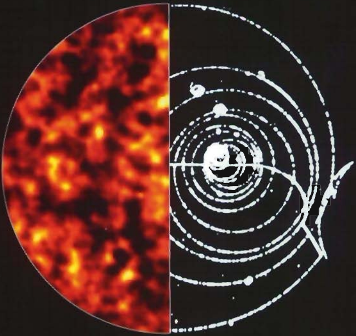

Quarks, Leptons and the Big Bang

JONATHAN ALLDAY

IoP | SECOND EDITION

Quarks, Leptons and the Big Bang

SECOND EDITION

JONATHAN ALLDAY

Quarks, Leptons and The Big Bang is a clear, readable and self-contained introduction to particle physics and related areas of cosmology. It bridges the gap between non-technical popular accounts and textbooks for advanced students. The book concentrates on presenting the subject from the modern perspective of quarks, leptons and the forces between them. This approach enables readers to grasp the essential concepts more easily than the traditional historical approach involving the complex interactions of hadrons. It then moves on to apply these ideas to the modern theory of cosmology.

This second edition brings the reader right up to date with results established over the last few years, especially in cosmology. Necessary background material on relativity and quantum mechanics is included but advanced mathematics is avoided. The book assumes a knowledge of physics to roughly senior secondary school level.

This book will be of interest to students, teachers and general science readers interested in fundamental ideas of modern physics.

From reviews of the first edition

"...provides a valuable insight into the complex world of particle physics and its interface with cosmology." ASTRONOMY NOW

"...clearly written and well produced ... will be warmly welcomed ..." PHYSICS EDUCATION

"...remarkably clear, informative and comprehensive ..." SCHOOL SCIENCE REVIEW

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Second Edition

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Jonathan Allday

The King's School, Canterbury

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Preface to the second edition

It is surely a truism that if you wrote a book twice, you would not do it the same way the second time. In my case, *Quarks, Leptons and the Big Bang* was hauled round several publishers under the guise of a textbook for schools in England. All the time I knew that I really wanted it to be a popular exposition of particle physics and the big bang, but did not think that publishers would take a risk on such a book from an unknown author. Well, they were not too keen on taking a risk with a textbook either. In the end I decided to send it to IOPP as a last try. Fortunately Jim Revill contacted me to say that he liked the book, but thought it should be more of a popular exposition than a textbook…

This goes some way to explaining what some have seen as slightly odd omissions from the material in this book—some mention of superstrings as one example. Such material was not needed in schools and so did not make it into the book. However, now that we are producing a second edition there is a chance to correct that and make it a little more like it was originally intended to be.

I am very pleased to say that the first edition has been well received. Reviewers have been kind, sales have been satisfying and there have been many emails from people saying how much they enjoyed the book. Sixth form students have written to say they like it, a University of the Third Age adopted it as a course book and several people have written to ask me further questions (which I tried to answer as best I could). It has been fun to have my students come up to me from time to time to say that they have found one of my books on the Amazon web site and (slightly surprised tone of voice) the reviewers seem to *like* it.

Well here goes with a second edition. As far as particle physics is concerned nothing has changed fundamentally since the first edition was published. I have taken the opportunity to add some material on field theory and to tweak the chapters on forces and quantum theory. The information on what is going on at CERN has been brought more up to date including some comment on the Higgs 'discovery' at CERN. There are major revisions to the cosmology sections that give more balance to the two aspects of the book. In the first edition cosmology was dealt with in two chapters; now it has grown to chapters 12, 13, 14 and 15. The new chapter 13 introduces general relativity in far more detail and bolsters the coverage of how it applies to cosmology. The evidence for dark matter has been pulled together into chapter 14 and brought more up to date by adding material on gravitational lensing. Inflation is dealt with in chapter 15. Experimental support for inflation has grown and there is now strong evidence to suggest that Einstein's cosmological constant is going to have to be dusted off. All this is covered in the final chapter of the book.

There are some quite exciting times ahead for cosmologists as the results of new experiments probing the background radiation start to come in over the next few years. Probably something really important will happen just after the book hits the shelves.

Then there will have to be a third edition…

Further thanks

Carlos S Frenk	(University of Durham) who spent some of his valuable time reading the cosmology sections of the first edition and then helping me bring them up to date.
Andrew Liddle	(University of Sussex) for help with certain aspects of inflationary theory.
Jim Revill	For continual support and encouragement at IOPP.
Simon Laurenson	Continuing the fine production work at IOPP.
Carolyn Allday	Top of the 'without whom' list.
Toby Allday	Another possible computer burner who held off.

Jonathan Allday
Jonathan.Allday@btinternet.com
Sunday, April 15, 2001

Preface to the first edition

It is difficult to know what to say in the preface to a book. Certainly it should describe what the book is about.

