Part One

The background
Chapter One

Introduction

This story is a first-hand account of one of the most exciting scientific searches in modern times, the recent search for the W and Z bosons. These particles play an important role in our world but most people know nothing of their existence. A prime aim of this book is to communicate to a wider audience some of the excitement of the most recent results from the study of particle physics. To appreciate these new results we have to take a journey into our imagination. Most people are aware that atoms exist and that all matter is composed of atoms, but very few know much more about this hidden world. This is very sad as we now have an enormous amount of information about the particles deep inside the atom and the forces that hold them together. Many of the results are very recent and yet the important ideas can be understood by anyone who is really interested in this subject.

Particle physics experiments are aimed at discovering the smallest particles that exist in an atom and understanding the forces that act between these particles. This study of the smallest known objects surprisingly has a number of common features with the study of our universe at large. They are both exciting frontiers of scientific research which are primarily aimed at discovering more about our natural surroundings.

This book is an account of an experiment carried out at the CERN laboratory near Geneva, which searched for the W and Z bosons in 1983. Some of the largest and most sophisticated accelerators, computers and electronic detectors in the world were used in this search. The early part of the book introduces the important properties of the atom and its nucleus and presents the experimental evidence which suggests that all matter is composed of structureless quarks...
Introduction

and leptons. The forces of nature can, we believe, be reduced to just four fundamental forces and the properties of the gravitational, electromagnetic, weak nuclear and strong nuclear forces are discussed. This is followed by a discussion of some of the important ideas and experiments that led to the unification of the electromagnetic and weak nuclear forces. This unification predicted the existence of the W and Z bosons, each with a mass approximately 100 times greater than a proton. The following chapters describe how the idea for the antiproton–proton collider project at CERN originated and also how these W and Z bosons might be detected. In order to appreciate fully the excitement of the search, it is necessary to have some knowledge of the accelerators and detectors which are used in particle physics experiments and so these are also introduced. There were two major detectors, known as UA1 and UA2, installed at the CERN collider and these both made crucial contributions in the search for W and Z bosons. This book concentrates on the UA1 experiment as I can describe this from first-hand experience.

The story of the experiment begins with the design and construction of a 2000 tonne detector by an international collaboration. The main part of the book presents a vivid account of what it was like to work on the UA1 experiment and the tasks performed by the people involved in that collaboration. The exciting story of the preparations and running periods of the experiment are fully explained so it should be possible to get personally involved in the excitement of the search for these important new particles. The story continues with a description of the hectic analysis of results where the experimental data, recorded over many months, are carefully studied for evidence of the W and Z bosons and other new phenomena.

The book ends with a brief review of some of the most interesting current ideas and experiments in particle physics. I hope you enjoy this journey into the world of the atom and this story of a very exciting experiment. I have certainly enjoyed working on it and trying to explain some of the important and interesting ideas to you.
Chapter Two

Inside the atom

2.1 All matter is made of atoms

Our normal surroundings, although apparently solid and unchanging, conceal a vast number of rapidly moving atoms which are too small to be seen. The air that we breathe is made up of a large number of atoms which are moving unseen and rapidly around us. We are also made up of atoms and so are the seemingly solid objects that we see around us. Matter exists in a variety of forms – solids, liquids and gases. These are all composed of atoms but they appear to be very different because the atoms behave rather differently in each of these states. In a solid, each atom has a permanent location and merely vibrates about this position. This stability of position means that a solid retains its shape and size. As the temperature is raised the vibrations of the atoms increase, the atoms begin to move about more freely and eventually the solid becomes a liquid. The atoms in a liquid can move; however, this remains a local motion and the liquid will flow when poured. At higher temperatures the speed of the atoms increases still further, and once the temperature reaches the boiling point then the liquid changes into a gas. In a gas the atoms are moving very rapidly and a container is required to keep them in a localised volume. The atoms move in random directions and with varying speeds, colliding with each other and the walls of the container. These collisions are responsible for the pressure exerted by the gas. In several important gases, for example oxygen, the atoms prefer to travel in pairs and these are called molecules.

