1
Matter and Light

1.1 Introduction

The physical world we see around us has two main components, matter and light, and it is the modern explanation of these things which is the purpose of this book. During the course of the story, these concerns will be restated in terms of material particles and the forces which act between them, and we will most assuredly encounter new and exotic forms of both particles and forces. But in case we become distracted and confused by the elaborate and almost wholly alien contents of the microworld, let us remember that the origin of the story, and the motivation for all that follows, is the explanation of everyday matter and visible light.

Beginning as it does, with a laudable sense of history, at the turn of the last century, we have only to appreciate the level of understanding of matter and light around 1900, and some of the problems in this understanding, to prepare ourselves for the story of progress which follows.

1.2 The Nature of Matter

By 1900 most scientists were convinced that all matter is made up of a number of different sorts of atoms, as had been conjectured by the ancient Greeks millennia before and as had been indicated by chemistry experiments over the preceding two centuries. In the atomic picture, the different types of substance can be seen as arising from different arrangements of the atoms. In solids, the atoms are relatively immobile and in the case of crystals are arranged in set patterns of impressive precision. In liquids they roll loosely over one another and in gases they are widely separated and fly about at a velocity depending on the temperature of the gas; see Figure 1.1. The application of heat to a substance can cause phase transitions in which the atoms change their mode of behaviour as the heat energy is transferred into the kinetic energy of the atoms' motions.

Many familiar substances consist not of single atoms, but of definite combinations of certain atoms called molecules. In such cases it is these molecules which behave in the manner appropriate to the type of substance concerned. For instance, water consists of molecules, each made up of two hydrogen atoms and one oxygen atom. It is the molecules which are subject to a specific static arrangement in solid ice, the molecules which roll over each other in water and the molecules which fly about in steam.

The laws of chemistry, most of which were discovered empirically between 1700 and 1900, contain many deductions concerning the behaviour of atoms and molecules. At the risk of brutal over-simplification the most important of these can be summarised as follows:

(1) Atoms can combine to form molecules, as indicated by chemical elements combining only in certain proportions (Richter and Dalton).

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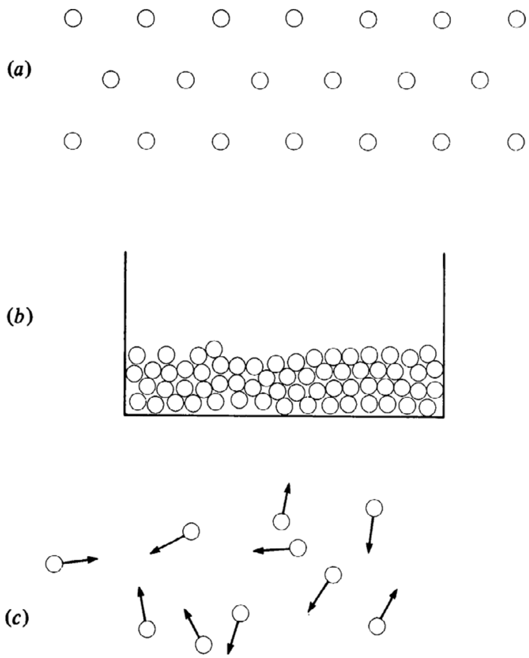

Figure 1.1. (*a*) Static atoms arranged in a crystal. (*b*) Atoms rolling around in a liquid. (*c*) Atoms flying about in a gas.

(2) At a given temperature and pressure, equal volumes of gas contain equal numbers of molecules (Avogadro).
(3) The relative weights of the atoms are approximately multiples of the weight of the hydrogen atom (Prout).
(4) The mass of each atom is associated with a specific quantity of electrical charge (Faraday and Webber).
(5) The elements can be arranged in families having common chemical properties but different atomic weights (Mendeleeff's periodic table).
(6) An atom is approximately 10^{-10} m across, as implied by the internal friction of a gas (Loschmidt).

One of the philosophical motivations behind the atomic theory (a motivation we shall see repeated later) was the desire to explain the diversity of matter by assuming the existence of just a few fundamental and indivisible atoms. But by 1900 over 90 varieties of atoms were known, an uncomfortably large number for a supposedly fundamental entity. Also, there was evidence for the disintegration (divisibility) of atoms. At this breakdown of the 'ancient' atomic theory, modern physics begins.

