

PREFACE

It was already an important question to the philosophers of antiquity: of what does matter fundamentally consist? When repeatedly dividing some piece of matter such as wood or metal or a diamond, does one reach a limit? If so, how does this limit manifest itself? Are there indivisible objects; is there a smallest possible object? Or does the limit exist only in the sense that any further division would seem to make no sense or be experimentally impossible?

Every careful observer of natural phenomena is bound to be impressed by the colorful and stunning diversity of the material world. One soon notes, however, that there does not exist total chaos in these phenomena. Things repeat themselves. A diamond here and another in some other place are as alike as peas in a pod. The leaves of an oak in Boston are indistinguishable from those of an oak in Denver.

So, within the uncountable diversity of phenomena, there are also constants, things that repeat themselves. It was this duality of

multiplicity and constancy that inspired the Greek philosophers, most notably Leucippus of Milet and his student Democritus of Abdera in the 5th century BC, to formulate the hypothesis that the universe is made up of many small, indivisible building blocks called atoms (derived from the Greek word *atomos*, which means essentially the same thing as indivisible). A small number of different atoms and their unending new combinations should suffice, so they claimed, to make up the diversity of things. “Nothing exists,” spoke Democritus, “except atoms and empty space.”

A slightly different concept was brought into play by Anaxagoras around 500 BC. He spoke of an infinity of basic elements which, by mixing, would produce the diversity of objects in the world. These basic elements were furthermore said to be indestructible, and the changes observable in physical objects were considered the result of motion causing new combinations of the elements. Empedocles, who was ten years younger than Anaxagoras, postulated that the basic materials of the world were the four elements earth, water, air, and fire.

It is interesting to note that it is in the conceptualization of the atom that empty space plays a role for the first time. Up to this point, space had been seen as filled with matter, and the idea of empty space was therefore unthinkable. In the context of the theory of the atom, empty space took on an important function. It became the bearer of geometry, the structure in which the atoms moved. So now matter and geometry are two different things.

Atoms move in space and they have geometrical qualities. Democritus said: “Just as tragedy and comedy can be written down with the same letters, different phenomena can be realized in our world by the same atoms, provided they assume different positions and different movements. Some given matter may have the appearance of a given color; may appear to us as tasting sweet or bitter — but in reality there are only atoms and empty space.”

Later the Greek philosophy adopted the elements of the theory of the atom and developed the idea further. Plato, in his dialogue *Timaeus*, discusses possible connections between atoms and the Pythagorean theory of the harmony of numbers. For instance, he identified the atoms of the elements earth, water, air, and fire with the regular solids, the cube, octahedron, icosahedron, and tetrahedron. In speaking of the motion of the atoms, special reference is made to natural causality. Atoms are not moved by forces like love and hate, rather their motion is the consequence of true natural laws.

What started two and a half millennia ago on what is nowadays the west coast of Turkey was nothing less than the beginning of a revolution that continues today. For thousands of years before then, mankind had seen what occurred in the world as coming from some primarily mystic source. Magic and superstition ruled the world.

That changed 2500 years ago on the Ionian coast. The time and place were no accident. In the city states of the Ionian coast democratic values had taken hold. New ideas were accepted easily and could spread quickly. This was due in part to the switch around that time from hieroglyphic symbols to an alphabet. Religion played no or only a subordinate role.

Thus the idea that our world is somehow in the end knowable, and that natural processes can be analyzed with a rational mind, gained ground. "Atomism" was the very beginning of this development. The thread that winds its way through history from the Ionian coast 2500 years ago to this highly scientific and technological present day essentially concerns our knowledge of the building blocks of matter.

Many details about atomic theory as taught in antiquity were preserved for us by a chance event that occurred in Italy in 1417: a manuscript by Lucretius, a Roman poet and philosopher, was discovered. In this script, *De rerum natura*, which is composed in a measured hexameter, Lucretius not only describes the ideas of Leucippus and Democritus but also further develops them. In the work of Lucretius, the atomism of antiquity reaches its highest form. This book was one of the first to be

made after the invention of printing. Copies spread all over Europe and have influenced scientists ever since.

