Appendix B

The Particle Zoo, Energy and the Mutability of Matter

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§B.1 The Main Characters: The Electron, Proton and Neutron

The first half of the twentieth century was the Golden Age of physics. Incredible as it seems today, at the beginning of that century it was still perfectly respectable for a reputable physicist to doubt the existence of atoms. Yet within the first years of the twentieth century the foundations of quantum mechanics were laid and relativity theory developed. In little over three decades, not only was the existence of atoms established beyond doubt, but their internal constitution was discovered. In the fourth decade, antimatter was both discovered and its theoretical status understood (in the reverse order). In the fourth and fifth decades, the new science of nuclear physics was born and developed remarkably quickly. By the mid-1950s enough was known, or could be surmised, to permit Hoyle to deduce how the chemical elements are synthesised in stars. Altogether this was a staggeringly rapid advance in understanding in just half a century, barely more than one or two generations of physicists.

It may be added that this progress in physics was mirrored by parallel progress in chemistry. Understanding the nature of the atom meant that the physical basis of the chemical properties of the elements was explained. Mendeleeff's periodic classification, previously a purely empirical matter, became systematically comprehensible. Nor was biology far behind. The new science of biochemistry was put firmly on the map with the discovery of the structure of DNA in the 1950s.

At the risk of trivialising the full story, the understanding of the structure of matter which emerged in this period can be summarised as follows. Ordinary matter consists of three different types of particle bound together by four different types of force. The almost limitless variety of matter we see around us comes about simply by arranging the basic building blocks in different ways. A homely analogy is with a child's construction toy, such as Lego. Only a few types of brick are required to build whatever structure you wish. The word 'particle' conjures up a vision of a small sphere, like a miniature snooker ball or marble. However, you would find it difficult to construct anything from a bag of marbles. Lego bricks, on the other hand, can be joined to another brick, or more than one. Without this ability to 'bond' it would not be possible to make anything from the bricks. The same facility must be provided by nature to allow the fundamental particles to be joined together in order to form matter in all its variety. This facility to bind the particles together is provided by the basic forces of physics. There are only four of these fundamental forces – if indeed even these are to be regarded as distinct – but let's not get ahead of ourselves.

At the end of the nineteenth century, two of these forces were known. These were gravity and electromagnetism. Both were understood in terms of a mature classical[1] theory. Early in the nineteenth century, physicists would have said that there were three different

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[1] 'Classical' means 'not quantum'. Relativistic theories are regarded as classical.

forces, regarding electricity and magnetism as distinct. Thanks largely to Faraday and Maxwell, and later Einstein, these two forces were realised to be two aspects of the same underlying force – the electromagnetic field. In the miraculous first half of the twentieth century a further two basic forces were discovered, bringing the total to four. These two new forces were called - with an impressive display of imagination - the “weak nuclear force” and the “strong nuclear force”. No new forces have been discovered since. It is worth emphasising this fact. The number of known particles has grown like Topsy since the mid-twentieth century, but the number of forces has, if anything, shrunk. We will say a little more about these forces later. We turn now to particles.

Regrettably we cannot afford to dwell too long on the history of the development of physics, fascinating though the story is. We proceed, therefore, directly to the punch line. Ordinary matter, of which you and I and everything on the planet Earth are composed, is made up of atoms. Atoms come in 94[2] different naturally occurring types, called elements. A further 23 can be made artificially, though all are unstable and 14 have half lives of less than 11 minutes. Most elements can occur in more than one form, called isotopes. Different isotopes of the same element have identical chemical properties. This means that the way in which they combine chemically with other elements is generally similar to the point of being indistinguishable. However, different isotopes of an element have distinct *physical* properties, such as density, diffusion rates, etc. In the particular case of heavy water, in which hydrogen has been replaced by its isotope deuterium, there are significant biological differences[3].

Atoms are roughly a few Angstroms in size, an Angstrom being 10^{-10} metres. They consist of an even tinier, positively charged nucleus surrounded by a cloud of negatively charged electrons. The nucleus is roughly a few fermi in size, a fermi being 10^{-15} meters. Despite being so much smaller than the atom as a whole, the nucleus accounts for at least 99.95% of the mass of the atom. Actually it is misleading to say, “despite being so much smaller”. It is only in classical (macroscopic) physics that we expect smaller things to be lighter. In the sub-atomic world we are firmly in the quantum regime. The uncertainty principle holds sway and we may expect energies, and hence masses, to be *inversely* proportional to size, i.e., of order $\hbar / r$. In quantum mechanics it is more accurate to say that the nucleus accounts for most of the mass of the atom *because* it is so much smaller.

The electrons are very light in comparison. Consequently their wavefunction is spread over a much greater spatial extent than that of the nucleus, about 100,000 times greater. It is the electrons which give an atom its size and its chemical behaviour. This is why different isotopes of the same element have virtually indistinguishable chemical

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[2] It used to be thought that plutonium, technetium and promethium did not occur naturally, since all were first made artificially. However, plutonium and technetium have now been found terrestrially, and promethium has been detected in the universe.

[3] Surprisingly, the differences are chemical, due to the different strengths of the hydrogen bond and its deuterium equivalent. Biological enzyme function is very sensitive to the details of the hydrogen bond. Cell division ceases in eukaryotic organisms for concentrations of heavy water in excess of 25%. Thus, seeds will not germinate in heavy water. Laboratory animals will die if given only heavy water in place of ordinary water for several days. However, there is little danger to humans in drinking the occasional glass of heavy water since only a concerted effort over many days could raise the body’s heavy water content to dangerous levels. You would have the satisfaction of being a rather valuable corpse.

properties. They differ only in their nucleus, whilst their surrounding electrons are essentially identical.

Since the size of the nucleus is only about 10^{-5} times the size of the atom, it follows that the volume of the nucleus is only about 10^{-15} times the volume of the atom. As it contains virtually all the mass, the nuclear material must therefore have a density around 10^{15} times greater than that of ordinary atomic matter. This means that a spoonful of nuclear matter would weigh about a billion tons.

