CHAPTER 7

QUANTUM MECHANICS

In the last chapter we discussed one of the two revolutionary events in twentieth century physics: Einstein's Theory of General Relativity. In this chapter we will briefly mention the other revolutionary event: Quantum Mechanics. We need to know just a bit about what Quantum Mechanics (or QM) says in order to understand more fully the behavior of light and its interaction with matter. Of course, like GR, QM is a highly mathematical theory so we can only scratch the surface, but it is imperative that we try at least to get a feel for it.

In the early part of this century it was realized that classical mechanics (e.g., Newton's Laws) and the laws of electromagnetism did not explain many of the new phenomena observed at the atomic scale. GR also did not deal with atomic process, thus, in order to understand atomic and subatomic phenomenai, a different theory had to be devised. QM is that theory. It is important to realize that even though QM is a theory for the atomic world, the processes and phenomena which occur on that scale have tangible and important effects on our world. So, let us take a brief, superficial excursion into the world of Quantum Mechanics.

7.1) THE PHILOSOPHY OF QUANTUM MECHANICS

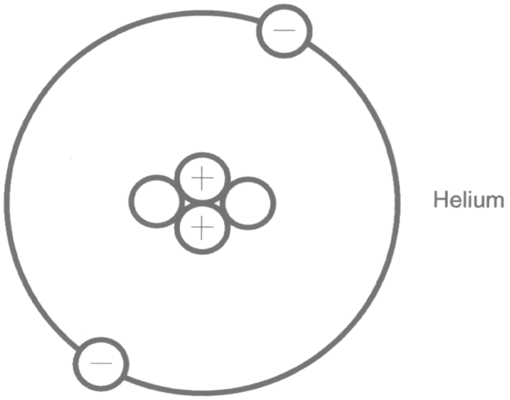
QM is radically different from classical physics. Although we did not delve into the mathematics of GR, the concepts involved are straightforward and make a lot of sense. There is nothing bizarre about the formulation of GR, but the way it is currently worked out, GR fails in describing the behavior of objects of atomic size or smaller. The equations can't be solved as the size scale gets smaller and smaller. In contrast, QM works in the atomic and sub-atomic world, but the price that has to be paid is that there are several assumptions or postulates which are contrary to our "common sense". This should not surprise us. Our common sense is based on the world that we interact with which exists on a much larger scale than that of atoms or nuclei. For instance, a human hair is typically 50 microns in diameter. A micron is 10^{-6} m, so a hair is 5×10^{-5} m in diameter. A hydrogen atom is about 5×10^{-11} m in size. How many hydrogen atoms would stretch across a human hair? To answer this, we just divide the size of a human hair by the size of a hydrogen atom. With the numbers quoted above, we can do the calculation in our head: You could stretch about a million hydrogen atoms across a typical human hair. In short, we never "see" the atomic or nuclear world and so we can not be familiar with what goes on there.

One of the fundamental tenets of QM is that there is an unavoidable uncertainty as you try to measure fundamental physical parameters like the position and velocity of a particle. In our big world (which we'll call the macroscopic world), there is no problem in measuring accurately the position and velocity of an object at any given time. QM states flatly that in the sub-microscopic world of atoms and nuclei, there is an absolute limit to how well you can simultaneously measure the position of an electron, for instance, and its velocity as it moves about an atomic nucleus. This uncertainty is called the Heisenberg Uncertainty Principle and it is a postulate of QM. No-one has ever found a way around this rule. It just seems to be the way the world (at the least the atomic world) works.

