

AN1**FUNDAMENTALS****OBJECTIVES****Aims**

This chapter is an introduction to some of the important concepts used in later chapters. The two major themes are the relativistic view of mass and energy and the quantum mechanical ideas of wave-particle duality.

You should aim to understand the idea of the equivalence of mass and energy and the need to introduce a new formula for kinetic energy. The idea of momentum, although not explicitly examinable by itself, will help you to understand some of the ideas about particle interactions in later chapters.

You should also aim to appreciate how wave and particle pictures are both used to describe different aspects of the behaviour for both electromagnetic radiation (including light) and material particles. You should gain some familiarity with schemes for naming and classifying particles and interactions between particles. However the details of fundamental particle theory (§1-8) are not examinable.

Minimum learning goals

When you have finished studying this chapter you should be able to do all the following.

1. Explain, use and interpret the terms
atom, nucleus, electron, proton, neutron, nucleon, neutrino, nuclide, atomic number, mass number, free particle, rest mass, rest energy, total energy (for a free particle), momentum, atomic mass unit, electronvolt, Planck's constant, de Broglie waves, photon, photoelectric effect.
2. (a) State, apply and discuss Einstein's relation between mass and energy and the variation of mass with speed (equations 1.1, 1.2, 1.3).
(b) State and apply the relation between kinetic energy and rest energy (equation 1.4).
3. Recall and apply formulas for
 - (a) the speed of light in terms of frequency and wavelength (equation 1.7);
 - (b) the energy of a photon in terms of wave frequency (equation 1.6);
 - (c) the momentum of a photon in terms of energy, wave frequency or wavelength (equations 1.8, 1.9).
4. (a) Describe examples of particle behaviour and wave behaviour.
(b) Describe experiments which show that particles have both particle and wave properties.
(c) State and apply the de Broglie formula for wavelength (equation 1.9).

TEXT

1-1 THE COMPOSITION OF MATTER

Atoms

According to the current view, solids, liquids and gases, the varieties of matter we meet every day, consist of **atoms** or groups of atoms called **molecules**. The atom is the basic unit of a chemical element. Each atom consists of a small, extremely dense, positively charged central **nucleus** surrounded by a cloud of negatively charged **electrons**. The charge of the nucleus is carried by **protons**, each of which has a positive charge (e) with the same magnitude as the electron's charge.

All atoms of the same chemical **element** have the same number of protons in the nucleus and, in its normal non-ionised state, each atom has the same number of electrons, making it electrically neutral. The number of protons is called the **atomic number** (symbol Z), so each chemical element has a unique atomic number. The structure and chemical behaviour of atoms can be described in terms of the arrangements of electrons within the atom and their interactions with each other and the nucleus.

The sizes of atoms vary in a complex way with atomic number; the diameters of most atoms lie in the range 0.1 nm to 0.5 nm.

The nucleus

The nucleus is very small compared with the size of an atom. Practically all of the nucleus of the an atom is confined within a roughly spherical region roughly 10^{-5} times smaller than the whole atom, that is about 5 fm (5×10^{-15} m) in diameter. Thus, nuclear matter is incredibly dense, about 2×10^{17} kg.m⁻³ or about 10^{14} times the density of water.

According the current model, the nucleus of every atom consists of **protons** and **neutrons**, which together are known as **nucleons**. A species of nucleus with a given mixture of protons and neutrons is called a **nuclide**.

Although all the atoms of a chemical **element** have the same number of protons in the nucleus, different atoms of the same chemical element may have different numbers of neutrons. In other words an element can consist of several nuclides with the same atomic number (Z) but different neutron numbers (N). The total number of nucleons in a nucleus is equal to the **mass number** ($A = Z + N$) of the atomic species or nuclide. Nuclides of the same element, with the same atomic number but different mass numbers, are called **isotopes** of the same element.

1-2 MASS AND ENERGY

Probably the best known equation in all of science is Einstein's relation between energy and mass:

$$E = mc^2 . \quad \dots(1.1)$$

Here c is the speed of light in vacuum. The equation is a prediction from the special theory of relativity, which is a theory about space, time, light and matter that was worked out at the beginning of the twentieth century by Albert Einstein. You don't have to understand that theory in order to appreciate the mass-energy relation. The interpretation is that mass and energy are essentially the same thing. Although we conventionally think of mass and energy as separate physical quantities, relativity theory says that any thing which has mass also has an equivalent amount of energy. A definite amount of energy is always associated with a definite mass. By analogy with currency conversions, the equation specifies the 'exchange rate' between energy and mass (but, unlike money exchange, the conversion factor, c^2 , is a constant fixed by nature).