1.3 Atomic Radiations

1.3.1 *Electrons*

In the late 1890s, J. J. Thomson of the Cavendish Laboratory at Cambridge was conducting experiments to examine the behaviour of gas in a glass tube when an electric field was applied across it. He came to the conclusion that the tube contained a cloud of minute particles with negative electrical charge – the electrons. As the tube had been filled only with ordinary gas atoms, Thomson was forced to conclude that the electrons had originated within the supposedly indivisible atoms. As the atom as a whole is electrically neutral, on the release of a negatively charged electron the remaining part, the ion, must carry the equal and opposite positive charge. This was entirely in accord with the long-known results of Faraday's electrolysis experiments, which required a specific electrical charge to be associated with the atomic mass.

By 1897, Thomson had measured the ratio of the charge to the mass of the electron (denoted e/m) by observing its behaviour in magnetic fields. By comparing this number with that of the ion, he was able to conclude that the electron is thousands of times less massive than the atom (and some 1837 times lighter than the lightest atom, hydrogen). This led Thomson to propose his 'plum-pudding' picture of the atom, in which the small negatively charged electrons were thought to be dotted in the massive, positively charged body of the atom (see Figure 1.2).

1.3.2 *X-rays*

Two years earlier in 1895, the German Wilhelm Röntgen had discovered a new form of penetrating radiation, which he called X-rays. This radiation was emitted when a stream of fast electrons (which had not yet been identified as such) struck solid matter and were thus rapidly decelerated. This was achieved by boiling the electrons out of a metallic electrode in a vacuum tube and accelerating them into another electrode by applying an electric field across the two, as in Figure 1.3. Very soon the X-rays were identified as another form of electromagnetic radiation, i.e. radiation that is basically the same as visible light, but with a much higher frequency and shorter wavelength. An impressive demonstration of the wave nature of X-rays

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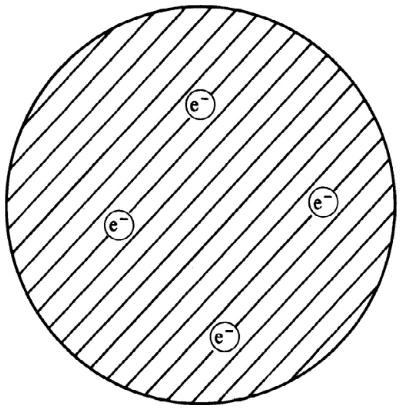

Figure 1.2. Thomson's 'plum-pudding' picture of the atom.

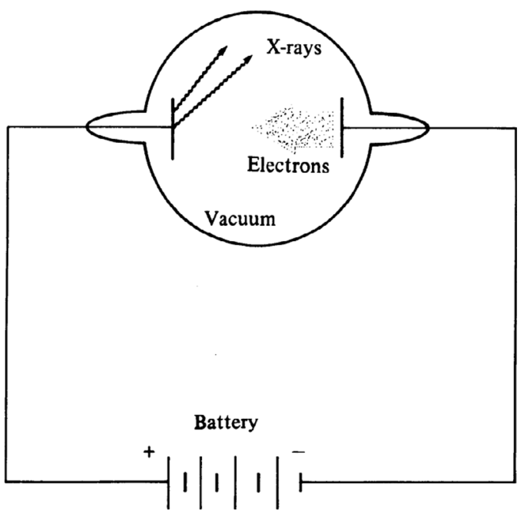

Figure 1.3. The production of X-rays by colliding fast electrons with matter.

was provided in 1912 when the German physicist Max von Laue shone them through a crystal structure. In doing so, he noticed the regular geometrical patterns characteristic of the diffraction which occurs when a wave passes through a regular structure whose characteristic size is comparable to the wavelength of the wave. In this case, the regular spacing of atoms within the crystal is about the same as the wavelength of the X-rays. Although these X-rays do not originate from within the structure of matter, we shall see next how they are the close relatives of radiations which do.

1.3.3 *Radioactivity*

At about the same time as the work taking place on electrons and X-rays, the French physicist Becquerel was conducting experiments on the heavy elements. During his study of uranium salts in 1896, Becquerel noticed the emission of radiation rather like that which Röntgen had discovered. But Becquerel was doing nothing to his uranium: the radiation was emerging spontaneously. Inspired by this discovery, Pierre and Marie Curie began investigating the new radiation. By 1898, the Curies had discovered that the element radium also emits copious amounts of radiation.