Closely related to this concept is the role of the observer in QM. It turns out that QM does not predict the position of a particle the way Newtonian mechanics or GR does. Instead, QM gives you the probability of finding a particle in one place. This is a radical departure from the other, older theories of physics (usually lumped together as "classical physics"). In principle, with the older theories, if you knew the position and velocities of all particles in the Universe at a given time, then you could use the formulas of Newtonian Mechanics or GR to determine their future positions. In effect, the future is pre-determined by the past behavior of all the particles comprising the Universe. You don't have to worry about this because it is absolutely impossible to determine the position and velocity of all particles in the Universe, so you can never really know exactly what is going to happen. However, QM does away with even the pretense of determinism by introducing a probabilistic approach to describing the location of particles. Some physicists (including Einstein) hated the indeterminate aspect of QM. However, the repeated successes of the theory in explaining atomic and even nuclear phenomena has made QM almost universally accepted as an excellent model of the small-scale world.

7.2) THE STRUCTURE OF ATOMS

Let's look briefly at the structure of atoms. Most of you are probably familiar with the particles called protons, neutron, and electrons. If you're not or you don't remember, we'll refresh your memory. Atoms are made up of clusters of protons and neutrons called nuclei (the singular form is nucleus). The protons have positive electric charges and the neutrons have no electric charge; they are electrically neutral, hence their name. Both particles have nearly the same mass, although that mass is very small, of order $10^{-27}\ kg$. The size of a nucleus is very small, of order $10^{-15}\ m$. Notice that this is much smaller than the size of the hydrogen atom that we mentioned above. What is the difference between a nucleus and an atom? Well, we've mentioned protons and neutrons as being in the nucleus, but what about electrons? Electrons are negatively charged particles which are not in the nucleus itself, but are orbiting or moving at some distance from the nucleus. Electrons are much less massive than protons or neutrons - almost 2000 times less massive - but they have the same amount of charge as a proton. Now that we know a bit about all the parts, we can put them together to form our atom. A carbon nucleus, for instance, is composed of 6 protons and 6 neutrons. A great distance from it orbit 6 electrons, and the totality of the nucleus and the orbiting electrons make up what we call a carbon atom. This is basically the picture of the atom that we have from high school courses or TV documentaries. For instance, a helium atom has 2 protons, 2 neutrons, and 2 electrons, and we have been taught to draw as follows:



This picture is completely misleading. It is at best a cartoon and is similar to claiming that a stick figure is a realistic portrait of a person. If we look at the size of the hydrogen atom, which we quoted above as 5×10^{-11} m and then think about the size of the nucleus, 10^{-15} m, we realize that there is an enormous gulf of empty space between the nucleus and its orbiting electrons.

In the early part of this century, a famous experiment by Rutherford showed that atoms had to have a tiny but very dense core. Rutherford and his assistants were firing alpha particles (which you should recall are nothing more than helium nuclei travelling at nearly the speed of light) at sheets of aluminum foil to see how the foil would deflect the alpha particles. Rutherford described the experiment as similar to shooting artillery shells at tissue paper. Imagine his surprise when a very small fraction of the alpha particles bounced right back at him!. That's quite a surprising "tissue paper". Rutherford correctly concluded that the atoms had to be composed of very dense but very small cores (later called nuclei) which take up very little volume (otherwise, a much larger fraction of alpha particles would collide with the nuclei and bounce back towards the source).

Perhaps an analogy can drive this concept home a bit more clearly. Imagine that our helium nucleus is the size of a baseball sitting on second base at the new Turner Field. At that scale, the electron would be the size of a fly or a mosquito flying about *outside* the stadium in a distant parking lot. Let this idea sink in for a minute or two. In this model, the inescapable conclusion is that atoms are, for the most part, empty space. Because matter is made up of atoms, then all matter is mostly empty space.

If you really think about this situation, it is somewhat disturbing. Why isn't everything transparent if matter is composed of so much empty space? Why can't I walk through walls or put my hand through my desk if the particles which make up space are fill up so little volume? The answers to these questions have to do with the way the electrons distribute themselves about the nucleus. Part of the cartoon picture of atoms drawn above seems to imply that the electrons orbit the nucleus like the Earth orbits the Sun. Nothing could be farther from the truth. As stated in the previous chapter, if a charged particle accelerates, it gives off electromagnetic radiation (*i.e.*, photons or waves of light). An electron in orbit about a nucleus is executing accelerated motion so it must be continuously radiating and, thus, continuously losing energy. But this energy loss would cause the electron to crash quickly into the nucleus, much like removing the Earth's orbital energy would cause it to crash into the Sun. The classical picture of electrons oribiting a nucleus had to be changed. But how?