A word of warning is in order. We were careful to preface the typical sizes given above with the word ‘roughly’. At the atomic level, and below, the vagaries of quantum mechanics imply that the concept of size is not well defined. Thus, electrons can be ascribed no meaningful size at all, in general. Within relativistic quantum field theory (quantum electrodynamics) the electron is regarded as strictly point-like. Despite this, quantum electrodynamics holds the record for the most accurate scientific calculation confirmed by experiment. This might be regarded as vindicating the assumed zero size for the electron. However, some sophisticated mathematical machinery is required to achieve this result. We will avoid such deep waters.

The nuclei of atoms also have a sub-structure. They are composed of two types of particle: protons and neutrons. The generic name for either particle is a nucleon. The protons carry the positive charge exhibited by the nucleus, whereas the neutrons, as the name implies, are electrically neutral. As remarked above, protons and neutrons have almost the same mass, differing by only 0.14%. Nevertheless, the size of this small mass difference is crucial to the stability of matter. Unlike atoms, which are highly inhomogeneous with the mass being concentrated at the centre, the nuclei are essentially homogeneous, in as far as this is a meaningful statement at all.

The reason why the cloud of negatively charged electrons is bound to the positively charged nucleus is readily apparent. Opposite electric charges attract due to the electrostatic force. The negatively charged electrons therefore orbit the positively charged nucleus in much the same way as the planets orbit the Sun under the influence of the attractive force of gravity. There is, however, a snag. A body undergoing circular motion is exhibiting an oscillating acceleration, and a charged body undergoing oscillating acceleration emits electromagnetic radiation. Rather like an Earth satellite in a decaying orbit, this would mean that the electron should spiral into the nucleus and all atoms would be unstable. All matter would collapse to form nuclear material, which, as we have seen would occupy only 10^{-15} of the volume and be 10^{15} times as dense. This posed a rather serious problem to physicists in the first decades of the twentieth century, the resolution of which lead to the development of quantum mechanics.

The requirement to explain the stability of the ‘orbits’ of electrons in atoms was the motivation for Bohr’s quantum theory of the atom, later made more complete and precise by Schrodinger and Heisenberg (and even more complete and precise by Dirac). The details need not concern us now. Suffice it to say that, in the quantum mechanical theory of an electron bound to a positively charged nucleus, the electron cannot have any arbitrary energy but only energies taken from a certain, well defined, discrete set of energies – the so-called quantum states. Moreover, there is a lowest energy state of finite, non-zero size – the ground state. The electron can ‘spiral down’ in its orbit only so far.

When it reaches the ground state, there is nowhere else for it to go. This is the usual explanation for the stability of matter which physics students are taught. It is correct, of course, but seriously incomplete. In Chapter 10 of the "Cosmic Coincidences" we identify another mechanism which could easily have resulted in matter being unstable, related to the neutron - proton mass difference. There are more conditions necessary to ensure the stability of matter than just the discreteness of the electronic quantum states.

The alert reader will have noticed another snag in the above picture of the atom. As well as opposite charges being attractive, like charges are repulsive. So why does the positive nucleus not fly apart? The positive protons have, after all, been crammed very tightly together. Let us say for sake of argument that we accept that some unknown agency ensures that an individual proton is stable, holding it together against its own electrostatic repulsion. Yet we still must explain why a nucleus containing two or more protons does not break up into its constituent protons. Indeed, when Rutherford obtained the first experimental evidence for a concentrated, central, positively charged nucleus, he was most surprised. The expediency was to postulate the existence of a new force of nature specifically to make the nucleus stable. Because the repulsive electrostatic energy increases at small distances proportionally to the reciprocal of distance, and since the nucleus is so very small, it is clear that this new nuclear force must be very strong to overcome the large electrostatic repulsion. It was therefore called the "strong nuclear force". This name is still used today[4]. Of the four forces of physics, the strong nuclear force is the strongest, the most complicated, and the least well understood (providing the quantum behaviour of gravity be excluded).

The above picture accounts completely for all atoms, and hence all familiar matter whether gaseous, liquid or solid. Just one additional fact is required, namely that the magnitude of the electric charges on the electron and proton are precisely equal (though opposite in sign). This being the case, an atom is made up of the same number of electrons as protons in the nucleus, thus ensuring electrical neutrality overall. The different chemical elements are thus defined simply by the number (Z) of protons in the nucleus: Z =1 (hydrogen); Z =2 (helium); Z =3 (lithium); Z = 4 (beryllium); Z = 5 (boron), etc. The chemistry of an element is determined by the structure of the electron orbitals. But since the number of electrons is equal to the number of protons, Z, it follows that there is a unique set of chemical behaviours for a given value of Z (with the exception of hydrogen / deuterium[3]). The isotopes of a given element differ as regards the number of neutrons in the nucleus. The reason why the different isotopes of a given element all have the same chemical properties is thus explained, since they all have the same Z.

The number of possible isotopes of a given element, i.e., the possible number of neutrons in a nucleus with a specified number, Z, of protons is not arbitrary. As a very crude guide, for medium sized nuclei, the number of neutrons cannot be too different from the number of protons. For larger nuclei, the number of neutrons tends to be a little greater than the number of protons. The reason is that the neutrons contribute to the strong-force nuclear 'glue' which holds the nucleus together against the electrostatic repulsion of the

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[4] The lack of imagination regarding the name may be forgiven. Since we have no direct apprehension of the strong nuclear force, we are hardly in a position to adopt any more homely attitude towards it. Nevertheless, one could wish for a better name.

protons. Thus, a nucleus with a preponderance of protons would not be stuck together strongly enough. And because the repulsive electrostatic force increases as Z(Z-1), elements with larger Z require an increasing proportion of neutrons. Even so, the largest nuclei tend to be unstable. The reason why nuclei with too many neutrons compared with protons are not stable either is more subtle. This is discussed in Chapter 9 of the “Cosmic Coincidences”.