In the work of Lucretius, one finds the best and most detailed description of the atomic theory of antiquity, but, in the end, the theory could not prevail against Plato's and Aristotle's system of ideal forms. His work combined scientific questioning and the demystification of nature with a deep respect for nature and its immutable rules.

Had Lucretius's teachings prevailed two millennia ago, the course of world history would have been different. It would have been less marked by religious excesses and the religious wars in Europe and Asia. Alas, the reality was different.

After the collapse of the Roman Empire, the western world sank into intellectual oblivion for more than a millennium, dominated by religious fanaticism and superstition. It was not until the Italian Renaissance that the brilliant intellectual clarity of Greek thought came to wide parts of Europe again, after being lost for more than a thousand years. The scientific epoch commenced then, led by such heroes of the mind as Copernicus, Leonardo da Vinci, Johannes Kepler, and Galileo Galilee.

In the 17th century, the atomism of the philosophers of antiquity was combined with scientific ideals for the first time. At this time, scientists came to the conclusion that chemical elements such as hydrogen, oxygen, and copper were composed of similar atoms. Isaac Newton, the inventor of mechanics and thereby also the inventor of theoretical physics, was even of the opinion that the consistency of materials, the hardness of a metal for example, was somehow linked to the forces between atoms.

In the second half of the 19th century, atomism was applied with success to the field of chemistry. Chemists found that chemical reactions were best understood if one assumed the substances involved to be made up of small, indivisible building blocks, or atoms. A chemical element, hydrogen say, was thought to consist of a single type of atom. And chemical methods made it possible to determine the approximate size of

such an atom: 10^{-8} cm. One billion hydrogen atoms stacked on top of one another would reach a height of around 10 cm.

Nowadays, we know of 110 different elements, that is to say, 110 different kinds of atom. This fact would have posed a serious problem for the ancient Greek philosophers: they would certainly never have considered it possible that more than 100 different atoms exist. For the first time, there were doubts about whether the atom was truly an indivisible entity. In the end, it was physicists, not chemists, who realized, at the start of the 20th century, that atoms are not indivisible in the sense understood by the ancient Greeks. They discovered that atoms are made up of smaller components: electrons, the particles that make up the atomic shells, and the atomic nucleus, which constitutes the greatest part of the mass of an atom. Atoms became complicated systems.

In the 1920s and 1930s, atomic physics had its great breakthrough. With the help of the newly developed field of quantum mechanics, it was possible for the first time to understand atoms, and hence the structure of atomic matter, both quantitatively and qualitatively on the basis of a small number of principles. Most of the problems that physicists and chemists had grappled with in the previous century could now be solved elegantly.

Physicists then applied the same principles to the atomic nucleus, in the hope that they would quickly reach a similar, more profound understanding of the nucleus. But this hope was not to be fulfilled. They discovered that the atomic nucleus, far from being an indivisible object, is made up of nuclear particles called protons and neutrons. This knowledge, however, hardly helped to reveal very much about the properties of the atomic nucleus itself.

Soon it was observed that when particles are collided at very high energy, new particles are created. Nobody had anticipated this. Einstein's now famous equation $E = mc^2$, which states that matter and energy are interchangeable, was seen in full effect. A whole zoo of new particles

was discovered. Some physicists despaired at this confusing diversity and compared subnuclear physics to botany.

Finally, between 1960 and 1980, a breakthrough was achieved that brought order to the chaotic world of subnuclear physics. The 20th century will enter into history as the epoch in which the substructure of matter was largely elucidated. Today we know that normal matter is made up of quarks, which are the building blocks of the atomic nucleus, and electrons. In the 1970s, a clear picture of the microstructure of matter finally evolved, often prosaically named the Standard Model of particle physics. This model also describes the fundamental interactions qualitatively and quantitatively in a simple form. The interactions are the chromodynamic force, which acts between quarks, and the electroweak force, which acts between quarks and leptons, such as electrons.