In the 1910's, Niels Bohr hit upon the idea the energy of an atom can occur only at certain, specific values which differed depending on the atomic species. Since the energy of an atom is determined by the configuration of its electrons, Bohr's idea was tantamount to saying that the electrons in an atom could only have specific energy values with all other values forbidden. The energy of the electrons was said to be discrete or quantized. This quantization of energy for the electrons in turn implied that the electrons could not be in any old place with any old energy. They could only be in specific regions with very specific values of the energy. Most positions and energies were prohibited. There was just no way for the electrons to be there. The specific regions were called energy levels. An alternative name for energy levels is quantized levels or states.

This is a very different situation than that of a planet orbiting a star or a satellite orbiting a planet. These objects can be at any position from the planet. There are no discrete steps or levels with the in-between regions forbidden. To orbit at a given distance you need a certain energy (in other words, you can't be at 5 Earth radii from the center of the Earth and have any energy you want - depending on the type of orbit, the eccentricity, *etc.*, you can have only one energy), but all values of the energy and corresponding position are allowed. This is a critical difference between the macroscopic, classical world and the sub-microscopic quantum world.

Since this was a decidedly non-classical way of looking at things, Bohr suggested tha the normal rule that accelerating charges radiate (and thus lose) electromagnetic energy didn't hold within the atom. In addition, an electon changes orbits not gradually but abruptly by absorbing or emitting a photon (this was discussed in Chapter 6) which contains the exact energy difference between the two orbits or quantized states. This is where the expression "quantum jump" or "quantum leap" comes from. The irony is that in colloquial usage this means a large jump whereas, in reality, the jump is quite small.

Let's expand a bit on this idea. Let's say that an electron is in one energy level and we want it to move to the next higher energy level. The electron needs more energy to be in the higher level just like a satellite would need more energy to orbit farther from its planet. Let's say that the higher energy level is exactly 2.0 units of energy higher than the level the electron is currently on. By injecting 2 or more units of energy into the electron, the electron should jump to the higher level - at least that's what common sense tell us should happen. If you need to generate a certain amount of muscular energy to jump over a fence and you somehow generate 50% more than that minimum amount, you will easily clear the fence. However, that is not what happens in the atom. If you deliver just a tiny bit more energy to the electron, say 2.05 units instead of exactly 2.0 units of energy, the electron will not make the jump and have that extra bit of energy to spare. In fact, the electron does not move unless 2.0 and only 2.0 units of energy are delivered. Delivering 2.1 or 2.2 or 2.00001 units of energy does absolutely nothing. Just like the quantization or discreteness of the energy levels, this business about needing the exact difference between two energy levels in order to go from the lower one to the higher one is a very non-classical, counter-intuitive phenomenon.

Note one thing, however. If you deliver a large amount of energy, larger than the energy required to bind the electron to the nucleus via the electromagnetic force, then you will literally rip the electron right out of the atom and you will have a free electron and an atom that is missing one electron. The atom missing the electron is called an ion, the amount of energy required to bind the electron to the atom is called the binding energy or ionization energy, and the process of giving the electron more energy than the binding energy is called ionization. Once you provide more energy to the electron than its binding energy, you no longer have to worry about specific or discrete energy quantities. Any amount above the binding energy will do. So an electron has quantized energy states *only* when it is bound to the atom. You might not have expected this, but that's the way QM works.