An important aspect of the equivalence of mass and energy is that whenever an object acquires kinetic energy it also acquires mass! In other words: mass depends on speed. Clearly this conclusion contradicts the assumption of newtonian physics that the mass of a fixed amount of matter is constant, so we need to be explain why nobody ever noticed the difference before. The

answer is that the difference becomes noticeable only at very high speeds - close to the speed of light. At low speeds the variation of mass with speed is very small.

The equivalence between mass and energy applies even when an object is at rest: although it then has no kinetic energy, it still has energy associated with its mass. The value of a body's mass when it is stationary is called its **rest mass** (m_0) which is associated with a **rest energy** (E_0):

$$E_0 = m_0 c^2.$$

The relation between mass (m) and speed (v) is

$$m = \gamma m_0 \quad \dots (1.2)$$

where

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \quad \dots (1.3)$$

The factor γ is often called the **relativistic factor**.

An important consequence of the mass-energy relation is that the familiar formula for kinetic energy, $\frac{1}{2} m_0 v^2$, is no longer valid at high speeds. It is easy to work out the correct form, using the results above. To do that consider a **free particle** moving at a high speed. A free particle is defined as one that has no forces acting on it - a reasonable approximation in much of atomic and nuclear physics. The total energy, E , of the particle is, by Einstein's relation, equal to mc^2 . This must be equal to the sum of the rest energy $m_0 c^2$ and the kinetic energy, K . So

$$\begin{aligned} K &= mc^2 - m_0 c^2 \\ &= (\gamma - 1) m_0 c^2. \end{aligned}$$

i.e.

$$K = (\gamma - 1) E_0 \quad \dots (1.4)$$

This formula gives answers quite different from the old, 'non-relativistic', formula when the particle's speed is a substantial fraction of the speed of light, but at low speeds, the answers are essentially the same - as they must be unless we believe that the old physics was a huge mistake. (To see how the old and new formulas relate mathematically read Appendix 1.)

To appreciate why you may not have noticed the equivalence of mass and energy before it may help to do a few simple calculations.

Example

Calculate the relativistic factors for electrons moving at $0.500c$, $0.100c$ and $0.001c$.

$$\text{For } v = 0.500 c, \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - 0.500^2}} = 1.155.$$

$$\text{For } v = 0.100 c, \quad \gamma = 1.0050.$$

$$\text{For } v = 0.0100 c, \quad \gamma = 1.000\ 050.$$

You can see that for low speeds, $v \ll c$, the relativistic factor is very close to being exactly 1 but it becomes large as v approaches c . For a car moving at 20 m.s^{-1} , for example, the factor is equal to 1 to better than 1 part in 10^{14} . This means that for low speeds the relativistic change in mass that occurs when an object moves is essentially undetectable. People often ask how one can know when to use relativistic or non-relativistic formulas. The answer is that if you are not sure then relativistic formulas (such as 1.4) are always correct and the only disadvantage in using them is that they are a little more complex to use than approximations such as $\frac{1}{2} m_0 v^2$.

The formulas for mass and kinetic energy give a very significant prediction. If you put $v = c$ into the expression for γ , you will see that it takes an infinite value, so that both mass and energy would also be infinite. The interpretation of that ridiculous result is that you can't have any material thing going that fast - there is a universal speed limit for material objects (and signals also) of $3.00 \times 10^8 \text{ m.s}^{-1}$.

Conservation of mass and energy

Since mass and energy are equivalent, the separate principles of conservation of energy and conservation of mass become one principle, which is sometimes referred to as conservation of mass-energy. In applying the principle it does not matter whether you calculate mass or energy, provided that you count it all. There is no need to do separate calculations for mass and energy.

1-3 MOMENTUM

Kinetic energy is an important property of a moving object but you can't describe direction of motion or change in direction using energy. To include direction of a body's motion we define a new quantity - its **momentum**. The magnitude (p) of a particle's momentum is just the product of its mass (m) and its speed (v). The direction of the momentum is the same as the direction of motion, i.e. the direction of the velocity. This definition works for both relativistic and non-relativistic speeds, provided that the mass is defined as it was above.

For all particles:
$$p = mv = \gamma m_0 v \quad \dots (1.5)$$

and for slow particles with $v \ll c$
$$p \approx m_0 v.$$

One important use of the idea of momentum is in the study of interactions between particles. In a system of particles where the total external force is zero or negligible, the total momentum of the system remains constant. Because momentum is a vector quantity, calculations of momentum use components of momentum or velocity. (Such calculations are not required in this course but the principle will be helpful in understanding some kinds of particle interactions.)