All matter consists of elements, which each have slightly different properties, and all the atoms of a given element are identical. As there are over 100 different chemical elements it was a formidable task to classify them and group together those with similar properties. This
Inside the atom

was achieved by the Russian chemist Dmitri Mendeleev when he constructed his periodic table of elements. The table was organised so that similar elements occurred together and he also predicted the properties of three extra elements which seemed to be missing from the pattern. Over the next 30 years these missing elements were discovered by scientists in France, Germany and Scandinavia and are now known as gallium, germanium and scandium. This was a triumph in the classification of atoms and was the basis for dramatic progress in chemistry which deals with the interactions between atoms.

The size of atoms

We can directly observe objects as small as one-tenth of a millimetre, or $10^{-1}$ metres, without any extra equipment. Once we use an optical microscope we can see much smaller objects, perhaps down to $10^{-7}$ metres, 1000 times smaller. This means that we can study living cells with optical microscopes, but atoms are 1000 times smaller again, $10^{-10}$ metres. We can imagine how small this is by realising that the relative sizes of an atom and an apple are the same as an apple and the earth! In an optical microscope the resolution is limited by the wavelength of the light that can be detected by the human eye, but even smaller objects can be studied using an electron microscope. In an electron microscope, electrons are accelerated to very high velocities and these take over the role that light plays in an optical microscope. We are already talking of replacing light, which is a wave, by an electron, which is surely a particle. This is just the first of many surprises that we shall meet in our exploration of the world of the atom. The electron microscope can be used to take pictures of objects as small as complex molecules and a field ion microscope can even produce a visual picture of individual atoms.

Part of this story concerns the proton, which is about 100000 times smaller than the atom, with a size of $10^{-15}$ metres. How can we conceivably investigate this particle and its movements? When we study the detectors used in particle physics, we will find that there are several different techniques, for example the bubble chamber, which can be used to record the paths of these tiny particles. We can never observe particles directly, but we can follow their movements very precisely indeed, because when a collision produces new particles we can record every detail of their motion, and even their identity in many cases, by the trails they leave in various detectors.

This makes it much easier to appreciate what is happening when these small particles interact or decay because we can record a
Looking inside the atom

‘picture’ of this event. The journey deep inside the atom will still require imagination but many of the important discoveries and results are recorded as spectacular pictures of the paths of these tiny particles.

2.2 Looking inside the atom

The next big step forward in our understanding of atoms occurred early in this century with the work of Lord Ernest Rutherford and colleagues. The experiments that were designed to investigate the structure of the atom have several things in common with our more recent experiments and so we will discuss these experiments in a little detail. The electron had been discovered in 1897 and was known to carry a negative charge and be much lighter than even the lightest atom. The atoms were known to be uncharged but the distribution of the electrons and the form of the balancing positive charge were not known at all. One popular idea was that the small electrons and balancing positive charge were spread evenly through the volume of an atom and not concentrated in small lumps. This was known as the ‘plum-pudding’ model of the atom.

In order to test this idea, Rutherford decided to fire a beam of $\alpha$ particles, which are heavy, positively charged particles, at atoms in a stationary target. What results were expected? If the $\alpha$ particle passed close to an electron in the atom it would be deflected by the force between the charges. However, the $\alpha$ particle has a mass many thousands of times that of the electron and is travelling very rapidly, so the expected deflection was less than one degree from a single collision. If the atom was filled with evenly spread positive charge then the positively charged $\alpha$ particle would be repelled by this charge. However, if the $\alpha$ particle entered the atom, then this force would be small, as these repulsive forces would all act in different directions. Consequently the $\alpha$ particles were expected to be only scattered through very small angles if this picture of the atom was correct. There were no particle accelerators at this time and so Rutherford used the naturally radioactive source of radium to produce the $\alpha$ particle beam in his experiments. The radioactive source was kept in a lead container which had a small hole providing a collimated beam of $\alpha$ particles. This was an early example of an experiment involving a beam, a target and a detector. The experiment concerning the W and Z bosons to be described in this book is a present-day version of this type of experiment, which probes even deeper into the atom.