The situation gets even stranger. In 1925, a French physicist named de Broglie proposed a hypothesis that matter had wave properties in addition to its regular particle properties. This gave matter a wave-particle duality just like light. We can not easily detect the wave properties of matter because the wavelengths are so small. For instance, the wavelength of a proton travelling at 100 $m\ s^{-1}$ is only $4 \times 10^{-8}\ m$ (the expression is $\lambda = \frac{h}{mv}$ where h is Planck's constant). But de Broglie went farther. He proposed that the special orbits that Bohr had postulated for the electrons in an atom corresponded to orbits that could fit an exact number of electron wavelengths within their paths. If a particular orbit needed 3.5 electron wavelengths to cover it, for instance, then it was not allowed.

Although we are not quantifying these ideas, physicist took them seriously because the formulas associated with these concepts predicted the specific spectral patterns of various atoms which were discussed in the last chapter. So these ideas, strange as they were, seemed to work.

But if the electron is just a wave phenomenon orbiting the nucleus, where in the actual wavetrain was the electron located? A german physicist named Schroedinger advanced the idea that the position of the electron could be described statistically. In other words, an equation (named Schroedinger's equation in his honor) could tell you that you had a certain probability of finding the electron in a given position along the orbit and another probability of finding it elsewhere. Once again, the probability aspect of QM is very different from the exactness and determinism of classical physics.

So the electrons are distributed in various regions about the nucleus with a specific formula, Schroedinger's equation, for finding out with what probability you could find the electron in any given region. We will not work out the consequences of Schroedinger's equation in any more detail, but we will now answer the original questions that took us down this particular scientific path: Why isn't everything transparent if matter is composed of so much empty space? Why can't I walk through walls or put my hand through my desk if the particles which make up space are fill up so little volume?

Instead of worrying about the exact statistical distribution of the electrons in an atom as given by Schroedinger's equation, for the time being, let's make believe that the electron is "spread out" far from the nucleus in a thin spherical shell. Some solutions of Schroedinger's equation actually predict this type of behavior for the electron so we are not so far off base. So, we'll assume the nucleus of every atom is surrounded by this thin shell of negative charge. It doesn't matter if there is one electron or 100 electrons; we'll make believe that the negative charge is spread evenly all over this thin shell. The inside of the thin shell is, of course, almost entirely empty. But when you bring two such atoms together, the negative shell of one repels the negative shell of the other (remember that like charges repel and unlike charges attract) and neither can penetrate the space of the other. This is the explanation for why you can't put your hand through your desk or walk through a wall. The negative charges from the shell of one atom prevent the shell of another atom or molecule from getting through into the empty inner region. In addition, Matter isn't transparent because electrons love to interact with light as we saw in Chapter 6. So even a large number of optical photons get absorbed and re-emitted by matter and so, in general, matter is not transparent despite it being mostly "empty".

As we have seen, QM has some very particular rules about the way electrons behave in the presence of a nucleus. They can only have very distinct or discrete values of energy. This implies they can only be in certain places with respect to the nucleus, but these regions can only be specified with a certain probability without actually doing the measurement. Of course, once we do the experiment, we have interfered with the original state of the system and so we only know exactly the state it settled in - but we still don't know exactly what state it was in before the measurement. Finally, there is a limit to our knowledge of certain physical parameters of the atom which is not due to our lack of fine instrumentation but rather, to a vagueness or uncertainty which is actually built into nature. All in all, you can see why QM is such a bewildering business. But despite the sometimes disturbing philosophical implications of this theory, QM is consistent with experiments and is the best thery we have of the atomic and nuclear world as of the end of the twentieth century. Historically, QM was the fruit of the labor of many physicists in the 1920's, so both major revolutions in physics, GR and QM, were complete by the end of the third decade of this century. We have been refining them ever since but there has been no truly revolutionary breakthrough in physics for nearly 7 decades.

7.3) THE FOUR FORCES OF NATURE

We saw in the section above that despite the fact that atoms are mostly empty space, they can get no closer to each other under terrestrial conditions than their negatively charged outer electron shells. The repulsive force produced by the negatively charged shell is produced by the electric force. It turns out that in addition to this electric behavior, charged particles can create magnetic fields when they are moving so it is better to call this effect part of the electromagnetic force. We have now met two of the four forces in nature: the gravitational force and the electromagnetic force. The time has come to discuss the other forces in nature. It turns out that there are only two others; the strong nuclear force and the weak nuclear force.