1-4 UNITS

Although the SI units of mass and energy are the kilogram and the joule, a lot of atomic and nuclear physics uses the non-SI units, unified **atomic mass unit** (symbol u) and the **electronvolt** (eV). The conversions are as follows:

$$u = 1.660\,566 \times 10^{-27} \text{ kg}.$$

$$\text{eV} = 1.602\,189 \times 10^{-19} \text{ J}.$$

These units have sizes appropriate for atomic and nuclear physics and chemistry. The atomic mass unit has been defined so that the mass of one atom of carbon-12 is exactly equal to 12 u, so the masses of atoms range from 1 u to about 250 u. The electronvolt is defined as the change in potential energy of an electron when it moves through a potential difference of exactly one volt. Energy levels of atoms are conveniently expressed in electronvolts, while energies associated with nuclear processes are typically several megaelectronvolts.

The energy corresponding to one atomic mass unit, given by Einstein's mass-energy relation, is

$$(1.000\,000 \text{ u})c^2 = 931.5016 \text{ MeV}.$$

Thus the rest energy of an electron is about $\frac{1}{2}$ MeV, and the rest energies of a proton, a neutron and a hydrogen atom are all about 1 GeV. Some more exact values are given in table 1.1.

Particle	Rest mass/u	Rest energy/MeV
electron, positron	0.000 549	0.511
proton	1.007 276	938.280
neutron	1.008 665	939.573
hydrogen atom	1.007 825	938.790

Table 1.1. Rest masses and energies

1-5 WAVES AND PARTICLES

By the beginning of the twentieth century the physicist's conception of nature was based on two abstractions from reality - the wave and the particle. The recently discovered electron had been shown to be charged and to have a definite mass - its deflection in electric and magnetic fields was just what would have been expected for a charged particle (although the charge and mass were extremely small by usual standards, 1.6×10^{-19} C and 9.11×10^{-31} kg).

The electron was believed to be a constituent of atoms. However, application of newtonian mechanics and the laws of electricity and magnetism could not explain the observed line spectra emitted by atoms. In fact, if these laws were applied to the atom, such atoms should be unstable and last for less than a nanosecond. Other phenomena such as the radiation from heated bodies and the recently discovered radioactivity had features which were inexplicable using concepts that were current at the time.

In the new view, developed since 1900, the concepts of wave and particle as separate entities must be abandoned. In reality nothing behaves exactly like a 'classical' wave or a classical particle. In some cases, such as electron in a TV tube, the behaviour of an electron matches the idea of a classical particle. In others, the wave description is more appropriate; electrons exhibit diffraction patterns when they bounce off crystals, for example. A similar situation holds for light; interference and diffraction are explained using the wave idea. On the other hand, the photoelectric effect is explained by saying that light consists of particles. But the two kinds of explanation don't mix. For example, in a diffraction experiment with electrons, any attempt to investigate the positions of individual electrons (i.e. applying particle concepts) destroys the diffraction pattern (the wave aspect). In the intermediate region where neither a particle nor a wave description alone is really appropriate, we use the very mathematical theory of **quantum mechanics**, which reduces to the simpler ideas of waves and particles in appropriate limiting cases. While nobody doubts that quantum mechanics works, its interpretation is still a matter of great argument. Since our conceptions of particles and waves are derived from watching things like falling apples and ripples on ponds, one should not be too surprised to find that those concepts do not help much in picturing what is happening on the sub-atomic scale. On the other hand quantum mechanics can describe and make predictions about a great deal more of the phenomena occurring in the universe than we can using the large scale theories of mechanics (described in the Forces and Energy unit) or the classical theory of electromagnetism (described in the Electricity unit).

1-6 PHOTONS

Many aspects of the behaviour of light and other varieties of electromagnetic radiation can be explained using a wave model. This model is most successful in explaining how light propagates through space, and how interference and diffraction effects occur. It is not so successful in explaining all aspects of the interaction of electromagnetic radiation with matter - we need a particle theory of light as well as a wave theory.

