begin{array}{ccll} & \text{electron capture} & & \text{lifetime} \\ {}^{7}_{4}\text{Be} + e^- & \longrightarrow & {}^{7}_{3}\text{Li} + \nu_e & 76.9 \text{ day}\,, \\ {}^{41}_{20}\text{Ca} + e^- & \longrightarrow & {}^{41}_{19}\text{K} + \nu_e & 1.50 \text{ Myr}\,. \end{array}$$

This mode of decay is only possible if the atom is not fully ionized, so that one or more electrons are bound to the nucleus. If that is not the case, neutron-poor nuclei can convert a proton into a neutron via *positron emission.* A *positron*, denoted e^+, is a particle with the same mass as an electron, but with charge $+e$ instead of $-e$. It is an example of an *antiparticle*, discussed below. (Actually we have already "snuck" in the concept of antiparticles by mentioning both neutrinos *and* antineutrinos above.) The carbon-11 nucleus preferentially decays via positron emission even when it has an orbital electron it could otherwise capture,

$$\begin{array}{ccll} & \text{positron emission} & & \text{lifetime} \\ {}^{11}_{6}\text{C} & \longrightarrow & {}^{11}_{5}\text{B} + e^+ + \nu_e & 29.4 \text{ min}\,. \end{array}$$

Since this process creates a positron rather than absorbing an electron as above, the energy released by the change in the nucleus must be larger (to satisfy overall energy conservation).

Certain nuclei have multiple modes of decay with measurable rates. For example, potassium-40 (${}^{40}_{19}$K) has a lifetime of 1.8 billion years. In 89% of its decays, potassium-40 undergoes beta-decay to calcium-40, but in the remaining 11% of its decays, potassium-40 decays to argon-40 via electron capture or positron emission.

In addition to the above types of nuclear decay, in which a neutron is converted into a proton or vice-versa, some nuclei which are very proton-rich decay by simply ejecting a proton, or in some cases, an alpha particle. And some very neutron-rich nuclei simply eject a neutron.

Many excited states of nuclei decay to their ground states by emitting photons (just like excited atomic states). But in the case of nuclei, excited state energies are typically in the range of several MeV, so the photons emitted in nuclear decays are in the *gamma ray* portion of the electromagnetic spectrum (to the far right in Figure 4.5).

4.4 Photons

One other elementary particle which plays a major role in innumerable aspects of everyday life is the *photon*. Photons are quantized excitations of the electromagnetic field, and are the "force carriers" for the electromagnetic interaction (we say that an electromagnetic interaction has occurred when a photon is exchanged). They have no rest mass (unlike the other particles we have discussed so far). The spectrum of electromagnetic radiation is illustrated in Figure 4.5 from long wave lengths (low energy photons) on the left to short wave lengths (large energy photons) on the right. Photons carry one unit of angular momentum, in units of $\hbar$. We typically express this point by the phrase "photons are spin 1 particles."

In everyday life, quantum aspects of the electromagnetic field are not readily apparent. For a great many applications, a classical treatment of electromagnetism suffices, *i.e.*, the number of photons