The total number of nucleons is usually denoted A, so the number of neutrons is A – Z. The conventional notation for nuclei is ${}^{A}_{Z}X$ where ‘X’ is the chemical symbol. The isotopes of hydrogen are graced with their own names. A few light isotopes are,

${}^{1}_{1}H$	Hydrogen (as an atom) or a proton (as a nucleus)
${}^{2}_{1}H$	Deuterium (as an atom), or a deuteron (as a nucleus), sometimes written ‘D’
${}^{3}_{1}H$	Tritium, sometimes written ‘t’
${}^{3}_{2}He$	Helium-3
${}^{4}_{2}He$	Helium-4
${}^{6}_{3}Li$	Lithium-6
${}^{7}_{3}Li$	Lithium-7, etc.

Strictly, the chemical name is redundant, being defined uniquely by Z.

Not all isotopes are stable. The decay of unstable isotopes is the cause of radioactivity. The phenomenon of radioactivity was already being studied in the late 19th century, before the atomic structure was known. With the increasing understanding of atomic structure came the realisation that radioactivity must be caused by the decay of the nucleus[5]. This can cause transmutation into a different element since the number of protons in the nucleus can change. Radioactivity itself is not important to the subject of this Appendix[6]. What *is* crucially important is the *cause* of radioactivity.

Those isotopes which are radioactive generally survive for an extremely long time by nuclear standards. The nuclear time-scale can be defined as the time it takes a signal at the speed of light to cross a nucleus. Since nuclei are roughly a few Fermi (10^{-15} metres), and since the speed of light is 3×10^{8} metres per second, it follows that the nuclear time-scale is of order 10^{-23} seconds[7]. So any radioactive substance with a half-life of seconds,

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[5] When Frederick Soddy first realised this, he cried out to his colleague, Ernest Rutherford, “This is transmutation!” To which Rutherford replied, “For Christ’s sake, Soddy, don't call it *transmutation*. They'll have our heads off as alchemists.”

[6] But note that radioactivity is crucial in keeping the centre of the earth hot, and hence is the ultimate cause of vulcanism and earthquakes. It is feasible that hot sub-surface conditions were essential to the emergence of life on Earth (see Reference [3]). If so, then radioactivity could be crucial to the origin of life. But we have not pursued this idea.

[7] This may seem like a rather arbitrary timescale, and less than convincing. It might be better to call it the “strong interaction timescale” rather than the nuclear timescale. It is found experimentally that a certain class of extremely unstable particles known as resonances, whose existence and decay is a purely strong-force phenomenon, do indeed have lifetimes of the order of 10^{-23} seconds.

or minutes, or hours, or longer, actually survives a very long time indeed in comparison with this nuclear time-scale. The cause of the radioactive decay must therefore be a relatively weak force. In a further display of outstanding nominative imagination, physicists called it “the weak nuclear force”.

But if radioactivity is not of interest to us, why do we mention the weak force at all? What else does the weak nuclear force do? At this point we are obliged to reveal a little of the truth about the strange nature of the sub-atomic particles. They are not merely hard immutable lumps of stuff with no other properties than being able to stick together. In fact, it is rather an over-simplification to regard nuclei as composed of separate protons and neutrons. It turns out that the particles of matter are considerably more mysterious than just miniature Lego bricks. This is discussed further in §B.3, but first we must say a little about energy.

§B.2 Energy

In referring to the four basic forces of physics as “forces” we have followed the terminology usually employed by physicists themselves. However, it is really a misnomer in the quantum age. The concept of “force” belongs squarely in the world of classical physics. Since gravity and electromagnetism can be formulated as classical theories, they can be described meaningfully as “forces”. It is by analogy with gravity and electromagnetism that the nuclear forces, both strong and weak, are also loosely referred to as “forces”. However, the nuclear “forces” have no classical counterpart. They are essentially quantum mechanical in origin. And the concept of “force” plays no part in quantum mechanics. Consequently, there is strictly no real meaning to attach to the phrase “strong nuclear force”.

The utility of the concept of force in classical physics is due to the fact that it determines the motion of a body. The acceleration of a body is proportional to the force applied to it. In quantum mechanics, the idea of “acceleration” does not occur either. Quantum mechanics is predominantly about the distribution and movement of energy. In this respect, quantum mechanics is more akin to thermodynamics than it is to classical mechanics. Consequently, it is more meaningful to talk about “strong nuclear energy” and “weak nuclear energy” than to talk about forces. Since gravity and electromagnetism can also be formulated in terms of energy, all four types of fundamental interaction can be described in comparable terms if energy is employed. Nevertheless, following common usage, the nomenclature “nuclear force” will still be used in the text, but it should be understood as being merely a label.

Having agreed that the fundamental interactions are best regarded as energies rather than forces, what exactly *is* energy? The new-age fraternity makes much use of the word. Invariably this is in reference to fanciful and undetectable influences, for which no explanatory power would be lost if the word “energy” were replaced by “spirit” or “ghost”. So, are we in a better position in regard to the use of the word “energy” in physics? The answer is emphatically, “yes”. In any specific application, say the electromagnetic interaction between two charged particles, the quantity of the energy is defined through mathematical expressions imposed by the theory. This energy is then related through physical theory to phenomena which can be observed and quantified. The theory can therefore be subject to experimental validation or refutation, as the case may be. This is the distinction between science and non-science. Science continually exposes itself to the possibility of being disproved by experimental test.

Whilst the *quantity* of energy is well defined in any given case, attempting to define exactly what energy *is*, in general, can be challenging. We attempt to provide an intuitive appreciation for energy as follows. A body in motion is distinguished from a similar stationary body by the possession of energy. This form of energy is called kinetic energy. A body in a situation which gives it the potential to start moving, or to increase its speed, is said to possess potential energy. By this simple contrivance, we make the idea of energy useful by endowing it with the property of being conserved. Thus, as a book falls off a high shelf towards the floor, its original potential energy is converted into kinetic energy, the sum of the two remaining the same. Actually, there are deep theoretical reasons why a conserved energy must exist. It is related to the homogeneity of time. The fact that the laws of physics are the same today as they were yesterday actually implies[8] that energy must be conserved. Regrettably, it would be too long a digression to discuss this further.

Our definition of energy in terms of motion, or the potential for motion, may seem puzzling. The word ‘energy’ is now commonly used in everyday life. We are all used to considering our domestic electricity, gas, oil and coal supplies under the generic term “energy”. In what sense can they be considered as “motion or the potential for motion”. Well, of course, they all come under the heading “potential for motion”. Their use is to produce heat or light, or to power electrical devices like motors or electronic equipment such as computers, televisions, etc. We shall briefly examine each of these uses in turn in order to show that the production of motion is the end product.