To explain some experiments, which will be described shortly, Einstein conceived electromagnetic radiation as travelling, localised packets of energy, which we now call **photons**. If the frequency of the radiation viewed as a wave is f , then there is only one possible magnitude for the energy content of a photon:

$$E = hf \quad \dots (1.6)$$

Here h is a universal constant of nature, called **Planck's constant**:

$$h = 6.63 \times 10^{-34} \text{ J.s} = 4.14 \times 10^{-15} \text{ eV.s.}$$

In atomic and nuclear work we do not measure the frequencies of electromagnetic waves directly. Instead we know their wavelengths, λ , (in air or vacuum) which are related by the equation:

$$c = f\lambda \quad \dots (1.7)$$

So, in terms of wavelength the energy of a photon is

$$E = \frac{hc}{\lambda} .$$

The combined constant hc which occurs here is used so often that it is worth noting its value in units which are commonly used for atomic-scale energies (eV) and wavelengths of light (nm):

$$hc = 1.24 \times 10^3 \text{ eV.nm} = 1.24 \text{ keV.nm}.$$

In the quantum model emission or absorption of electromagnetic radiation can take place only by emission or absorption of photons. So energy transfers are discontinuous - in contrast to the classical picture of electromagnetic radiation in which a wave transfers energy continuously to a charged object.

It has long been known that electromagnetic waves carry momentum as well as energy. So you might expect that a photon should also have momentum. Its magnitude is given by the relation:

$$p = \frac{hf}{c} . \quad \dots (1.8)$$

Another way looking at this is to relate the wavelength (in vacuum) and momentum. Using the relation $c = f\lambda$ we get

$$\lambda = \frac{h}{p} . \quad \dots (1.9)$$

It is important to remember that whenever a photon interacts with matter, it is destroyed. In most cases the photon transfers all its energy to the matter. Sometimes a new photon with lower energy may be created.

The photoelectric effect

In the late nineteenth century it was found that when light was shone on to the surface of some metals they emitted electrons. However, to get electrons out of a particular metal the light had to have elementary wave components with frequency greater than some critical value. You could have as powerful a beam of light as you liked below that critical frequency and no electrons would come out. Contrariwise, as weak a beam of light as you liked above that frequency would produce electrons. All this is totally inconsistent with the idea that the effect is due to electrons slowly but continuously absorbing energy from the incoming electromagnetic wave. In 1905 Albert Einstein suggested that energy propagation in an electromagnetic wave should be regarded as taking place in localised packets which we now call photons. He then gave the following explanation for the photoelectric effect. A solid metal consists of a crystal lattice of metal ions interpenetrated by a gas of electrons. The electrons are held inside the crystal at the boundaries by the electrostatic attraction of the positive ions. To get one electron out of the crystal requires a certain minimum energy, ϕ , called the work function of the material. Typical values of the work function range from 1 eV to 6 eV. If we now assume that electrons can absorb light only in packets of energy (of size hf) we see that unless $hf > \phi$ the electrons can not get out of the crystal, no matter how intense the original beam (i.e. however rapidly photons arrive). If the photon energy is greater than ϕ , the excess energy could appear as kinetic energy of the emitted electron.

1-7 DE BROGLIE WAVES

Just as we need a wave model and a particle model to make sense of light, it turns out that the properties of material 'particles', such as electrons, cannot be fully described by a classical particle model. There are cases when a wave model seems to be better. For example when electrons are fired through a thin crystal they produce a diffraction pattern of just the kind that classical waves give. Moreover, the spacing in this pattern enables us to find the associated wavelength.

The wavelength, λ , associated with an object whose momentum has magnitude p is given by the equation

$$\lambda = \frac{h}{p} \quad \dots (1.9)$$

where h is Planck's constant. This equation was suggested in 1924 by Louis de Broglie who reasoned from special relativity theory. He suggested that, since light exhibits particle properties, it may be that matter could exhibit wave properties. The relation above, between wavelength of de Broglie waves and momentum of a material particle, is the same as that connecting the wavelength of an electromagnetic wave and the momentum of its photon.

For non-relativistic speeds you can write the de Broglie equation in terms of the particle's rest mass m_0 and its speed v :

$$\lambda = \frac{h}{m_0 v}$$

but for photons there is no way of expressing momentum in terms of rest mass.

The simple idea of de Broglie waves was soon developed into the modern theory of quantum mechanics, first by Erwin Schrödinger who introduced the idea of a wave-function which could be used to describe atomic-scale systems and then by Max Born, who developed an interpretation of the wave function in terms of probabilities of observing a system in various states.

Electron diffraction

The wave nature of electrons was shown experimentally in 1927 by Davisson and Germer in America and G.P. Thomson in England. They reflected beams of electrons off crystalline solids and observed characteristic interference patterns associated with the diffraction of waves; as well as the main peak in reflected intensity when the angle of reflection equals the angle of incidence, they observed maxima at other angles. Since then, many people have done experiments on diffraction of electron beams by single and multiple slits. These effects cannot be explained by thinking of electrons as particles.