In Rutherford’s experiment, the positively charged particles were
emitted with an energy of more than a million electronvolts. (The energy gained by an electron, or particle of the same charge, when accelerated through a potential difference of one volt is called an electronvolt (ev).) This high energy enabled them to penetrate very close to the positive charge in the atom before being deflected by electrical repulsion. Ideally, the experimental target would have been a single layer of atoms but in practice a thin gold foil containing several hundred layers of atoms was used. The $\alpha$ particles were detected after they had scattered from this target and the detector, which consisted of a zinc sulphide screen and a microscope, could be moved to different positions. When an $\alpha$ particle hit the screen a small flash of light was emitted. Providing observation was made in a darkened room this light could be observed through a microscope. A schematic view of the experimental arrangement is shown in figure 2.1. The experimenters made careful observations of the number of $\alpha$ particles that were scattered at various angles by moving the zinc sulphide screen to different positions. These experimental results were then compared to the theoretical predictions for the ‘plum-pudding’ model.

The vast majority of the $\alpha$ particles were not deflected at all, as was expected. However, the other results of the experiment were very surprising. Of the $\alpha$ particles that were scattered, many more were deflected through larger angles than expected. Some were even deflected through one hundred and eighty degrees! This surprise was expressed graphically by Rutherford – ‘It was about as credible as if you had fired a fifteen inch shell at a piece of tissue paper and it

![Figure 2.1](image.png)

Schematic diagram of the early $\alpha$ particle scattering experiment which revealed that the positive charge of an atom is contained in a small nucleus. The natural radioactive source of $\alpha$ particles strikes a thin gold foil and the scattered $\alpha$ particles are detected by flashes of light on a zinc sulphide screen viewed in a darkened room with a microscope. Many more $\alpha$ particles were scattered through large angles than had been expected.
came back and hit you’. These experimental results could only be explained by considering the atom as being composed of a very small, heavy, positively charged nucleus, surrounded at a large distance by the much lighter electrons. In this case, the incident $\alpha$ particles would frequently not be deflected at all, because a large volume of the atom is completely empty. The large deflections occur when the $\alpha$ particle approaches very close to the concentrated positive charge of the nucleus. This positively charged nucleus is at least 10000 times smaller than the atom itself. Electrons, which are each negatively charged, move through the remaining volume of the atom, balancing the positive charge on the nucleus and keeping the atom electrically neutral. Since the electrons are also very small, only a tiny fraction of the atom’s volume is occupied by matter. We have now started our journey into the atom, but to reach the smallest known pieces of matter we have much further to go. These results early in the twentieth century led directly to our current view of the atom. Rutherford had shown that the results of a scattering experiment could be used to learn about the internal structure of an atom. We shall see that similar higher-energy experiments have been used to probe the structure of the nucleus and more recently the proton.

2.3 New ideas from the quantum world

We can compare the movements of an electron around the nucleus in an atom with those of the earth orbiting the sun in our solar system and we immediately find an interesting difference. We can predict the exact position and speed (velocity) of a planet or any other object which is much larger than an atom very accurately, but this is not true for an electron inside an atom. We can either know its position or its velocity well, but never both simultaneously. At first sight this does not seem sensible but many more of the familiar properties of everyday life are changed in the atomic world. We will be considering the properties of matter at very small distances and at very high energies. We shall need to introduce the most important ideas from both relativity and quantum mechanics in order to describe particles in these extreme conditions. These two theories, which were developed earlier in this century, are not very important in everyday life when we are dealing with objects containing large numbers of atoms travelling at speeds much less than the speed of light. However, in our study of the atom these new ideas are essential.
Inside the atom

Wave–particle duality

In everyday life there seems to be a very clear distinction between matter and waves. All matter is composed of atoms and, although small, these are particles. However, the various types of electromagnetic radiation, for example the light from the sun, are waves. The coloured spectrum which is obtained when this light is passed through a glass prism shows that these waves have many different wavelengths (the distance between successive crests of the waves).