In the case of turning an electric motor (vacuum cleaners, washing machines, central heating pumps, etc) it is clear that the initial electrical potential energy is converted into the motion of the motor and whatever the motor drives. But what about heating and lighting and so on? Most domestic energy usage is for heating. How does heat fit into the description of energy as “motion or the potential for motion”? Well, heat consists simply of the motion of the molecules of the substance being heated. The molecules of a hot substance are in a more rapid state of motion than those of a cooler sample of the same material. Once again, the potential energy inherent within gas, oil, coal, or an electricity supply, is being converted to motion when heating takes place.

The case of lights and electronic devices like computers and televisions is only slightly more complicated. Initially, the electrical potential energy is converted to the motion of electrons, since this is what constitutes an electric current. We could stop at this point and rest our case. However, we note that the end product of these devices is variously light, sound and heat. The production of heat accounts for the majority of the energy consumed by all these devices. The energy which is emitted as sound or light also ends up later as heat, except perhaps for an infinitesimal amount that might escape into outer space as light or other electromagnetic radiation. Hence, we see that once again motion is the end result, in the form of heat.

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[8] Strictly this is true only if we assume theories formulated in a certain manner, namely via a stationary Lagrangian. But virtually all the physics of non-dissipating systems can be so formulated.

Taking a closer look at sound (or noise), this may be generated by, say, the motion of a speaker cone inducing an oscillatory motion in the air. Thus, noise is also a form of motion. The motion of the speaker cone induces the motion of pressure waves through the air. As a sound dies away, the orderly form of the original coherent sound waves gives way to a chaotic motion of the air molecules as the sound is converted to heat. Thus, in summary, the energy flow relating to sound production is: electrical potential → electron motion → speaker motion → coherent air motion (sound) → air molecular motion (heat). This again illustrates the conversion of potential energy to kinetic energy (motion) of several different types.

The case of light is more interesting. Ultimately the light becomes absorbed by the surrounding matter, and, like sound, emerges as heat and hence as motion. But whilst it is still in the form of light, what sort of energy is it? Light is actually an electromagnetic wave. Light is therefore a manifestation of one of the fundamental "forces" rather than a property of "matter". Hence, the question of the nature of light energy brings us back to the question "what is the nature of the fundamental forces"? We have seen that kinetic energy is associated with the motion of matter, but what is the nature of potential energy? The answer to these two questions is the same. We can identify potential energy as the manifestation of one or other of the four fundamental "forces".

This sounds innocent enough, but it actually represents a significant paradigm shift. Instead of the potential energy being assigned to the book on the high shelf, the potential energy is being assigned to gravity itself. Since a physical property is being assigned to it, namely energy, it is unavoidable that gravity be considered as an aspect of physical reality. Thus, gravity is not merely the name attached to an influence that one piece of matter exerts upon another. On the contrary, the gravitational field is an element of the physical world in its own right. This gravitational field exists at all points in space and, amongst other properties, carries the potential energy. Thus, as our book falls to the floor, energy is conserved because energy merely moves from the gravitational field to the book.

Be warned that relativists may squirm at the above description of gravitational energy. There are theoretical problems with considering a gravitational field as possessing a local energy density. Moreover, the total gravitational energy is negative. This may seem like an inconvenient detail, but it is actually the single most important fact in cosmology. The argument is less contentious for, say, the electrostatic interaction between two electric charges. As the electrostatic interaction induces a change of motion in the charges, and hence a change in their kinetic energy, energy moves to or from the electric field to keep the accounts balanced. In this case, the field energy is sensibly positive – and localised.

Thus, the fundamental "forces" of physics can be regarded as fields of energies which occur due to the presence of particles of matter. The particles of matter act as the source of these energy fields, though not all types of particle give rise to all types of energy field. In turn, the energy fields cause the motion of the particles of matter. In some cases, the energy fields cause the particles to bind together, as with electrons in atoms or nucleons in nuclei.

The implication of this view of the fundamental "forces", namely that they are energy fields, is that they form part of the "stuff" of the universe. That is, the "forces" are not merely the name given to effects, but rather they are "things" in their own right. That this is an inescapable conclusion is reinforced by relativity theory. Since Einstein, our understanding has been that any quantity of energy, E, possesses a mass, m, given by undoubtedly the most famous equation in physics, $E = mc^2$, where c is the speed of light in a vacuum (186,000 miles per second). This means that every Joule of energy has associated with it an inertial mass of about 10^{-17} kilograms. Not very much, admittedly, but not zero – and equal to the mass of about 6 billion nucleons.

To recap, we have outlined a view of the material universe as consisting of,

- Three types of matter particle (e,p,n) and four types of "forces";
- Both matter particles and the "force" fields possess energy;
- As a consequence, the "force" fields must also possess mass and hence be part of the material world;
- Changes in the motion of matter consist of the exchange of energy between the matter and the "force" fields;
- Matter can be divided only so far: all familiar matter is composed of atoms which can be regarded as consisting of the three particle types, (e,p,n), each of which has a finite (non-zero) mass.

So as not to mislead, note that we shall shortly see that there are a great many more particle types than just three (§B.3,4).

There are two further key properties of the material world which we must add to complete the picture. The first concerns a rather obvious lack of symmetry between matter and the "force" fields in the above description. Whilst both may possess energy, which is equivalent to mass, only matter has been specified as appearing in discrete particles of well defined, finite mass. Our first additional property is that,

- The "force" fields consist of discrete packets, or quanta, of energy of finite magnitude.

This is the defining characteristic of the quantum theory. These quanta, or discrete packets of energy, can be regarded as particles of the "force" field. Because matter acquires its motion by exchange of energy with the "force" fields, and because the "force" fields consist of discrete packets of energy, it follows that matter can change its motion only in these discrete amounts. Thus, in the right circumstances, the quantisation of the "force" fields will induce a discrete spectrum of possible states on matter. Once again, a more complete description of quantum theory and its origins would be too long a digression. The tale has been told elsewhere, [Ref.?]. Fortunately, we can progress without knowledge of the details.

