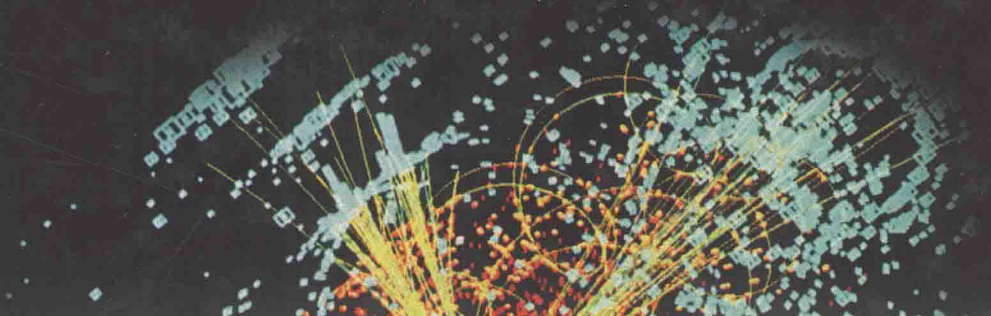
B.R. Martin

Nuclear and Particle Physics

AN INTRODUCTION



Second Edition

WILEY

Nuclear and Particle Physics

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B. R. MARTIN

Department of Physics and Astronomy,
University College London

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To Claire

Preface to the First Edition

It is common practice to teach nuclear physics and particle physics together in an introductory course and it is for such a course that this book has been written. The material presented is such that different selections can be made for a short course of about 25–30 lectures depending on the lecturer's preferences and the students' backgrounds. On the latter, students should have taken a first course in quantum physics, covering the traditional topics in non-relativistic quantum mechanics and atomic physics. A few lectures on relativistic kinematics would also be useful, but this is not essential, as the necessary background is given in an appendix and is only used in a few places in the book. I have not tried to be rigorous, or present proofs of all the statements in the text. Rather, I have taken the view that it is more important that students see an overview of the subject, which for many, possibly the majority, will be the only time they study nuclear and particle physics. For future specialists, the details will form part of more advanced courses. Nevertheless, space restrictions have still meant that it has been necessarily to make a choice of topics and doubtless other, equally valid, choices could have been made. This is particularly true in Chapter 8, which deals with applications of nuclear physics, where I have chosen just three major areas to discuss. Nuclear and particle physics have been, and still are, very important parts of the entire subject of physics and its practitioners have won an impressive number of Nobel Prizes. For historical interest, I have noted in the footnotes many of these awards for work related to the field.

Some parts of the book dealing with particle physics owe much to a previous book, *Particle Physics*, written with Graham Shaw of Manchester University, and I am grateful to him and the publisher, John Wiley & Sons, Ltd, for permission to adapt some of that material for use here. I also thank Colin Wilkin for comments on all the chapters of the book; to David Miller and Peter Hobson for comments on Chapter 4; and to Bob Speller for comments on the medical physics section of Chapter 8. If errors or misunderstandings still remain (and any such are of course due to me alone) I would be grateful to hear about them. I have set up a website (www.hep.ucl.ac.uk/~brm/npbook.html) where I will post any corrections and comments.

Brian R Martin
January 2006

Preface to the Second Edition

The structure of this edition follows closely that of the first edition. Changes include the rearrangement of some sections and the rewriting and/or expansion of others where, on reflection, I think more explanation is required, or where the clarity could be improved; the inclusion of a number of entirely new sections and two new appendices; modifications to the notation in places to improve consistency of style through the book; the inclusion of additional problems; and updating the text, where appropriate. I have also taken the opportunity to correct misprints and errors that were in the original printing of the first edition, most of which have already been corrected in later reprints of that edition. I would like to thank those correspondents who have brought these to my attention, particularly Roelof Bijker of the Universidad Nacional Autonoma de Mexico, Hans Fynbo of the University of Aarhus, Denmark and Michael Marx of the Stony Brook campus of the State University of New York. I will continue to maintain the book's website, (www.hep.ucl.ac.uk/∼brm/npbook.html) where any future comments and corrections will be posted.

Finally, a word about footnotes: readers have always had strong views about these, ('Notes are often necessary, but they are necessary evils' – Samuel Johnson), so in this book they are designed to provide 'non-essential' information only. Thus, for those readers who prefer not to have the flow disrupted, ignoring the footnotes should not detract from understanding the text.

Brian R. Martin
November 2008

Notes

References

References are referred to in the text in the form of a name and date, for example Jones (1997), with a list of references with full publication details given at the end of the book.

Data

It is common practice for books on nuclear and particle physics to include tables of data (masses, decay modes, lifetimes etc.) and such a collection is given in Appendix E. Among other things, they will be useful in solving the problems provided for most chapters. However, I have kept the tables to a minimum, because very extensive tabulations are now readily available at the 'click of a mouse' from a number of sites and it is educationally useful for students to get some familiarity with such sources of data.

For particle physics, a comprehensive compilation of data, plus brief critical reviews of a number of current topics, may be found in the bi-annual publications of the Particle Data Group (PDG). The 2008 edition of their definitive *Review of Particle Properties* is referred to as Amsler *et al.* (2008) in the references. The PDG Review is available online at http://pdg.lbl.gov and this site also contains links to other sites where compilations of particle data may be found.

Data for nuclear physics are available from a number of sources. Examples are: the Berkeley Laboratory Isotopes Project (http://ie.lbl.gov/education/isotopes.htm); the National Nuclear Data Center (NNDC), based at Brookhaven National Laboratory, USA (http://www.nndc.bnl.gov); the Nuclear Data Centre of the Japan Atomic Energy Research Institute (http://wwwndc.tokai-sc.jaea.go.jp/NuC); and the Nuclear Data Evaluation Laboratory of the Korea Atomic Energy Research Institute (http://atom.kaeri.re.kr). All four sites have links to other data compilations.