Wave-particle duality

You may wonder how a decent scientific theory can regard something as being sometimes a wave and sometimes as a particle. Why is it not always one or the other? The resolution of the paradox lies in a theory of measurement which needs more detail than we can give here, but briefly one answer is that if you stick to what can be measured, there is never a conflict between the two models. Here is one example.

Think about Young's twin-slit interference experiment. The existence of the interference-diffraction pattern can be described using wave theory; each wave goes through both slits and when the separate parts come together again, interference effects occur. What happens if the light is so weak that only one photon at a time arrives at the observing screen? This experiment has been done and the answer is that photons are seen to arrive at many different points. When the dim light is first turned on, there is no interference pattern. Photons are detected at various well-defined places on the screen and a pattern gradually builds up. As more photons arrive it is found that their distribution is not uniform. There are many photons at the positions where wave theory predicts a maximum intensity and no photons at places where wave theory says that there should be no light! Wave theory correctly predicts the statistical distribution of many photons but it cannot predict where any individual photon will show itself. Furthermore, it makes no sense to ask which of the two slits any individual photon went through! If you actually try to do an experiment to answer that question, you will destroy the interference pattern. The only way to find out if a photon goes through a particular hole is to put a detector at the hole. However to detect a photon is to destroy it - if you find a photon at one of the slits it will never reach the screen. The conclusion is that we can use wave and particle models for different purposes, but any question that leads to a contradiction between the models is

essentially unanswerable. Modern quantum theory avoids conflicts between the wave and particle models by using abstract mathematics instead of concrete pictures of 'waves' and 'particles'.

1-8 THE UNCERTAINTY PRINCIPLE

Closely related to the problem of wave-particle duality is the famous uncertainty principle formulated by Werner Heisenberg. The principle says that it is not possible to know precise values of all the dynamical variables, such as position, time, energy and momentum, of a system or a particle. For example it is not possible to know both the exact momentum and the exact position for a particle. If we write the uncertainty in the particle's x -coordinate of position as Δx and the uncertainty in the x -component of its momentum as Δp_x , then the product of those uncertainties has a certain irreducible minimum value:

$$\Delta x \cdot \Delta p_x \geq \frac{h}{2\pi}$$

where h is Planck's constant. There is also a restriction on knowing exact values of energy and time for any system:

$$\Delta E \cdot \Delta t \geq \frac{h}{2\pi} .$$

These statements do not refer to the fact that it is difficult to measure anything with perfect accuracy; they actually say that it is not even possible to *know* the values exactly. Note the complementary nature of the uncertainties. For example if you know a particle's energy with great precision, ΔE is small, so that Δt must be large. That means that you don't really know much about the time at which the particle had its accurate value of energy. On the other hand if you ask what is going on during an extremely short time interval Δt , you haven't got much of a clue about the value of the energy. Similarly, if you know a particle's velocity (and hence its momentum) very closely, you don't know much about where it is!

If you look at some examples using the value of Planck's constant, you will see that the uncertainty principle does not upset everyday human-scale calculations, but it is important on the scale of atoms and nuclei. For example, the time required to be sure that you have an energy accurate to 1 μJ (which is pretty accurate on a human scale) is only about 10^{-31} s, an incredibly short time. On the other hand, if we say that the energy of an atom is known to the nearest 0.01 eV, we could not be sure about what is happening to the atom over a time scale of about a tenth of a picosecond (10^{-13} s) - not such a short time for an atom.

1-9 PARTICLES AND THEIR INTERACTIONS

A simple view is that matter consists of three kinds of material particle, electrons, protons and neutrons. Detailed studies of the interactions among these particles, especially at high energies, has revealed the existence of many other particles, while theoretical studies indicate that there may be still more to be discovered. Other particles which will be mentioned in this course include positrons, neutrinos, and quarks. Some particles, such as electrons and protons, can exist on their own - as free particles - whereas others, such as quarks, can exist only in combination with other particles. Some properties of the free particles considered in this course are summarised in table 1.2.