Notice that we have reached the point now where,

(a) the "force" fields are best regarded as fields of energy, but matter particles also possess energy;

(b)the “force” fields are part of the “stuff” of the universe, just as matter is;

(c)both matter and the “force” fields are to be regarded as comprised of particles of finite energy.

The distinction between matter and energy is becoming hard to discern. Indeed, from our description so far, the only distinction which appears to remain is that whilst quanta of “force” field energy can be created or absorbed when matter changes its state, a particle of matter (e.g. a proton) appears to be immutable. Even this distinction is, however, doomed to fade way. We explore this next, in our final key property of the material world.

§B.3 The Mutability of Matter

The ancient Greek philosophers were considerably exercised by the nature of change in the world. One school of thought, associated with the name of Heraclitus, maintained that change is continuous, universal and unavoidable (“you cannot step in the same river twice”). In stark opposition, the Parmenides school held that no real change was possible. Things are as they are, and anything that appears to change was never actually real in the first place. The opposing schools were united by Democritus. He observed that if matter were composed of unchangeable units (atoms), and if the myriad diversity of matter in our world could be regarded as these atoms being combined in different ways, then the two schools of thought could both be satisfied. In this view, the fundamentally unchanging nature of things is due to the immutability of atoms. For example, this would explain the conservation of mass (were it true!). On the other hand, the variety and continuous flux in the world is attributed to the endless ways in which the atoms may be combined. This philosophy may loosely be labelled as “material-reductionism”. Prior to the early twentieth century, this material-reductionism had been the prevailing *scientific* philosophy for nearly two and a half thousand years. To this day it remains the working philosophy of most scientists. There is little reason for chemists or biologists to be unhappy with it. It has, however, been overturned.

It is well known that atoms are not indivisible. The existence of nuclear power and nuclear weapons has seen to that. So has the phenomenon of radioactivity, which transmutes one chemical element into another. We have seen in §B.1 that atoms have a sub-structure, so their divisibility is easily explained. The divisibility of atoms does not, in itself, undermine the material-reductionist philosophy. It can simply be claimed that the “atoms” of the Greeks should be identified, not with our modern atoms, but with their constituent particles, the protons, neutrons and electrons. All would then be well for material-reductionism if the protons, neutrons and electrons were immutable. Unfortunately, they are not.

The particular form of radioactivity known as beta decay is sufficient to establish that the nucleons are not immutable. In this form of radioactivity, the decaying atom transmutes into the element one atomic number higher in the periodic table. For example, cobalt-60 undergoes beta decay to form nickel-60,

$$^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni} + e^- + \overline{\nu}_e \qquad \text{(example of beta decay)}$$

The final particle, an anti-neutrino, is new to this discussion. We shall have more to say about the neutrinos in §B.4.

The nucleus of cobalt-60 contains 27 protons and 33 neutrons. That of nickel-60 contains 28 protons and 32 neutrons. Thus, beta decay can be considered as the transmutation of a neutron into a proton (together with an electron and an anti-neutrino, of which we will speak more later). That is,

$$n \rightarrow p + e^- + \overline{\nu}_e \qquad \text{(all beta decays)}$$

So, the nucleons are not the immutable “atoms” of the Greeks either.

Given that beta decay can be regarded as a decay of the neutron, $n \rightarrow p + e^- + \overline{\nu}_e$, it is reasonable to ask whether neutrons themselves are stable particles. There are not. Free neutrons decay with a half-life of ~15 minutes. The interesting question, therefore, is why are the small and medium sized nuclei stable? Why don’t all nuclei beta decay? The answer is discussed in Chapter 9 of the Cosmic Coincidences.

Following the description of the sub-structure of atoms and nuclei in §B.1, the reader may have been wondering whether the nucleons also have a sub-structure. They do, though of an odd kind since their constituents have never been observed directly. Roughly speaking, nucleons are composed of quarks plus the energy of the strong nuclear “force” (gluons). The quarks are responsible for the net quantum numbers of the nucleons (e.g. their electrical charge) whereas the gluons account for most of their mass. These are again deep waters which we have no wish to enter. However it is important to say a little about the substructure of the nucleons in order to dispel any idea that the quarks may be, finally, the Greeks’ immutable “atoms”. All we need note here is that the nucleons are composed of two types of quark, so-called “up” (u) and “down” (d) quarks. The former has charge $^2/_3$ whereas the latter has charge $-^1/_3$ (these being, as usual, multiples of the proton charge). Both nucleons consist of three quarks: the neutron is udd, so that it is electrically neutral, whereas the proton is uud, so that it has a net charge of +1. Consequently, the conversion of a neutron into a proton (udd → uud) in beta decay can be interpreted as the conversion of a “down” quark into an “up” quark. That is, we can interpret beta decay as,

$$d \rightarrow u + e^- + \overline{\nu}_e \qquad \text{(all beta decays)}$$

So, the quarks are not immutable either!

Actually, there is a much simpler argument to demonstrate that we must abandon the idea that matter comes in immutable particles. This is the existence of antimatter. When any particle of “matter” meets its antiparticle, their net quantum numbers cancel. This implies that they will annihilate into pure energy[9], i.e. the outcome is the production of quanta of the “force” fields but no “matter” particles. So, for example, an electron and a positron annihilate into two gamma photons (quanta of the electromagnetic field),

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[9] Even if the particles have very little kinetic energy, there must be at least $2mc^2$ of energy released. Note that a particle and its antiparticle have the *same* mass. The antiparticle does not have a negative mass.

$$e^- + e^+ \rightarrow 2\gamma$$

So, under the right circumstances, “matter” can be destroyed. The material-reductionist philosophy, at least in the old-fashioned sense of immutable particles, is discredited. Of course, all sense of decorum is not lost. Whilst the conservation of mass is no longer true, it is replaced by the conservation of mass-energy. Thus, the total kinetic energy of the electron and positron in the above annihilation, plus their rest mass equivalent energy ($2mc^2$), exactly equals the resulting energy of the two photons.