The Standard Model is, however, far more than a theoretical model of the elementary particles and their interactions. Its claim to fame is that of a complete unified theory for all the observed phenomena associated with elementary particles. For specialists, the whole theory can be reduced to a couple of lines. This makes it something like the *Weltformel* that theoretical physicists such as Albert Einstein and Werner Heisenberg had unsuccessfully looked for in the past.

Could this theory prove to be a last and thereby final truth? Are electrons and quarks indeed nature's elementary objects, meaning that physicists have finally found the atoms of Democritus and Lucretius? The answer to this question remains undecided. The Standard Model has a number of unsatisfactory characteristics, so many physicists today assume that it is merely an approximation, albeit a very well-functioning approximation, to a more comprehensive theory. If so, physicists should soon find evidence in their experiments for phenomena not explained by the Standard Model, perhaps even evidence for a new substructure of matter.

Electrons and quarks are not simple building blocks that can be combined at will. They are subject to forces such as electromagnetic

forces which are, in turn, transmitted by small particles. That is why in particle physics we should avoid speaking of fundamental forces acting on particles, rather we should speak of interactions between particles.

It turns out that interactions in the Standard Model are governed by very specific laws that are based on symmetry. Symmetry in nature and elementary particles are closely connected. Plato had already referred to such a connection in antiquity. Werner Heisenberg, one of the founders of quantum mechanics and one of the most important physicists of the 20th century, had the following to say: “For Plato is the elementary particle not an unchangeable and indivisible object. The elementary particle is reduced to mathematics. The roots of the observed phenomena are not matter, but the mathematical law and the underlying symmetry.”

Are ideas finally more important than matter? Or does the distinction between matter and ideas disappear as we attempt to describe the limits of particle physics? Until today, the answer to this question is undecided; it is even unclear whether this is a valid question at all.

Our lives are full of change. Everything is in flux, nothing stays as it was. But this is not the whole truth. There is a continuity in the world that allows us to predict objects and occurrences. We scientists discover that some things stay the same, the laws of nature, for instance. These laws, however, depend on strange numbers that we call the constants of nature. Experiments allow us to determine these numbers with ever increasing precision. But the more precise our answer, the stranger these numbers seem.

The constants of nature reflect a profound knowledge of the universe. They characterize our universe. The fact that they exist tells us that, in other regions of our universe, laws similar to our own apply. But other universes could exist and could have different natural constants. Some physicists don't even speak of “the” universe anymore, because it may not exist in such a form. They speak of a whole collection of universes, called the multiverse.

At the same time, these natural constants stand for our knowledge of the universe and they stand for our ignorance. We do not know how their values come to be. Introducing values that cannot be derived but which must be fixed by experimentation is not satisfactory. Scientists cannot be reconciled to this situation.

Are the values of the natural constants a consequence of some hitherto unknown natural laws, or are they merely a random product of the Big Bang? We do not know. To date, no one has been able to explain the value of any of the natural constants. This is one of the mysteries of science, perhaps the biggest mystery in our world.

Life in the universe is only possible for certain very special values of these natural constants. Why do the natural constants take precisely these values here in our universe? We do not know. What is clear, however, is that if they had other values, life could not exist and there would be no one around to ask the question.

The problem of the natural constants arose due to the increased precision in determining their values that particle physicists have been capable of since the 1970s. That is why the discussions in this book center around particle physics. Quantum mechanics is also discussed along with questions concerning the Big Bang and astrophysics.

It was the Scottish physicist James Clerk Maxwell who first suggested basing certain standards on microscopic objects that are to be found everywhere, such as molecules. Up to that point, standards had been set using objects specially designed for the purpose. Maxwell was impressed by the fact that hydrogen molecules, for example, are the same everywhere, unlike large bodies which have their own particularities. As president of the British Association for the Advancement of Science, a society formed in the 19th century and modeled on the *Gesellschaft Deutscher Naturforscher und Ärzte* (a society of German scientists and medical doctors), Maxwell wrote: "If, then, we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet,

but in the wavelength, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules.”