Particle	Symbol	Rest mass	Rest energy	Charge	Examples of occurrence or production
proton	p	1.0 u	0.9 GeV	+e	<ul style="list-style-type: none"> Bound in nuclei. A free proton is a hydrogen nucleus or a hydrogen ion.
neutron	n	1.0 u	0.9 GeV	0	<ul style="list-style-type: none"> Bound in nuclei. Released by nuclear fusion and fission. Free neutrons are unstable.
electron	e ⁻	0.0005 u	0.5 MeV	-e	<ul style="list-style-type: none"> Bound in atoms. Released when an atom is ionised Created in beta-minus decay of a nucleus.
positron	e ⁺	0.0005 u	0.5 MeV	+e	<ul style="list-style-type: none"> Created in beta-plus decay of a nucleus.
photon	γ	0	0	0	<ul style="list-style-type: none"> Low energy photons are produced in atomic processes. X rays (intermediate energy) High energy photons are produced in nuclear processes.
electron neutrino	ν_e	0 (?)	0 (?) (< 60 eV)	0	<ul style="list-style-type: none"> Created in beta-plus decay of a nucleus.
electron antineutrino	$\bar{\nu}_e$	0 (?)	0 (?) (< 60 eV)	0	<ul style="list-style-type: none"> Created in beta-minus decay of a nucleus.

Table 1.2 Properties of some free particles

Here, e is the elementary charge, 1.6×10^{-19} C.

Some of the particles in table 1.2 are known as **antiparticles** of other particles: the positron is the antiparticle of the electron, and the antineutrino is the antiparticle of the neutrino. The electron and the positron have exactly the same rest mass and exactly opposite charges. When an electron and a positron interact, they disappear completely leaving only two or three photons which carry away all the original energy (rest energy plus kinetic energy) of the particle-antiparticle pair.

Note that photons have zero rest mass; since photons are particles of light or other electromagnetic radiation which travels at the speed of light, they can never be at rest - all their energy must be kinetic energy. They also have momentum. Photons interact with charged particles but not with other photons.

According to what is called the 'standard model' of particle physics, all matter is composed of fundamental families of particles called **quarks** and **leptons**. The model indicates that there may be four families of quarks and four associated families of leptons, but only three complete families have been observed so far. The composition of the ordinary matter in our environment (the Earth) can be understood in terms of one family of leptons, comprising the electron and its associated electron

neutrino together with their antiparticles, and one family of quarks, the up quark and the down quark together with their antiparticles.

As far as we know, **neutrinos** and **antineutrinos** have zero rest mass, or if their rest mass is not zero it is extremely small. They do, however, carry energy and momentum. Once they have been created, neutrinos interact only very weakly, i.e. rarely, with nuclear matter. They can, for example, pass right through the earth without interacting with anything! Consequently they are very difficult to detect. There are three known kinds of neutrino, one associated with the electron (the electron neutrino) and two others with unstable particles called the muon and tauon (mu and tau neutrinos). Each kind has its own antiparticle.

The two kinds of particles, protons and neutrons, which comprise the nuclei of atoms are known collectively as nucleons. As far as we know, electrons and neutrinos are truly fundamental particles; they have no internal structure. Nucleons, on the other hand, are considered to be made up of quarks. The quarks that exist within nucleons are classified into two families which are called, for no very good reason, "up" and "down". Up quarks have an electric charge of $+2e/3$ and down quarks carry charge of $-e/3$. A proton contains two up quarks and a down quark, giving it a total charge of $+e$, while the neutron has one up and two down quarks, a charge of zero. Although the quarks exist within nucleons, it appears that nucleons cannot be taken apart to form free quarks.

Fundamental interactions and exchange particles

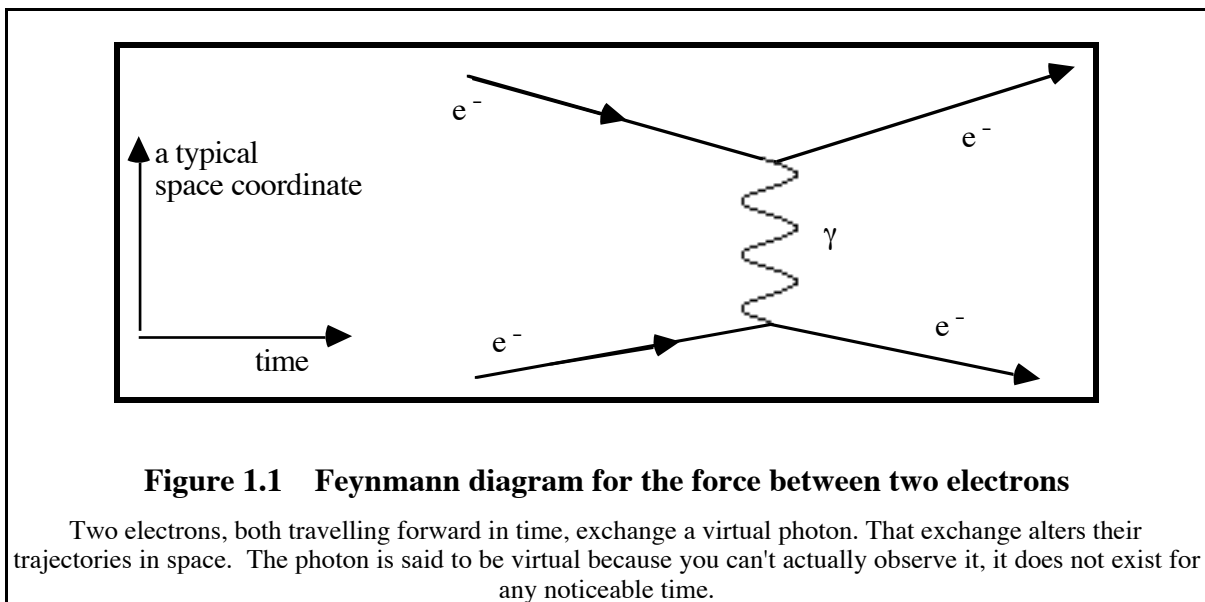
Table 1.3 lists the four fundamental types of interaction or 'force' that we introduced in chapter FE2.