This is a book about particle physics (the strange world of objects and forces that exists at length scales much smaller than the size of an atom) and cosmology (the study of the origin of the universe). It is quite extraordinary that these two extremes of scale can be drawn together in one book. Yet the advances of the past couple of decades have shown that there is an intimate relationship between the world of the very large and the very small. The key moment that started the forging of this relationship was the discovery of the expansion of the universe in the 1920s. If the universe has been expanding since its creation (some 15 billion years ago) then at some time in the past the objects within it were very close together and interacting by the forces that particle physicists study. At one stage in its history the whole universe was the microscopic world. In this book I intend to take the reader on a detailed tour of the microscopic world and then through to the established ideas about the big bang creation of the universe and finally to some of the more recent refinements and problems that have arisen in cosmology. In order to do this we need to discuss the two most important fundamental theories that have been developed this century: relativity and quantum mechanics. The treatment is more technical than a popular book on the subject, but much less technical than a textbook.

Another thing that a preface should do is to explain what the reader is expected to know in advance of starting this book.

In this book I have assumed that the reader has some familiarity with energy, momentum and force at about the level expected of a modern GCSE candidate. I have also assumed a degree of familiarity with mathematics—again at about the modern GCSE level. However, readers who are put off by mathematics can always leave the boxed calculations for another time without disturbing the thread of the argument.

Finally, I guess that the preface should give some clue as to the spirit behind the book. In his book *The Tao of Physics* Fritjof Capra says that physics is a 'path with a heart'. By this he means that it is a way of thinking that can lead to some degree of enlightenment not just about the world in which we live, but also about us, the people who live in it. Physics is a human subject, despite the dry mathematics and formal presentation. It is full of life, human tragedy, exhilaration, wonder and very hard work. Yet by and large these are not words that most people would associate with physics after being exposed to it at school (aside from hard work that is). Increasingly physics is being marginalized as an interest at the same time as it is coming to grips with the most fundamental questions of existence. I hope that some impression of the life behind the subject comes through in this book.

Acknowledgments

I have many people to thank for their help and support during the writing of this book.

Liz Swinbank, Susan Oldcorn and Lewis Ryder for their sympathetic reading of the book, comments on it and encouragement that I was on the right lines.

Professors Brian Foster and Ian Aitchison for their incredibly detailed readings that found mistakes and vagaries in the original manuscript. Thanks to them it is a much better book. Of course any remaining mistakes can only be my responsibility.

Jim Revill, Al Troyano and the production team at Institute of Physics Publishing.

Many students of mine (too many to list) who have read parts of the book. Various Open University students who have been a source of inspiration over the years and a captive audience when ideas that ended up in this book have been put to the test at summer schools.

Graham Farmello, Gareth Jones, Paul Birchley, David Hartley and Becky Parker who worked with Liz and I to spice up A level physics by putting particle physics in.

Finally thanks to family and friends.

Carolyn, Benjamin and Joshua who have been incredibly patient with me and never threatened to set fire to the computer.

My parents Joan and Frank who knew that this was something that I really wanted to do.

John and Margaret Gearey for welcoming me in.

Robert James, a very close friend for a very long time.

Richard Houlbrook, you see I said that I would not forget you.

Jonathan Allday
November 1997

Prelude

Setting the scene

What is particle physics?

Particle physics attempts to answer some of the most basic questions about the universe:

- are there a small number of different types of objects from which the universe is made?
- do these objects interact with each other and, if so, are there some simple rules that explain what will happen?
- how can we study the creation of the universe in a laboratory?

The topics that particle physicists study from one day to the next have changed as the subject has progressed, but behind this progression the final goal has remained the same—to try to understand how the universe came into being.

Particle physics tries to answer questions about the origin of our universe by studying the objects that are found in it and the ways in which they interact. This is like someone trying to learn how to play chess by studying the shapes of the pieces and the ways in which they move across the board.

Perhaps you think that this is a strange way to try to find out about the origin of the universe. Unfortunately, there is no other way. There are instruction manuals to help you learn how to play chess; there are no instruction manuals supplied with the universe. Despite this handicap an impressive amount has been understood by following this method.

Some people argue that particle physics is fundamental to all the sciences as it strips away the layers of structure that we see in the world and plunges down to the smallest components of matter. This study applies equally to the matter that we see on the earth and that which is in the stars and galaxies that fill the whole universe. The particle physicist assumes that all matter in the universe is fundamentally the same and that it all had a common origin in the big bang that created our universe. (This is a reasonable assumption as we have no evidence to suggest that any region of the universe is made of a different form of matter. Indeed we have positive evidence to suggest the opposite.)