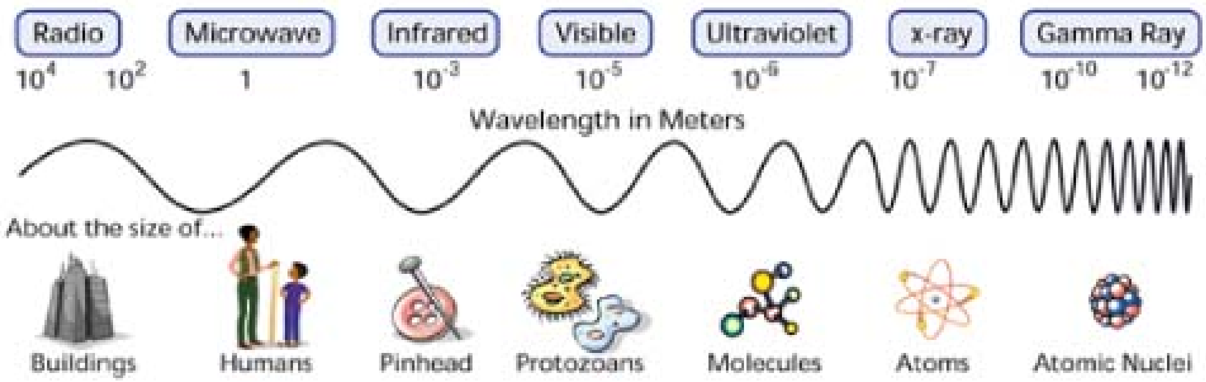


Figure 4.5: Illustration of the spectrum of electromagnetic waves.

present is enormous and we cannot readily detect the emission or absorption of a single photon. But the quantized nature of light is revealed in phenomena such as the photoelectric effect, the presence of stimulated emission in lasers and masers, and the operation of sensitive photo-diodes which can detect *single* photons.[7]

4.5 Antiparticles

Early studies of cosmic rays revealed the existence of *positrons*, particles with the same mass as electrons but opposite charge. When a positron collides with an ordinary electron, they can interact and scatter like any two electrically charged particles. However, they can also under go a very special process, allowed only for the case of particle and antiparticle. They can annihilate with each other and produce (only) photons,

$$e^+ + e^- \longrightarrow \gamma + \gamma\,.$$

Accelerator-based scattering experiments have also revealed the existence of *antiprotons* and *antineutrons*, denoted $\bar{p}$ and $\bar{n}$, respectively. They can similarly annihilate with their ordinary partners to produce photons,

$$p + \bar{p} \longrightarrow \gamma + \gamma\,,$$
$$n + \bar{n} \longrightarrow \gamma + \gamma\,.$$

When one combines quantum mechanics and special relativity (leading to relativistic quantum field theory), a remarkable theoretical prediction is that antiparticles *must* exist. Charged particles must have distinct antiparticles with exactly the same mass and spin, but opposite electric charge. For certain neutral particles, such as the photon, there is no distinction between particle and antiparticle — one can say that the photon is its own antiparticle. At the moment it is unclear whether the other really neutral particle, the neutrino, is its own antiparticle or not. Our friends at CENPA (the

[7] Human vision, when fully dark-adapted, can nearly detect single photons of visible light. See, for example, the classic paper *Energy, Quanta, and Vision* by Hecht, Shlaer and Pirenne.

UW physics laboratory on the other side of campus) are involved in the MAJORANA experiment that test will this idea by looking for neutrino-less double beta decays. Such decays can occur only if neutrinos are their own antiparticle (such self-conjugate fermions are called Majorana fermions). (Note that, while electrically neutral, the neutron does carry another "charge" called baryon number and is unambiguously distinct from the antineutron.) Although antimatter is not present in everyday life (this is another mystery - why is the universe so antisymmetric between matter and antimatter, which was presumably not the case at the time of the big bang?), antiparticles do exist, and the laws of nature are almost, but not quite, symmetric under the interchange of ordinary matter and antimatter. We will discuss these issues further in a later chapter.

4.6 Leptons

Electrons (e^-) and electron neutrinos (ν_e) are members of a class of particles known as *leptons*. Their antiparticles, the positron (e^+) and electron antineutrino ($\bar{\nu}_e$), are *antileptons*. Leptons (and antileptons) are spin 1/2 particles. All leptons participate in the weak interactions (*leptos* is Greek for weak) and the (electrically) charged leptons also participate in the electromagnetic interactions. However, leptons do not participate in the strong or nuclear interactions (*i.e.*, they are *not* bound states of quarks). In addition to the electron, two other charged leptons are known, the muon (μ^-) and the tau (τ^-). As the superscripts indicate, these particles are negatively charged; their charge is (apparently) *identical* to that of the electron. Their antiparticles are the antimuon (μ^+) and antitau (τ^+). There are distinct neutrinos associated, through the weak interactions, with each charged lepton. In addition to the electron neutrino, there is a muon neutrino (ν_μ) and a tau neutrino (ν_τ), as well as the corresponding antineutrinos ($\bar{\nu}_\mu$, $\bar{\nu}_\tau$). So an important question is - why 3 kinds of leptons?