Interaction	Acts on:	Carrier or exchange particle
Gravitational	Everything	Graviton
Electromagnetic	Electrically charged particles	Photon
Weak force	Leptons: particles such as electrons and neutrinos	Vector boson
Strong force	Quarks	Gluon
Residual strong force	Hadrons: particles like neutrons and protons	Mesons

Table 1.3 Interactions and their carrier particles

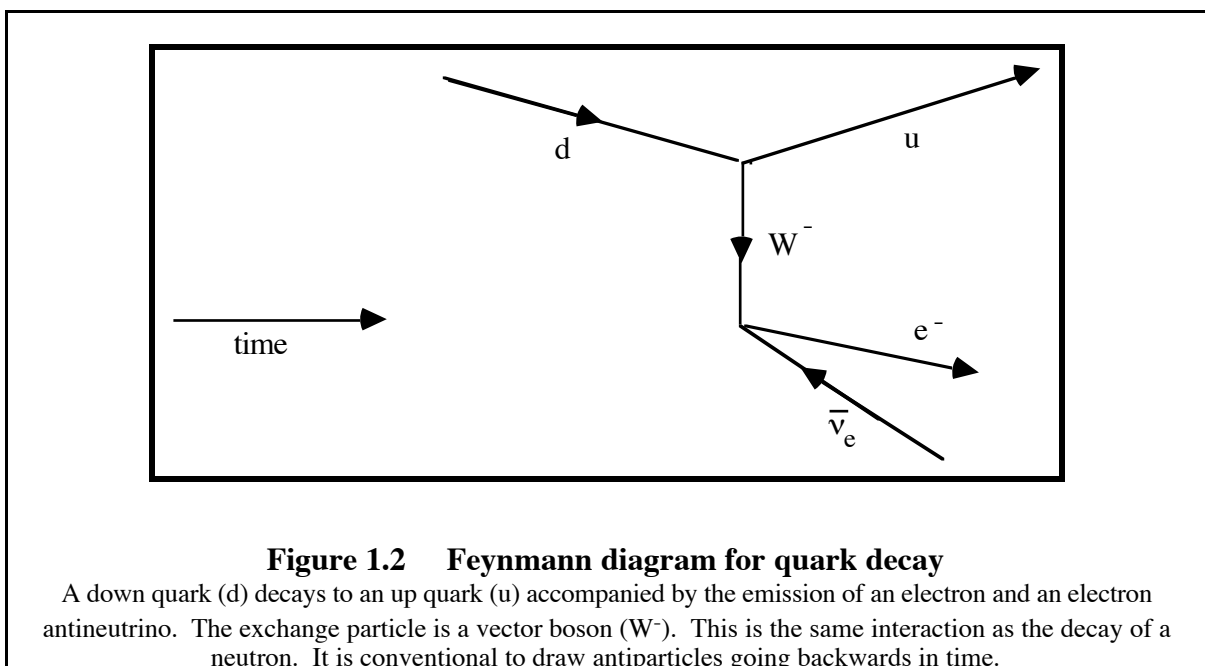
The classical or newtonian model of force explains interactions in terms of action at a distance. That idea does not work at the level of fundamental particles. Instead, the current model explains particle interactions using the concept of **exchange particles** rather than forces. The idea is that particles interact by sending out and receiving other particles. Th interactions are represented in a semi-pictorial way using sketches called Feynmann diagrams (figures 1.1 and 1.2). In these diagrams there is an inescapable resemblance to the tracks left by two dirty billiard balls, both moving, showing their paths before and after collision. The value of the diagrams extends much further than showing particle tracks; physicists use the diagrams to do calculations. This is similar in some ways to drawing a vector diagram showing the forces acting on an object and then writing down the equations giving the net force or some other quantity.