The currently accepted scientific theory is that our universe came into being some fifteen billion years ago in a gigantic explosion. Since then it has been continually growing and cooling down. The matter created in this explosion was subjected to unimaginable temperatures and pressures. As a result of these extreme conditions, reactions took place that were crucial in determining how the universe would turn out. The structure of the universe that we see now was determined just after its creation.

If this is so, then the way that matter is structured now must reflect this common creation. Hence by building enormous and expensive accelerating machines and using them to smash particles together at very high energies, particle physicists can force the basic constituents of matter into situations that were common in the creation of the universe—they produce miniature big bangs. Hardly surprisingly, matter can behave in very strange ways under these circumstances.

Of course, this programme was not worked out in advance. Particle physics was being studied before the big bang theory became generally accepted. However, it did not take long before particle physicists realized that the reactions they were seeing in their accelerators must have been quite common in the early universe. Such experiments are now providing useful information for physicists working on theories of how the universe was created.

In the past twenty years this merging of subjects has helped some huge leaps of understanding to take place. We believe that we have an accurate understanding of the evolution of the universe from the first 10^{-5} seconds onwards (and a pretty good idea of what happened even earlier). By the time you have finished this book, you will have met many of the basic ideas involved.

Why study particle physics?

All of us, at some time, have paused to wonder at our existence. As children we asked our parents embarrassing questions about where we came from (and, in retrospect, probably received some embarrassing answers). In later years we may ask this question in a more mature form, either in accepting or rejecting some form of religion. Scientists that dedicate themselves to pure research have never stopped asking this question.

It is easy to conclude that society does not value such people. Locking oneself away in an academic environment ‘not connected with the real world’ is generally regarded as a (poorly paid) eccentricity. This is very ironic. Scientists are engaged in studying a world far more real than the abstract shuffling of money on the financial markets. Unfortunately, the creation of wealth and the creation of knowledge do not rank equally in the minds of most people.

Against this background of poor financial and social status it is a wonder that anyone chooses to follow the pure sciences; their motivation must be quite strong. In fact, the basic motivation is remarkably simple.

Everyone has, at some time, experienced the inner glow that comes from solving a puzzle. This can take many forms, such as maintaining a car, producing a difficult recipe, solving a jigsaw puzzle, etc. Scientists are people for whom this feeling is highly magnified. Partly this is because they are up against the ultimate puzzle. As a practising and unrepentant physicist I can testify to the feeling that comes from prising open the door of nature by even a small crack and understanding something new for the first time. When such an understanding is achieved the feeling is one of personal satisfaction, but also an admiration for the puzzle itself. Few of us are privileged enough to get a glimpse through a half-open door, like an Einstein or a Hawking, but we can all look over their shoulders. The works of the truly great scientists are part of our culture and should be treated like any great artistic creation. Such work demands the support of society.

Unfortunately, the appreciation of such work often requires a high degree of technical understanding. This is why science is not valued as much as it might be. The results of scientific experiments are often felt to be beyond the understanding, and hence the interest, of ordinary people. Scientists are to blame. When Archimedes jumped out of his bath and ran through the streets shouting 'Eureka!' he did not stop to explain his actions to the passers by. Little has changed in this respect over the intervening centuries. We occasionally glimpse a scientist running past shouting about some discovery, but are unable to piece anything together from the fragments that we hear. Few scientists are any good at telling stories.

The greatest story that can be told is the story of creation. In the past few decades we have been given an outline of the plot, and perhaps a glimpse of the last page. As in all mystery stories the answer seems so obvious and simple, it is a wonder that we did not think of it earlier. This is a story so profound and wonderful that it must grab the attention of anyone prepared to give it a moment's time.

Once it has grabbed you, questions as to why we should study such things become irrelevant—*it is obvious that we must*.

Chapter 1

The standard model

This chapter is a brief summary of the theories discussed in the rest of this book. The standard model of particle physics—the current state of knowledge about the structure of matter—is described and an introduction provided to the 'big bang' theory of how the universe was created. We shall spend the rest of the book exploring in detail the ideas presented in this chapter.

1.1 The fundamental particles of matter

It is remarkable that a list of the fundamental constituents of matter easily fits on a single piece of paper. It is as if all the recipes of all the chefs that have been and will be could be reduced to combinations of twelve simple ingredients.

The twelve particles from which all forms of matter are made are listed in table 1.1. Twelve particles, that is all that there is to the world of matter.

The twelve particles are divided into two distinct groups called the *quarks* and the *leptons* (at this stage don't worry about where the names come from). Quarks and leptons are distinguished by the different ways in which they react to the fundamental forces.

There are six quarks and six leptons. The six quarks are called up, down, strange, charm, bottom and top[1] (in order of mass). The six leptons are