The basic properties of the leptons are summarized in Table 4.1 . The electric charge listed is in units of $|e|$. Neutrinos have much smaller rest masses then the charged leptons, so much smaller that it is extraordinarily difficult to measure neutrino masses (and we have not yet succeeded). On the other hand, the observation of neutrino oscillations, which will be discussed in a later chapter, implies that neutrinos must have non-zero masses. But at the moment only an upper bound on the actual values of the neutrino masses is known. (Note that research groups within the UW Department of Physics have played important roles in the experiments leading to our current understanding of the properties of neutrinos, and continue to do so.)

As indicated in Table 4.1, the "heavy" leptons decay into the light ones. The muon decays into an electron plus an electron antineutrino and a muon neutrino. The heavier tau has more options, decaying to both electrons and muons, *and* into a final state with hadrons (2 pions) and just the single lepton (the tau neutrino). In all of these processes "lepton number" is conserved. *Lepton number*, denoted L, is defined as the total number of leptons minus antileptons,

$$L \equiv (\#\ \text{leptons}) - (\#\ \text{antileptons})\,. \tag{4.6.1}$$

All known interactions conserve lepton number.[8] In fact, the dominant interactions (but not, for example, neutrino oscillations) conserve lepton number separately for each lepton "flavor", electron,

[8] Actually, this is not quite true. The current theory of weak interactions predicts that there are processes which can change lepton number. However, the rate of these processes is so small that lepton number violation is completely unobservable.

muon and tau. So e^- and ν_e have $L_e = +1$, while e^+ and $\bar{\nu}_e$ have $L_e = -1$, and the same for L_μ and L_τ. In the decays noted in the table below we see, for example, $\mu^- \to e^-\bar{\nu}_e\nu_\mu$ with $L_e = 0$, $L_\mu = 1$ in both the initial and final states (and similarly for the decays of the τ^-). We will see later that this structure is built into the (perturbative) definition of the weak interactions.

particle	**rest energy**	**lifetime**	**dominant decay**	**charge**	***L***
ν_e	< 2 eV	$\approx$ stable	—	0	1
ν_μ	< 2 eV	$\approx$ stable	—	0	1
ν_τ	< 2 eV	$\approx$ stable	—	0	1
e^-	0.511 MeV	stable	—	-1	1
μ^-	105.7 MeV	2.2 μs	$e^-\bar{\nu}_e\nu_\mu$	-1	1
τ^-	1777 MeV	0.29 ps	$\pi^-\pi^0\nu_\tau$, $e^-\bar{\nu}_e\nu_\tau$, $\mu^-\bar{\nu}_\mu\nu_\tau$	-1	1
$\bar{\nu}_e$	< 2 eV	$\approx$ stable	—	0	-1
$\bar{\nu}_\mu$	< 2 eV	$\approx$ stable	—	0	-1
$\bar{\nu}_\tau$	< 2 eV	$\approx$ stable	—	0	-1
e^+	0.511 MeV	stable	—	$+1$	-1
μ^+	105.7 MeV	2.2 μs	$e^+\nu_e\bar{\nu}_\mu$	$+1$	-1
τ^+	1777 MeV	0.29 ps	$\pi^+\pi^0\bar{\nu}_\tau$, $e^+\nu_e\bar{\nu}_\tau$, $\mu^+\nu_\mu\bar{\nu}_\tau$	$+1$	-1

Table 4.1: Leptons and antileptons.