Figure 1.1 shows the electromagnetic interaction between two electrons. The same idea extends, in principle, to the other three types of force.



"Classically" we describe the electromagnetic force with the idea of electric and magnetic fields: the charge on a particle produces an electric field which acts on other charged particles nearby. In the exchange force picture one envisages a swarm of photons (the particles of light) in the space between the charged particles. The photons are *real* if radiation is emitted, or *virtual* if there is no radiation. (The virtual photons are trapped in the system of the two interacting electrons.) The emission or absorption of a photon (real or virtual) by one charged particle is accompanied by a force acting on that particle so it is this process that transmits the force from one charged particle to the other.

The electromagnetic force is carried by a single type of exchange particle - the photon. For the weak force, up to three types of particle can be involved. One of these is shown in figure 1.2.



QUESTIONS

Use the data table on the inside front cover.

- Q1.1** Estimate the de Broglie wavelength for a beam of electrons that have moved through a potential difference of 15 kV. Compare the answer with a typical wavelength for visible light and comment. Would you expect to notice the wave properties (interference and diffraction) of 15 keV electrons in a TV tube?
- Q1.2** Would the wave nature of particles need to be taken into account to provide a reasonable description of the following phenomena?
- A 10 kg cannon ball is shot at a gap of 1.0 m wide in a wall. The speed of the cannon ball is $100 \text{ m}\cdot\text{s}^{-1}$.
 - A beam of visible light passes through the prongs of a fork.
 - An electron of kinetic energy 10 keV passes through a slit of width 1.0 nm.
 - An electron of kinetic energy 10 eV passes through a slit of width 1.0 nm.
- Q1.3** Neutron diffraction studies of crystal structure are now carried out routinely, just like x-ray diffraction. What wavelength do we associate with a neutron whose kinetic energy is 0.025 eV? Such a neutron is non-relativistic.
- Q1.4**
- Calculate the relativistic factor for an electron that has been accelerated through a potential difference of 100 kV.
 - Calculate the speed of this electron.
 - Calculate the mass of an electron when it is moving at this speed.
- Q1.5** What is the kinetic energy of a proton travelling at $2.90 \times 10^8 \text{ m}\cdot\text{s}^{-1}$? Express the answer in electronvolts. How does the kinetic energy compare with the rest energy?
- Q1.6** An electron in a television set is accelerated through 20 kV. What is the percentage increase in its mass?
- Q1.7** In a nuclear reaction, the sum of the rest masses of the products is $1.8 \times 10^{-34} \text{ kg}$ less than the sum of the rest masses of the initial ingredients. Assuming that all the excess energy is concentrated in a high speed electron (a β particle), calculate that electron's kinetic energy and speed.
- Q1.8 Pair production.** In the intense electric field near a nucleus, it is possible for a photon to turn into an electron and a positron (a particle of the same mass as the electron but with opposite charge). Assuming that the energy given to the nucleus in this process may be neglected, find the minimum value of the radiation frequency needed for pair production to occur.
- Q1.9** When a positron and an electron collide, they annihilate and the energy is often released as two photons with equal energies.
- Calculate the energy in joules and electronvolts when a positron and an electron annihilate.
 - Calculate the wavelength of the radiation.
- Q1.10** The wavelengths of light in the visible spectrum range from about 400 nm to about 650 nm.
- What colours do wavelengths of 400 nm and 600 nm correspond to?
 - Calculate the energies of 400 nm and 600 nm photons.
 - Does an ultraviolet photon have more or less energy than a visible light photon?
- Q1.11** Estimate the number of photons emitted in one second from the following sources, given that each is radiating power at 1.0 mW at the wavelength in question:
- a sodium lamp, $\lambda = 589 \text{ nm}$,
 - a helium-neon laser, $\lambda = 630 \text{ nm}$,
 - an x-ray tube emitting a line spectrum at 75 pm.

Discussion Questions

- Q1.12** Would you expect quantum mechanical effects to be more important at the high frequency end of the electromagnetic spectrum (radio waves) or the low frequency end (gamma rays and x rays). Why?
- Q1.13** Ordinary light does not affect our skin much, but ultraviolet light can be quite harmful. Could that have anything to do with photon energies?
- Q1.14** It is not correct to say that "matter cannot be created or destroyed". What can you say instead?
- Q1.15** An electron and a proton are travelling at the same speed. Which has the shorter wavelength?