As well as the possibility of matter being destroyed, matter can also be created – again under the right circumstances. For example, if there are plenty of photons around with energies exceeding $2mc^2$, where m is the electron mass, then the above annihilation reaction may occur in reverse, i.e.,

$$2\gamma \rightarrow e^- + e^+$$

thereby creating “matter” particles out of pure energy. Similarly, if there are plenty of photons around with energies exceeding $2Mc^2$, where M is the proton mass, then pairs of protons and anti-protons can be produced,

$$2\gamma \rightarrow p^- + p^+$$

When can pair production, as it is called, occur? One example is simply at extremely high temperatures. We are all familiar with things “glowing red hot”. Raising the temperature further results in the glow becoming yellow or white, or even pale blue. As the temperature is increased the dominant frequency of the emitted radiation also increases. At temperatures higher still, the frequency can become so high that the radiation is in the X-ray region, and then the gamma ray region. For any given temperature, there is a unique spectrum of photon energies in a so-called thermal or “black body” radiation field. (Recall that photons are the ‘particles’, or quanta, of the electromagnetic field, and that light is a particular frequency of electromagnetic wave). At temperature T the average photon energy is 2.7kT, where k is Boltzmann’s constant that converts the conventional measure of temperature (degrees Kelvin) to an energy measure.

Using the mass of the electron (0.9×10^{-30} kg) and $k = 1.38 \times 10^{-23}$ J/K, we find that a temperature of around 4×10^9 K is required to produce electron-positron pairs in copious quantities. Since protons are 1836 times heavier than electrons (mass 1.67×10^{-27} kg) the temperature required to produce large quantities of proton-antiproton pairs is roughly 8×10^{12} K. These temperatures are far higher even than those occurring in the centre of main sequence stars. However, temperatures of this magnitude occurred within the first seconds of the Big Bang. Consequently the free creation of matter “pairs” during the Big Bang is a key feature of the theory.

However, the creation of particle-antiparticle pairs is not the only form of matter creation occurring at high temperatures. We can also consider the reverse of the beta decay reaction, i.e.,

$$p + e^- + \overline{\nu}_e \rightarrow n \qquad \text{(reversed beta decay)}$$

Although possible in principle, this reaction is highly unlikely to occur simply because it requires three incoming particles to collide together simultaneously. However, it is closely related to another reaction obtained by moving the antineutrino to the other side, and changing it to a neutrino. Considering the reaction to be analogous to an equation, the subtraction of an antineutrino is equivalent to the addition of a neutrino. The exact statement of this principle requires the reaction to be viewed in terms of a Feynman diagram. In Feynman diagrams, an incoming antineutrino can also be interpreted as a neutrino “moving backwards in time”. It can be reinterpreted as a physically real but outgoing neutrino. Once again these are deep waters in which we will endeavour to avoid drowning, at least just now. The result is that we are led to consider the reaction,

$$p + e^{-} \Leftrightarrow n + \nu_e \qquad \text{(A)}$$

For suitable particle energies (i.e. at a suitable temperature) this reaction may go forwards or backwards, as indicated by the double headed arrow. Neutrinos will occur naturally at the very high temperatures envisaged during the first second or so of the Big Bang. Electrons will also be produced copiously at these times. Thus, we conclude that neutrons and protons may transmute into each other during the first seconds of the Big Bang. This is a key observation. It means that the relative abundances of the chemical elements in the primordial universe is determined, not by “act of God” but by the balance imposed naturally, and predictably, by reactions such as (A).

Of course, all these observations are of little relevance to everyday terrestrial conditions. Temperatures and particle energies are far too low for matter creation to occur, and matter transmutation is confined to radioactive decay. Were this not the case then antimatter would be more familiar to us.

§B.4 The Rest of the Zoo – The Standard Model of Particle Physics

The particles that we have introduced as our main players are: electrons, protons and neutrons, plus their antiparticles, together with photons, the quanta of the electromagnetic field. And we have also introduced the mysterious neutrinos. This cast of particles is generally sufficient for the purposes of the Cosmology Tutorial and the Critique of the Cosmic Coincidences on this site. However, it would be unfair to leave the reader with the impression that there are no other particles in nature. There is a bewildering variety. We shall therefore present an extremely brief account of the standard model of particle physics here. The sole purpose is to provide some context for the main players.

From the late-1940s onwards, particle accelerators have discovered large numbers of new particles. Most of these fall into two classes, according to their spin. The mesons have integral spin, whilst the baryons have half-integral spin. Collectively they are known as hadrons, their defining character being that they are subject to the strong nuclear force. Neutrons and protons are examples of baryons.

The first meson to be discovered was the pion (1947). The existence of the pion had been conjectured on theoretical grounds (Yukawa, 1935). By analogy with the role of the photon in carrying the electromagnetic force, so the pion was hypothesised to carry the strong nuclear force. Indeed, the mass of the pion aligns well with the range of the nuclear force. The concept of pions as mediators of the strong force continues to be helpful in nuclear physics, but it is certainly far too simplistic a picture of the strong force.

By the late 1960s many families of mesons and baryons were known. Some particles tended to come in different charge states (e.g., $\pi^-,\pi^0,\pi^+;\ K^+,K^0$), whereas some were neutral only ($\eta,\eta',\omega,\varphi$). Some neutral particles were their own anti-particle (e.g., π^0) whereas others had distinct anti-particles (e.g., K^0 is distinct from $\overline{K}^0$). Particles tended to group together into families with the same spin. The meson families had nine members. For example, one zero spin family comprised $\pi^-,\pi^0,\pi^+;\ K^+,K^0,\ \overline{K}^0,K^-$, η,η', and a spin-one family was $\rho^-,\rho^0,\rho^+,K^{*+},K^{*0},\overline{K}^{*0},K^{*-},\omega,\varphi$. There were also higher mass versions of these families, which it seemed might be excited states of the lowest lying families.

