Appendix 1

What is matter?

What are we humans, animals, plants, all forms of life, the Earth, the planets and the stars really made of? And is that familiar stuff really all there is to the Universe? These are deceptively simple questions that go right to the heart of the quest for dark matter. In this book we have explored different aspects of matter and its partner, energy, and have considered why some types of undiscovered matter are suspected so strongly that scientists have invested huge amounts of money in machines to look for them. This is the story of the origin of the Universe and how it led to the types and amounts of matter we see today. Here we review the basic ideas on the nature of matter, what it is made of, and how it is all put together.

DEFINITION OF MATTER

The first thing to understand about matter is that not all of it can be seen directly, and not everything you see around you is matter. Common examples of this are air and light. We can feel air, and even see its effects on things such as clothes on a washing line; but generally speaking we cannot see it – at least not without specialised equipment. In contrast, light allows us to see everything around us. Every sunrise we are bathed in it – and life would soon come to an end without it. But light is not matter; it is energy.

So, what is matter? There are several criteria that must be satisfied before an entity can be described as matter. First, it must occupy space. You are made of matter, and you can prove that you take up space each time you climb into a bath full of water. The rising level of the water is evidence that you have volume. Less obvious is that you resist change in motion. Perhaps a better example is a broken-down car. Faced with the need to push it off the road, you encounter inertia – the resistance to change in motion, even if that motion remains still. Admittedly, the friction of the tyres on the road provides further resistance, but even if you were to try pushing a car on an ice rink you would find it less likely to move than you, because it has more inertia than you do. In other words, there is more car than you.

Finally, matter has mass. Mass is defined as the amount of matter in an object, but it should not be confused with weight. The familiar example of comparing weight on the Moon with your weight on the Earth may temporarily make you feel better – but your mass and volume remain the same in either environment.

Matter is therefore anything that can be weighed, pushed, pulled, have its shape changed, and so on. This is intuitively obvious, but needs to be directly stated. What is far less obvious is the nature of matter. If we were to delve down into its very fabric, what would we see? Around 500 BC the Greek philosopher Democritus gave considerable thought to this, and in his mind saw tiny, indivisible particles that make up all matter. He called them atoms – meaning 'not able to be cut'. As smart as Democritus was – he was, after all, correct – he was only speculating. He had no evidence to support his ideas, and at the time, many other people disagreed with him. These days, however, we can not only delve into the world of matter to see what is there, but we have evidence to support our conclusions about this bizarre world. Some of the evidence is as beautiful as the revelations in this book, while some of it – such as nuclear bombs – is terrifying. The point is that we are now closer than ever before to understanding the true nature of matter – at least the matter we can see, and perhaps even matter that we cannot see.

MACROSCOPIC: CELLS

Consider a convenient example of matter: the pages of this book. Look closer, past the words, the letters and the full stop at the end of this sentence. Look at the fibres that make up the pages – fibres that were once living tissue in trees. That tissue is made of cells, and those cells are made of countless indescribably complex parts – membranes, cytoplasm, mitochondria, and so on – that once carried out the life processes now ended. Those parts are made up of some of the largest and most complex molecules in the Universe – a familiar example being the molecule of life, DNA, that carries the genetic code enabling us and all living things to reproduce.

MOLECULES

Molecules come in an astonishing variety of forms, and most of the material things that impact on our lives are composed of different types of molecule. For example, water, without which life would cease. It is a molecule consisting of two types of even smaller particles called atoms. Atoms come in different flavours, called elements, of which about a hundred are known. The two elements in water, for example, are oxygen and hydrogen. Elements combine to form all the molecules around us, and react together to form new substances in chemical reactions. Common examples are encountered when cooking, for instance, or when petrol combines with oxygen in your car. In both cases, there is an exchange of energy, but not of matter. In the case of cooking, energy is input so that the various molecules react and make the cake rise.

Inside a car's engine, on the other hand, an initially small input of energy (the spark from the spark-plug) triggers a reaction between the petrol and oxygen to release energy, which drives the car. In both instances, new combinations of elements and compounds are produced, but matter is neither created nor destroyed.

ELEMENTS

The entire Universe consists almost exclusively of two elements: hydrogen and helium. All the things that you and I find so interesting on a daily basis (with the exception of dark matter, of course) are made up of elements that are in the extreme minority. But all these elements – from the lightest and simplest (hydrogen) through to elements with heavy masses and heavier names such as ununnilium – are all made of atoms. But these are not the atoms conceptualised by Democritus.