These two forces are probably unfamiliar to you. This is because their sphere of action is the nuclear world. If we look once more at the nucleus with its cluster of protons and neutrons, we see a paradoxical situation. The protons all have positive charge and the neutrons have no charge. Electromagnetic theory states clearly and without exception that like charges repel. So why doesn't the nucleus blow itself apart? The answer is that the strong force overcomes the repulsion of the electromagnetic force (that's why it's called the strong force) and keeps the protons and neutrons together. In fact, the strong force attracts protons to protons, neutrons to neutrons, and protons to neutrons. Both protons and neutrons are part of a category of sub-atomic particle called hadrons and all hadrons are subject to the strong force. Now that we've explained why protons in a nucleus don't fly apart, you might wonder about the opposite problem: If the strong force is so strong, why don't the protons and neutrons from one atom attract the protons and neutrons from another atom and make one big nucleus? The answer here is that the strong force has a very limited range. Much beyond distances of 10^{-15} m (*i.e.*, the size of a nucleus) the strong force weakens dramatically so that by the time you get to the electrons, it has a strength of virtually 0. It turns out that electrons are part of a class of sub-atomic particles called leptons which are not subject to the strong force. So the strong force successfully keeps nuclei glued together but has no effect outside of the nucleus. Notice that the short range of the strong force is in direct contrast to the gravitational and electromagnetic forces which have infinite range.

The remaining force of nature, the so-called weak force, is much weaker and has even shorter range (10^{-17} m less than the strong force). The weak force produces the decay of neutrons and protons in order to prevent atoms from amassing too many neutrons in their nuclei. The main job of neutrons in an atomic nucleus is to stabilize it and prevent the electromagnetic force of the positively charged protons from ripping it apart. However, too many neutrons are not desirable, either. The weak force somehow keeps the right amounts of protons and neutrons in each atomic nucleus. However, there is some leeway in the mix of the two particles. Lighter atoms have about the same number of protons and neutrons, while the heavier atoms have more neutrons but always less than a factor of two. You should remember from chemistry that changing the number of protons actually changes the atomic species, while changing the number of neutrons gives you a different "flavor" of the same atomic element.

The number of protons determines the chemical element. Atoms with one proton are hydrogen; two protons, helium; three protons, lithium; and so on. Changing the number of neutrons, on the other hand, changes some of the physical properties of the elements (the mass for instance) but not the chemical properties. Hydrogen normally has no neutrons in the nucleus to accompany the proton. However, two rarer forms of hydrogen exist: deuterium has one neutron and one proton; and tritium has two neutrons and one proton. These relatives of normal hydrogen are called isotopes. In reality, all three forms can be called hydrogen but the understanding is that the most common isotope gets the element name by itself and the other isotopes get labelled as isotopes of the element. So, in summary, isotopes of an element have the same number of protons but different number of neutrons. No form of hydrogen exists with one proton and three neutrons. As a matter of fact, even tritium is not a happy camper having too many neutrons per proton. The weak force takes care of this situation by having one of the neutrons decay into a proton. This new nucleus now has two protons and one neutron in it and is no longer tritium but, instead, is a lighter than normal form of helium called ^{3}He (pronounced helium-three or three-helium). Normal helium is ^{4}He with 2 protons and 2 neutrons in its nucleus.