An even more dramatic illustration that light has the properties of a wave can be seen when light is passed through a small hole. If light was carried by small particles then we would expect to see light on the screen only in the geometrical area behind the hole. In fact the pattern has bright and dark regions which extend outside the area directly behind the hole as shown in figure 2.2. Surprisingly, if the hole is made smaller, the pattern of the light and dark regions gets even larger! This interesting effect of waves is called diffraction. Now, before you try to check this for yourself, be warned that the size of the hole must be comparable to the wavelength of light before this effect can be readily observed. As this wavelength is less than one-thousandth of a millimetre, only a very small pinhole or slit will be effective. A similar effect is observed when a fine wire is illuminated by a light source, when a more complicated pattern than a geometrical shadow is produced.

Figure 2.2. Parallel light illuminates a small slit which has a comparable size to the wavelength of the incident light. After passing through the slit the light is brought to a focus on a screen by a lens. The intensity of illumination varies across the screen, in a series of light and dark lines, caused by the diffraction of light through the slit. If the slit is made smaller the overall width of the pattern is increased.
New ideas from the quantum world

This idea can be turned around to our advantage if we wish to study even smaller holes, for example the spaces between atoms in a crystal. In this case X rays, which are electromagnetic radiation with a much smaller wavelength than light, replace the beam of light. In a crystal the atoms are arranged in a regular lattice and so the X rays produce a diffraction pattern which can be used to work out the spacing between the atoms. We are going to show that matter can also behave like a wave and we shall use a diffraction experiment to illustrate this. The ideas of diffraction will also be used in our search for smaller objects inside the protons.

The first evidence that matter also has wave properties came from Clinton Davisson and Lester Germer's studies of electron diffraction with crystals in 1927. The electron, one of the constituents of the atom, produced a diffraction pattern and was definitely behaving as a wave. This had been predicted a few years earlier by Prince Louis de Broglie (a French aristocrat), who had even calculated that the wavelength (λ) of such particles would depend on their momentum (p) and be given by λ = h/p (where h is Planck’s constant). So as the momentum of a particle beam increases, the effective wavelength of the particle decreases. For a beam energy of 50000 eV the equivalent wavelength is of the order of 10⁻¹¹ metres and can be used to investigate the spacing of atoms in crystals. (To avoid writing too many numbers we usually abbreviate 1000 eV to 1 keV and 1000000 eV to 1 MeV). This idea that a particle exhibits wave properties, with a wavelength which gets smaller as its momentum increases, is a crucial idea to which we will refer several times.

What about waves, do they ever behave like particles? The first evidence for this came from studies of the photoelectric effect, where electrons were emitted from a metal surface which was exposed to light. In 1905, Einstein suggested that in the photoelectric effect, energy was transferred from the light to the electron in a single, very rapid interaction. The electron was not continuously absorbing light, it either received a packet of energy or nothing at all. We call this packet of energy a photon and its energy (E) depends on the wavelength (λ) by E = hν/λ (where h is Planck’s constant and c is the speed of light). The energy of the photon is also given by E = hf where f is the frequency. The frequency multiplied by the wavelength equals the velocity for any wave. It takes a minimum amount of energy to eject an electron from a surface, and so this idea leads to a dramatic prediction. If the wavelength is large, the photon energy is small, and if this is too small no electrons at all will be emitted, however intense the light or however long it shines. If the wavelength is short then the energy of the photon will be large and the electron