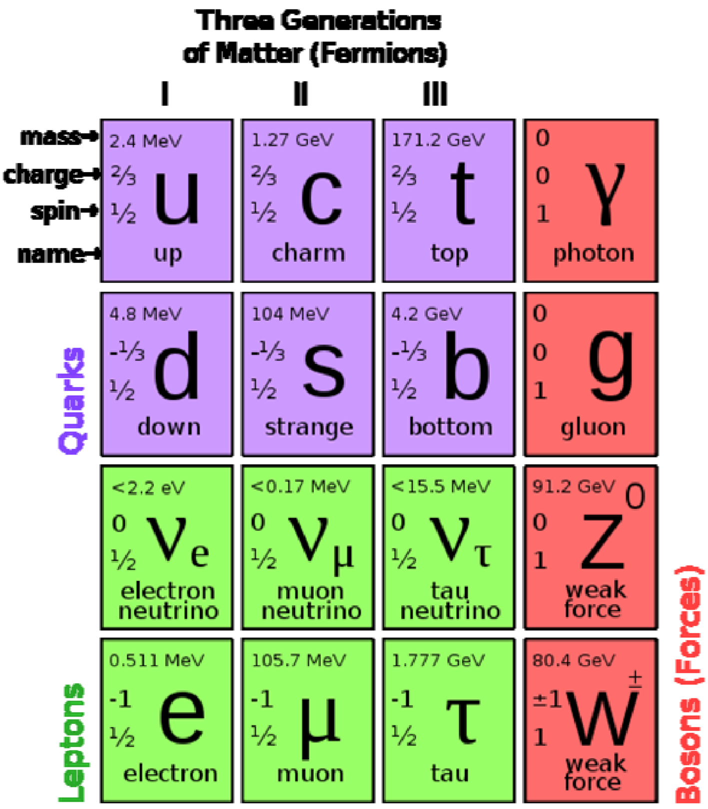
Similar regularities occurred amongst the baryons. Thus, the nucleons were part of a family of eight spin ½ baryons comprising $n^0,p^+,\Sigma^-,\Sigma^0,\Sigma^+,\Xi^-,\Xi^0,\Lambda^0$, whilst families of ten also occurred, for example the spin 3/2 group $\Delta^-,\Delta^0,\Delta^+,\Delta^{++},\Sigma^{*-},\Sigma^{*0},\Sigma^{*+},\Xi^{*-},\Xi^{*0}$, Ω^-. Again, there were also higher mass versions of these families, which it seemed might be excited states of the lowest lying families.

The existence of excited states, together with certain regularities in the reactions which could form these particles (and the particles into which they could decay) suggested a substructure for the hadrons. This is the quark model. Until 1974 there was experimental evidence only for particles comprised of three types (flavours) of quark (called *u, d, s*). However theoretical opinion was mounting that there should be a total of six quark flavours. By 1977 both the 4th and 5th quark flavours (*c* and *b*) had been ‘discovered’ in the form of $c\bar{c}$ and $b\bar{b}$ mesons. The top quark (*t*), because of its very high mass, was not discovered until 1995. The *c* and *b* quarks give rise to whole new families of hadrons. In recent years the study of mesons containing a *b* quark has been the focus of enormous experimental efforts. The top quark (*t*), however, decays so fast that it does not form hadrons.

However, the categorisation of the hadrons in terms of the quark model was not the only thing going on in particle physics during the 1960s & 1970s. There was also progress on the theoretical front. In particular, a theory of the weak nuclear force was discovered which united it nicely with electromagnetism. Early theories of the weak force were reasonably successful as far as they went, but were known to be ultimately mathematically catastrophic. Quantum field theory, at least when expressed in terms of perturbation series, has a habit of giving infinite results. The same problem plagued quantum electrodynamics (QED) for a long time. The trick to setting QED on a proper foundation is ‘renormalisation’, which essentially amounts to a careful distinction between what is experimentally measureable (and hence finite) and what is not (the divergent part). But any old theory is not renormalisable.

Weinberg, Salam, t’Hooft, Veltman and others realised that the feature of electrodynamics which made it renormalisable was that it was an example of a theory with a gauge symmetry, specifically due to the symmetry group U(1). So, to make the theory of the weak force sensible, they turned it into a gauge symmetric theory. The required symmetry group was SU(2). This required that there be a counterpart to the photon, the carrier of the electromagnetic force, which conveyed the weak force. Moreover, there would need to be both charged and neutral versions of these quanta, and they would need to be 'vector' (spin 1) bosons. The required "intermediate vector bosons", $W^{\pm}, Z^0$, duly arrived in experimental studies. The existence of the "neutral weak current" (i.e., Z^0) was a particular triumph for the theory. By the late 1970s the gauge symmetric electroweak theory was established.

But this theoretical advance had implications beyond the weak force. It was quickly realised that the same trick could be deployed for the strong force. Simplistic, low energy attempts to model the strong force (e.g., via pion exchange) also made no real mathematical sense. Moreover, the regularities in the observed hadrons and their interactions which had led empirically to the quark model were very nicely consistent with the symmetry requirements of the group SU(3). Given that QED and the weak force had required the groups U(1) and SU(2), this seemed very natural. The resulting theory is known as "quantum chromodynamics" (QCD) and is the theoretical underpinning of the standard model of particle physics. The fundamental particles required are summarised in the graphic below:-



This graphical does not display all the possible sub-varieties of these particles, however. Each of the six quarks can occur in three "colours" (r, g, b). And the quarks are distinct from their antiparticles, hence there are really 6 x 3 x 2 = 36 distinct quarks.

The gluons are the quanta of the strong force. They also carry colour charge. However, they carry both a colour and an anti-colour. More precisely, they are an 8-dimensional (octet) representation of SU(3), formed from certain linear combinations of terms like $C_1\overline{C}_2$ except for the colourless ("white") combination $\left(r\bar{r}+g\bar{g}+b\bar{b}\right)/\sqrt{3}$. In other words, there are eight different gluons.

The three massive leptons, e, μ, τ are distinct from their anti-particles, so there are six of them in total. (Incidentally, the terminology "lepton" means "light particle". This seemed appropriate when only the electron and the muon were known. But the tau is hardly light, it's about twice the mass of a nucleon. A further terminological confusion is that older texts may refer to the muon as the mu-meson. Of course, the muon is *not* a meson. The confusion is historical. The muon was actually detected before the pion, and was mistaken for the strong force mediating meson predicted by Yukawa).