And indeed these ideas of Maxwell are now followed. Our measure of length, for instance, is set by the wavelength of light emitted by atoms of krypton-86. Time is measured by caesium clocks using an atomic transition of caesium.

A large portion of this book deals with questions related to the natural constants that have been introduced in today’s Standard Model, or rather, that have had to be introduced in this model. These constants define, to a large degree, the structure of our world. This gives me the opportunity to report on some questions on which I worked with Murray Gell-Mann at the California Institute of Technology in the ’70s.

Towards the end of the book, a different question is addressed: are the natural constants really constant? Or are they, however minimally, time dependent? By examining the light emitted by distant quasars, which takes billions of years to reach us, it is possible to study the natural constants in the past. People have found a small yet measurable time dependency of the fine structure constant. Should these measurements truly be correct, the consequences are not yet foreseen. The natural constants could also be minimally dependent on the location in space. That means that the natural constants could have different values in different parts of the universe.

The natural constants confront us with one of the most profound riddles of our universe. Where do they come from? Are they really absolutely constant? Are they the same everywhere? Are they dependent on one another? At this point in time, we can give no definitive answers to these questions. Albert Einstein believed the natural constants to be fixed by the interactions, thus excluding any freedom. To date, however, we have not seen any way of verifying this. Presumably there is freedom in the choice of the constants. It may take hundreds of years to be sure.

At the beginning of the new millennium, particle physics is faced with new challenges, and in all probability physics stands at



Murray Gell-Mann (right) and the author Harald Fritzsch (left) in Berlin in 1995.

the threshold of new and important discoveries. In the 20th century, physicists delved ever deeper into the inner workings of matter. New, previously unknown worlds were accessed, new horizons opened up. The structure of the microphysical world became visible. This complex world can be described by a surprisingly simple theory, a theory that can be formulated mathematically.

The questions to be answered become ever more fundamental. Where does matter come from? What happens to it in the distant future? Where do the natural constants come from? Particle physics remains a great adventure. When a new experiment begins, usually after years of preparation, the physicists involved start on a journey into *terra incognita*.

The abyss between the world of particle physics and the everyday world has become huge. This book aims to reduce this abyss. Why should one set oneself the goal of exploring particles and phenomena that have practically nothing to do with our everyday life? The reasons

are the same as those that drive scientists to explore outer space, to push ever further into the depths of our oceans, or to overcome other frontiers. As with all fundamental research, particle physics is part of our culture, part of our effort to gain a rational understanding of the cosmic order.

Fundamental research in physics is, to a large extent, particle physics. The considerable investments made in this field have played a big role in the development of the open and enlightened societies that we find in most parts of the world today. The fascinating insights into the world of the microcosmos that particle physics has allowed us can be counted as one of the lasting achievements of the last century.

One of the essential goals of this book is to inform the general public, not primarily physicists, about the problem of the natural constants. To this end, I use a format that has been used with success before: an imagined dialogue between real and fictitious persons. In this book the persons are Isaac Newton, Albert Einstein, and a modern-day physicist named Adrian Haller, who comes from the University of Bern and is serving as a guest professor at the California Institute of Technology (Caltech) in Pasadena.

The dialogue form has been known since Plato's dialogues in ancient Greece. The famous dialogue *Timaeus*, for example, features the three figures of Critias, Socrates, and Timaeus. Another example is Galileo Galilei's dialogues published in the famous *Discorsi* from the Middle Ages. The format is useful because the reader is often confronted with questions that he may have wanted to ask, and these questions are then answered. The discussions in this book take place in California, in places where I was active years ago.

I wish the reader pleasure, new insights and success in understanding the problem of the fundamental constants.