These early experimenters first discovered the radiation through its darkening effect on photographic plates. However, other methods for detecting radiation were soon developed, including scintillation techniques, electroscopes and a primitive version of the Geiger counter. Then a great breakthrough came in 1912 when C. T. R. Wilson of the Cavendish Laboratory invented the cloud chamber. This device encourages easily visible water droplets to form around the atoms, which have been ionised (i.e. have had an electron removed) by the passage of the radiation through air. This provides a plan view of the path of the radiation and so gives us a clear picture of what is happening.

If a radioactive source such as radium is brought close to the cloud chamber, the emitted radiation will trace paths in the chamber. When a magnetic field is placed across the chamber, then the radiation paths will separate into three components which are characteristic of the type of radiation (see Figure 1.4). The first component of radiation (denoted α) is bent slightly by the magnetic field, which indicates that the radiation carries electric charge. Measuring the radius of curvature of the path in a given magnetic field can tell us that it is made up of massive particles with two positive electric charges. These particles can be identified as the nuclei of helium atoms, often referred to as α particles. Furthermore, these α particles always seem to travel a fixed distance before being stopped by collisions with the air molecules. This suggests that they are liberated from the source with a constant amount of energy and that the same internal reactions within the source atoms are responsible for all α particles.

The second component of the radiation (denoted γ) is not at all affected by the magnetic field,

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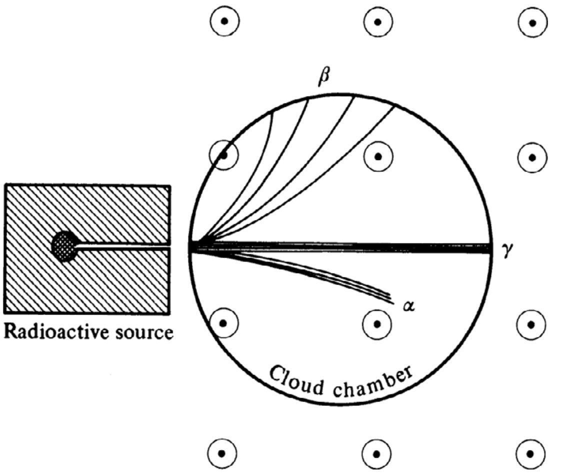

Figure 1.4. Three components of radioactivity displayed in a cloud chamber. ⊙ signifies that the direction of the applied magnetic field is perpendicular to, and out of the plane of, the paper.

showing that it carries no electric charge, and it is not stopped by collisions with the air molecules. These γ-rays were soon identified as the close relatives of Röntgen's X-rays but with even higher frequencies and even shorter wavelengths. The γ-rays can penetrate many centimetres of lead before being absorbed. They are the products of reactions occurring spontaneously within the source atoms, which liberate large amounts of electromagnetic energy but no material particles, indicating a different sort of reaction to that responsible for α-rays.

The third component (denoted β radiation) is bent significantly in the magnetic field in the opposite direction to the α-rays. This is interpreted as single, negative electrical charges with much lesser mass than the α-rays. They were soon identified as the same electrons as those discovered by J. J. Thomson, being emitted from the source atoms with a range of different energies. The reactions responsible form a third class distinct from the origins of α- or γ-rays.

The three varieties of radioactivity have a double importance in our story. Firstly, they result from the three main fundamental forces of nature effective within atoms. Thus the phenomenon of radioactivity may be seen as the cradle for all of what follows. Secondly, and more practically, it was the products of radioactivity which first allowed physicists to explore the interior of atoms and which later indicated

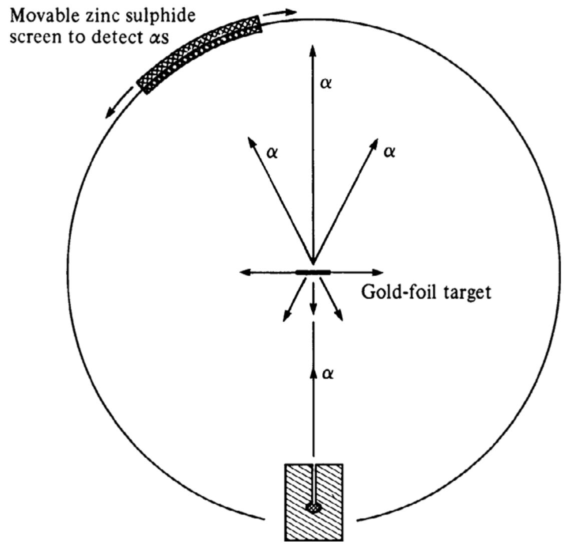

Figure 1.5. The Geiger and Marsden experiment. According to Rutherford's scattering formula, the number of α particles scattered through a given angle decreases as the angle increases away from the forward direction.

totally novel forms of matter, as we shall see in due course.