The three neutrinos are regarded as distinct from their anti-particles in the standard model, hence there are believed to be six of them also – making 12 leptons in all. But note that it is not established that anti-neutrinos are different from neutrinos.

The $W^{\pm}, Z^0$ are the quanta of the weak nuclear force. The W^+ is the anti-particle of the W^-, whilst the Z^0 is its own anti-particle. Hence, there really are only three such particles.

The quarks and the leptons are all spin ½ fermions. They are the "matter particles".

The force-carrying field quanta, the photon, the gluons and $W^{\pm}, Z^0$ are all spin 1 bosons ("vector bosons").

The photon, γ, and the gluons have zero mass. All the other particles have non-zero mass. The neutrinos used to be thought massless, but the phenomenon of neutrino oscillation has shown this cannot be so. The neutrino masses are probably a lot smaller than indicated by the rather generous upper bounds in the above graphic.

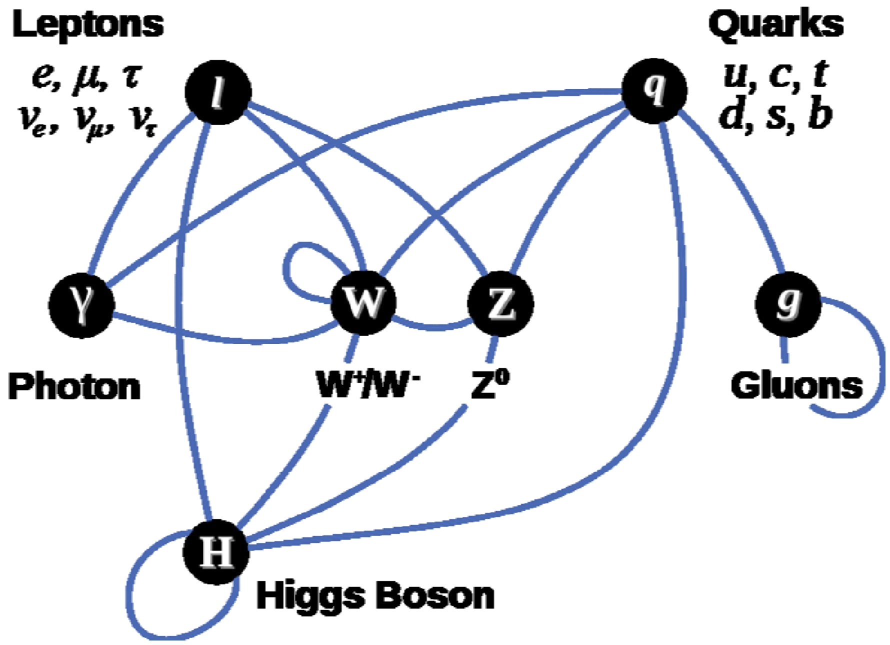
The whole zoo of hadrons is explained by the quark model. The mesons are bound states of a quark and an anti-quark. The baryons are bound states of three quarks (and the anti-baryons of three anti-quarks). The result is that all the hadrons have zero net colour charge ("colourless" or "white" or, more exactly, a colour singlet state). So SU(3) is a hidden symmetry.

The gauge symmetries of the standard model imply conservation of the corresponding "charges". The U(1) symmetry gives conservation of electric charge. The SU(2) symmetry gives conservation of each of the three lepton numbers. The SU(3) symmetry gives conservation of colour charge.

Lepton numbers are defined by assigning an "electron number" of +1 to the electron and the electron neutrino, and -1 to their antiparticles. Similarly, a "muon number" of +1 is assigned to the muon and the muon neutrino, and -1 to their antiparticles; and, , a "tau number" of +1 is assigned to the tau and the tau neutrino, and -1 to their antiparticles. The standard model implies exact conservation of each of the three lepton numbers separately. This means, for example, that when a muon decays it must produce a muon neutrino as a result. However, the phenomenon of neutrino oscillation implies that the lepton numbers are not individually conserved. This is related to the non-zero mass of the neutrinos. Conservation of the overall lepton number (the sum of the three numbers) is more precise, though still not necessarily absolutely precise. Note that individual lepton number conservation remains generally a good guide, due to the low mass of the neutrinos. However, its imprecision implies an extension is needed to the standard model. There is no problem in providing such extensions.

The only fundamental particle not displayed in the above graphic is the Higgs particle. This scalar (spinless) particle is predicted since it plays a crucial mathematical role in the standard model. Experimental discovery of the Higgs is currently the Holy Grail of particle physics.

The interactions between the particle types are summarised by:-



The salient points are:-

- The massive leptons, e, μ, τ , are subject to both the electromagnetic and weak nuclear forces. This is indicated in the above graphic by their coupling to the photon and the $W^{\pm}, Z^0$;
- The neutrinos are subject only to the weak nuclear force, coupling only to the $W^{\pm}, Z^0$;
- The quarks are subject to the electromagnetic force, and both the strong and weak nuclear forces, coupling to the photon, the $W^{\pm}, Z^0$ and the gluons;
- The gluons are subject only to the strong nuclear force;

- The gluons, the Higgs and the $W^{\pm}$ couple to themselves (as indicated by the little loops), which means that the gluons are subject to the strong force, the Higgs has mass, and the $W^{\pm}$ are subject to the weak force;
- The photon is the only force-carrying field quantum which does not interact with itself (even the graviton, if it exists, would do so);
- All the particles with non-zero mass, i.e., all the leptons, all the quarks and the $W^{\pm}, Z^{0}$, couple to the Higgs since this is the mechanism by which they acquire their mass;
- All particles are subject to gravity (even those with zero rest mass)

Finally, please note that we have discussed only the standard model here. If extensions to the standard model, such as supersymmetric theories (SUSY), are correct, then there will be further particles. SUSY in particular roughly doubles the number of particles.

The only known *stable* particles, however, are the electrons, protons and neutrinos, plus their anti-particles, and photons. The particles comprising dark matter, if they exist, must also be stable (be they WIMPs, axions, neutralinos, or whatever). The existence of the graviton is unproved.