The heavy forms of hydrogen can replace normal hydrogen in any molecule. Heavy water, an important constituent of hydrogen bombs, has deuterium or tritium in place of one of the normal hydrogen atoms. Except for its greater mass (because one deuterium atom is twice as massive as a normal hydrogen atom), heavy water behaves like normal water. Most isotopes are stable, but some isotopes are radioactive. For instance, tritium is radioactive. On average, every 12.3 years an atom of tritium decays, converting a neutron to a proton, and ejecting an electron at high speed from the nucleus (the electron carries away negative charge from the neutron leaving behind a positive charge which makes up the new proton). In addition, an elementary particle called a neutrino is also ejected at the speed of light. We mentioned earlier that in order to travel at the speed of light, an object has to have a mass of zero and, indeed, the neutrino has a mass of zero - just like the photon. The electrons from decaying tritium atoms come flying out of the nucleus at a speed close to that of light and act like little bullets penetrating tissue and disrupting any living cells they pass through. Getting elementary particles to move real fast constitute what is called particle radiation. The old phrase for this was corpuscular radiation. We have to be careful here because particle radiation is not at all like electromagnetic discussed in the last chapter. For the time being, you can think of particle radiation as being made up of fast moving elementary particles which rip into you much like a bullet would. Of course, the mass of an electron is of order $10^{-27}\ gm$ and the mass of a bullet is a few grams so the fast moving electrons (sometimes called beta particles) don't make a visible hole in your body the way bullets would. Nevertheless, on the cellular level, they do a lot of damage. If you are exposed to enough particle radiation, enormous amounts of cells will be disrupted and die and you will become ill with radiation sickness and perhaps even die. The brave men who rushed into the Chernobyl plant to try to contain the core meltdown died within a week of their exposure. Particle radiation can also be dangerous in small doses because some disrupted cells sometimes turn cancerous. This is a slower way to die, but it is also unpleasant.

Historically, as we mentioned, fast electrons were known as beta particles. Fast protons do not have a special name and neither do fast neutrons, but fast helium nuclei (bundles of two protons and two neutrons) were (and are sometimes) called alpha particles. You may also have heard of gamma radiation or gamma rays, but these are not particle radiation at all. Gamma rays are a high energy form of electromagnetic radiation as we saw in Chapter 6.

7.4) RADIOACTIVE DECAY AND DATING

It's not all doom and gloom with radioactive materials. There are many practical and medical uses for them. More importantly, for the purposes of this course, is that radioactive materials shed their fast particles (this is known as radioactive decay) at a steady rate. Typically, as more protons are added to produce ever larger atoms, the electrostatic repulsion in the nucleus makes these atoms unstable. The heavy atoms try to achieve stability by shedding mass in the form of fast-moving particles. Each radioactive element has its own particular rate of decay which is readily measured in a laboratory. By knowing the rate of decay and by measuring how much of the radioactive material has changed form (recall that when an element shed charged particles an element turns into a different element), we can determine how much time has passed from when the decay began. In other words, we can use the radioactive material as a type of clock. Since this is an important property which is used by geologists and astronomers to tell the ages of rocks and meteorites, we will explore these techniques in detail.

Let's begin by considering a block of radioactive material with a mass of 10 kg. We'll call this material barfium. The time it takes the block of barfium to change from 10 kg of barfium to 5 kg of barfium and 5 kg of whatever barfium decays into is called the half-life of barfium. Let's say the half-life of barfium is 1 minute. We start with a block of 10 kg pure barfium and in 1 minute we have 5 kg of barfium and 5 kg of barfium's decay product. You must realize that the barfium and the decay product are all mixed together. The radioactive decay takes place atom by atom all over the block; it proceeds randomly without any predetermined spatial pattern. Separating the barfium from the decay product is difficult but doable. Another minute passes and the 5 kg of barfium become 2.5 kg of barfium and 2.5 kg of the decay product. But we already had 5 kg of the decay product so now we have a total of 7.5 kg. In another minute, we have 1.25 kg of barfium and a total of 8.75 kg of the other material. The table on the next page shows how the decay proceeds:

Table 7.1

Radioactive Decay of Barfium

Time	Amount of Barfium	Decay Product	Total
0 min	10 kg	0 kg	10 kg
1 min	5 kg	5 kg	10 kg
2 min	2.5 kg	7.5 kg	10 kg
3 min	1.25 kg	8.75 kg	10 kg
4 min	0.625 kg	9.375 kg	10 kg
5 min	0.3125 kg	9.6875 kg	10 kg
6 min	0.15625 kg	9.84375 kg	10 kg

After 6 minutes we have a block of material which is at the 98.4375% level is composed of the decay product of barfium. There are only 156.25 gm of barfium left. But in real life it's not easy to find pure barfium (for one thing, we just invented it a few minutes ago) or any other concentration of a pure, radioactive element.