1.4 Rutherford's Atom

In the first decade of the twentieth century, Rutherford had pioneered the use of naturally occurring atomic radiations as probes of the internal structure of atoms. In 1909, at Manchester University, he suggested to his colleagues, Geiger and Marsden, that they allow the α particles emitted from a radioactive element to pass through a thin gold foil and observe the deflection of the outgoing α particles from their original paths (see Figure 1.5). On the basis of Thomson's 'plum-pudding' model of the atom, they should experience only slight deflections, as nowhere in the uniformly occupied body of the atom would the electric field be enormously high. But the experimenters were surprised to find that the heavy α particles were sometimes drastically deflected, occasionally bouncing right back towards the source. In a dramatic analogy attributed (somewhat dubiously) to Rutherford: 'It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you!'

The implication of this observation is that a very strong repulsive force must be at work within the atom. This force cannot be due to the electrons as they are

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over 7000 times lighter than the α particles and so can exert only minute effects on the α-particle trajectories. The only satisfactory explanation of the experiment is that all the positive electric charge in the atom is concentrated in a small nucleus at the middle, with the electrons orbiting the nucleus at some distance. By assuming that the entire positive charge of the atom is concentrated with the atomic mass in a small central nucleus, Rutherford was able to derive his famous scattering formula which describes the relative numbers of α particles scattered through given angles on colliding with an atom (see Figure 1.5).

Rutherford's picture of the orbital atom is in contrast with our perception of apparently 'solid' matter. From the experiments he was able to deduce that the atomic nucleus, which contains 99.9% of the mass of the atom, has a diameter of about 10^{-15} m compared to an atomic diameter of about 10^{-10} m. For illustration, if we took a cricket ball to act as the nucleus, the atomic electrons would be 5 km distant! Such an analogy brings home forcibly just how sparse apparently solid matter is and just how dense is the nucleus itself. But despite this clear picture of the atom, indicated from the experiment, explaining how it works is fraught with difficulties, as we shall see in Chapter 3.

1.5 Two Problems

Just as these early atomic experiments revealed an unexpected richness in the structure of matter, so too, theoretical problems forced upon physicists more-sophisticated descriptions of the natural world. The theories of special relativity and quantum mechanics arose as physicists realised that the classical physics of mechanics, thermodynamics and electromagnetism were inadequate to account for apparent mysteries in the behaviour of matter and light. Historically, the mysteries were contained in two problems, both under active investigation at the turn of the century.

1.5.1 *The Constancy of the Speed of Light*

Despite many attempts to detect an effect, no variation was discovered in the speed of light. Light emerging from a torch at rest seems to travel forward at the same speed as light from a torch travelling at arbitrarily high speeds. This is very different from the way we perceive the behaviour of velocities in the everyday world. But, of course, we humans never perceive the velocity of light, it is just too fast! This unexpected behaviour is not contrary to common experience, it is beyond it! Explanation for the behaviour forms the starting point for the theory of special relativity, which is the necessary description of anything moving very fast (i.e. nearly all elementary particles); see Chapter 2.

1.5.2 *The Interaction of Light with Matter*

All light, for instance sunlight, is a form of heat and so the description of the emission and absorption of radiation by matter was approached as a thermodynamical problem. In 1900 the German physicist Max Planck concluded that the classical thermodynamical theory was inadequate to describe the process correctly. The classical theory seemed to imply that if light of any one colour (any one wavelength) could be emitted from matter in a continuous range of energy down to zero, then the total amount of energy radiated by the matter would be infinite. Much against his inclination, Planck was forced to conclude that light of any given colour cannot be emitted in a continuous band of energy down to zero, but only in multiples of a fundamental quantum of energy, representing the minimum negotiable bundle of energy at any particular wavelength. This is the starting point of quantum mechanics, which is the necessary description of anything very small (i.e. all atoms and elementary particles); see Chapter 3.

As the elementary particles are both fast moving and small, it follows that their description must incorporate the rules of both special relativity and quantum mechanics. The synthesis of the two is known as relativistic quantum theory and this is described briefly in Chapter 4.