ATOMS

Atoms are in turn made of four things: protons and neutrons making up a nucleus, electrons surrounding the nucleus, and a large amount of space. But how much space? Imagine that the nucleus of the atom is the size of a walnut. At this scale the electrons would be whizzing around in a sphere more than a kilometre across. Despite this immense space, 99% of the matter in an atom is in the tiny nucleus. So what is holding it all together? The answer is energy: the electrical charge of the electrons is negative, and that of the nucleus (for reasons we shall see in a moment) are positive. The negative and positive charges attract and hold the electrons in place. But when it comes to atoms encountering other atoms, they repel each other for the simple reason that they have electrons on the outside – and two negative electrons repel each other. This property allows you to hold this book. The negatively charged electrons in the atoms and molecules of your hand are repelling the electrons in the atoms and molecules of the book. If this mutual repulsion did not take place, not only would the book literally slip through your fingers, but you would slip through the chair and then into the Earth. This is not as silly as it sounds, for there are particles of matter in the Universe that do just that. We will now continue our downward plunge into the essence of matter.

STRUCTURE OF THE ATOM: ELECTRONS, PROTONS AND NEUTRONS

In the very nucleus we find two more types of particle: protons and neutrons – the heavy components with all the mass. Protons have a positive charge – the same charge that attracts the electrons and stops the atom falling apart. Neutrons have no charge at all, but nonetheless are held in place inside the nucleus by another force different from the electrical force: the strong nuclear force.

QUARKS

Even more fundamental than protons and neutrons are the particles of which they are made: quarks. There are different types of quark – up, down, strange, charmed, top and bottom – that combine in different ways to make up matter. Protons, for instance, are made of two up quarks and a down quark, while the neutron is made up of two down quarks and an up quark. The names of the quarks have absolutely nothing to do with their properties, and are merely labels.

LEPTONS

What about the electrons? What are they made of? Electrons are part of a family of much lighter particles called leptons. Other members of the lepton family include the muon and tau particles, and each of these three has an associated particle called a neutrino: electron neutrino, tau neutrino, and muon neutrino. Neutrinos are strange beasts which can pass through ordinary matter as if it did not exist. This presents some interesting challenges for physicists intent on not only detecting them but trying to measure their mass. Leptons do not appear to be made of anything other than leptons; that is, they show no signs of having any internal structure.

There are, moreover, many other particles, and there are more than two hundred either known or predicted.

ENERGY

Ask a physicist what energy is, and the answer will be that it allows work to be done. It is an elusive concept, and although we can describe its properties, classify it in different ways, and predict not only its behaviour now but its relationship with matter at the beginning of the Universe, the nature of energy remains a mystery.

Energy is the capacity to do work – to change things. The following are some of the more commonly encountered types, although there are many variations:

- *Kinetic energy* Movement. Ride a bike, dance a waltz, fly to the Moon, and you are experiencing kinetic energy.
- *Potential energy* Stored energy, which manifests itself in a variety of forms such as chemical and gravitational energy. Food, petrol and water at the top of a cliff, about to fall, all have potential energy. One of the wonderful things we have learned to do over the millennia is to store energy in

everything from food silos that feed us to mini nuclear reactors that power spacecraft on their interplanetary voyages.

- *Thermal energy* Heat – the amount of energy contained within the excitedly moving particles that constitute matter. The faster the particles are moving, the more thermal energy they possess, and in sufficient numbers they can produce a tremendous amounts of energy. Although thermal energy is referred to as heat, an object with a large amount of thermal energy is not necessarily hot, while a hot object does not necessarily contain a lot of thermal energy. A swimming pool of warm water, for example, contains vastly more thermal energy than a red-hot nail, simply because there is a lot more water than nail!
- *Electrical energy* One of the most familiar forms of energy – for the very good reason that we use a large amount of it! It is a flow of electrons, which are amazingly simple to transport once the infrastructure is in place. Once electrical energy is delivered to our homes we can convert it into many other forms of energy.
- *Radiant energy* The most familiar example is light, but there are other forms: gamma rays, infrared (used for heating and in domestic remote-control devices), microwaves (for communications and cooking), X-rays (medicine), radio waves, and ultraviolet. All of these are part of the electromagnetic spectrum.

Each of these forms of energy (and those not mentioned here) fall into one of four fundamental forces in nature, which are carried from one place to another due to massless particles called bosons. These forces and their carriers are:

- Electromagnetic force, carried by the photon.
- Gravity, carried by the graviton.
- Strong nuclear force, carried by gluons.
- Weak nuclear force, carried by the W^+, W^- and Z^0 particles.

The importance of the relationship between matter and energy is that it is interchangeable: Matter is converted to energy inside stars, for example, and it is this conversion that allows us to continue living. But for the purposes of our story, it is important to understand that the Universe contains a certain amount of matter and a certain amount of energy, and, as we have discovered, a certain amount of dark matter. And that is it. No more, no less. In the history of the Universe there have been some bizarre conversions between matter and energy, and no doubt dark matter, but the total remains the same. One of the goals of cosmology is to determine how much of each – matter, energy and dark matter – exists in the Universe, simply because this will help reveal fundamental properties of the origin, evolution and fate of the Universe in which we live.

Appendix 2

Expressing mass

The mass of subatomic particles is expressed in electron volts (eV). The following are standard prefixes:

Multiple	*Prefix*	*Symbol*
10^3	kilo	keV
10^6	mega	MeV
10^9	giga	GeV
10^{12}	tera	TeV

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