Let's say that an isotope of uranium has a half-life of 1 million years. We pick up a 10 kg rock and we see that it contains 12.5 gm of this particular isotope of uranium. Before we figure out how hold the rock is, we need to find out how much uranium the rock had to begin with. In other words, we need to know the original abundance of uranium. Let's say we know that the original abundance of uranium with respect to the other materials in the rock is 1% (these numbers are way off and we're using them just to make the math easier). That means that originally, the rock started out with $10\ kg \times 0.01 = 0.1\ kg$ of uranium. This is equivalent to 100 gm of uranium which becomes 50 gm after one half-life, which becomes 25 gm after two half lives, which becomes 12.5 gm after three half-lives. So in three half-lives or three million years, the rock goes from its original uranium content of 100 gm to 12.5 gm. In short, the rock is three million years old.

Unfortunately, it is not always easy to determine the original abundance of a radioactive species. Thus, another technique has been developed which compares the *relative* amounts of decay products (called daughter species) to isotopes which are not the result of radioactive decay. For example, for meteorites which presumably formed at the same time, we look at the radioactive decay of ^{235}U (the U is the chemical symbol for

Uranium and the 235 is the atomic weight of this particular isotope of Uranium) and ^{238}U. The former decays (eventually) into ^{207}Pb (Pb is the chemical symbol for lead - it comes from the latin word for lead, *plumbum*) and the latter decays into ^{206}Pb. Fortunately, there is another isotope of lead, ^{204}Pb, which is never the result of any long-lived decay process. In other words, the amount of ^{204}Pb which you measure in a meteorite now is the amount it started out with. If you know the naturally occurring ratio of $\frac{^{206}Pb}{^{204}Pb}$ and $\frac{^{207}Pb}{^{204}Pb}$ and then measure the actual ratios in the sample you wish to date, the excess $\frac{^{206}Pb}{^{204}Pb}$ and $\frac{^{207}Pb}{^{204}Pb}$ must be due to the radioactive decay of the uranium isotopes. Thus, you can determine how long the sample must have been decaying to get to current lead isotope ratios. With this technique you do not need to know the original abundances of the radioactive species. All the quantities necessary to determine the age are measured in your sample.

The only remaining question is how do you know when the radioactive clock starts ticking? In other words, what do you mean by a "naturally occurring" abundance? The clock starts ticking when the rock goes from a molten state to a solid state. When a rock is in the molten state, all the elements have their original abundances (see Chapter 8). In the molten state, everything is mixed together so that a large enough sample of molten material should reflect the original or primordial mix of the elements. Once the rock solidifies, then the abundances are set in stone, if you forgive the pun, and any radioactive elements that are present start decaying so that their fractional amount in the rock starts decreasing. So we really need to know the original abundances of the elements and our clocks are all set. This can be obtained from molten rock after a volcanic eruption, for instance.

In summary, radioactive dating of long-lived species is a straightforward technique which requires minimal assumptions (the decay rate has to remain constant throughout the ages) and is based on nuclear physics which is testable in the laboratory. But the real beauty of this technique is that it depends only on nuclear process which are independent of the conditions the object may have found itself in at various stages of its existence. The nuclear decay rates do not depend on temperature, density, or anything else. The above techniques, when applied to meteorites which are bombarding the Earth daily, reveal that the oldest such objects are 4.5 - 4.6 billion years old. It is for this reason that we say the Solar System (note that we are not talking about the Universe here; our Solar System is but a small part of a larger cosmos) is 4.5 - 4.6 billion years old. We will come back to this point in Chapter 8.