Problems

Problems are provided for Chapters 1–8 and some Appendices; their solutions are given in Appendix F. The problems are an integral part of the text. They are mainly numerical and require values of physical constants that are given in Appendix E. Some also require data that may be found in the other tables in Appendix E and in the sites listed above.

Illustrations

Some illustrations in the text have been adapted from, or are based on, diagrams that have been published elsewhere. In a few cases they have been reproduced exactly as previously published. I acknowledge, with thanks, permission to use such illustrations from the relevant copyright holders, as stated in the captions. Full bibliographic details of sources are given in the list of references on page 437.

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Basic Concepts

1.1 History

Although this book will not follow a strictly historical development, to 'set the scene' this first chapter will start with a brief review of the most important discoveries that led to the separation of nuclear physics from atomic physics as a subject in its own right and later work that in its turn led to the emergence of particle physics from nuclear physics.[1]

1.1.1 The Origins of Nuclear Physics

Nuclear physics as a subject distinct from atomic physics could be said to date from 1896, the year that Becquerel observed that photographic plates were being fogged by an unknown radiation emanating from uranium ores. He had accidentally discovered *radioactivity*: the fact that some nuclei are unstable and spontaneously decay. The name was coined by Marie Curie two years later to distinguish this phenomenon from induced forms of radiation. In the years that followed, radioactivity was extensively investigated, notably by the husband and wife team of Pierre and Marie Curie, and by Rutherford and his collaborators,[2] and it was established that there were two distinct types of radiation involved, named by Rutherford α and β rays. We know now that α rays are bound states of two protons and two neutrons (we will see later that they are the nuclei of helium atoms) and β rays are electrons. In 1900 a third type of decay was discovered by Villard that involved the emission of photons, the quanta of electromagnetic radiation, referred to in this context as γ rays. These historical names are still commonly used.

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[1] An interesting account of the early period, with descriptions of the personalities involved, is given in Segrè (1980). An overview of the later period is given in Chapter 1 of Griffiths (1987).

[2] The 1903 Nobel Prize in Physics was awarded jointly to Henri Becquerel for his discovery and to Pierre and Marie Curie for their subsequent research into radioactivity. Ernest Rutherford had to wait until 1908, when he was awarded the Nobel Prize in Chemistry for his 'investigations into the disintegration of the elements and the chemistry of radioactive substances'.

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At about the same time as Becquerel's discovery, J.J. Thomson was extending the work of Perrin and others on the radiation that had been observed to occur when an electric field was established between electrodes in an evacuated glass tube and in 1897 he was the first to definitively establish the nature of these 'cathode rays'. We now know the emanation consists of free *electrons*, (the name 'electron' had been coined in 1894 by Stoney) denoted e^- (the superscript denotes the electric charge) and Thomson measured their mass and charge.[3] The view of the atom at that time was that it consisted of two components, with positive and negative electric charges, the latter now being the electrons. Thomson suggested a model where the electrons were embedded and free to move in a region of positive charge filling the entire volume of the atom – the so-called 'plum pudding model'.

This model could account for the stability of atoms, but could not account for the discrete wavelengths observed in the spectra of light emitted from excited atoms. Neither could it explain the results of a classic series of experiments started in 1911 by Rutherford and continued by his collaborators, Geiger and Marsden. These consisted of scattering α particles by very thin gold foils. In the Thomson model, most of the α particles would pass through the foil, with only a few suffering deflections through small angles. Rutherford suggested they look for large-angle scattering and indeed they found that some particles were scattered through very large angles, even greater than 90 degrees. Rutherford showed that this behaviour was not due to multiple small-angle deflections, but could only be the result of the α particles encountering a very small positively charged central *nucleus*. (The reason for these two different behaviours is discussed in Appendix C.)

To explain the results of these experiments Rutherford formulated a 'planetary' model, where the atom was likened to a planetary system, with the electrons (the 'planets') occupying discrete orbits about a central positively charged nucleus (the 'Sun'). Because photons of a definite energy would be emitted when electrons moved from one orbit to another, this model could explain the discrete nature of the observed electromagnetic spectra when excited atoms decayed. In the simplest case of hydrogen, the nucleus is a single *proton* (p) with electric charge $+e$, where e is the magnitude of the charge on the electron,[4] orbited by a single electron. Heavier atoms were considered to have nuclei consisting of several protons. This view persisted for a long time and was supported by the fact that the masses of many naturally occurring elements are integer multiples of a unit that is about 1 % smaller than the mass of the hydrogen atom. Examples are carbon and nitrogen, with masses of 12.0 and 14.0 in these units. But it could not explain why not all atoms obeyed this rule. For example, chlorine has a mass of 35.5 in these units. However, about the same time, the concept of *isotopism* (a name coined by Soddy) was conceived. *Isotopes* are atoms whose nuclei have different masses, but the same charge. Naturally occurring elements were postulated to consist of a mixture of different isotopes, giving rise to the observed masses.[5]

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[3] J.J. Thomson received the 1906 Nobel Prize in Physics for his discovery. A year earlier, Philipp von Lenard had received the Physics Prize for his work on cathode rays.

[4] Why the charge on the proton should have exactly the same magnitude as that on the electron is a puzzle of very long-standing, the solution to which is suggested by some as yet unproven, but widely believed, theories of particle physics that will be briefly discussed in Section 9.5.1.

[5] Frederick Soddy was awarded the 1921 Nobel Prize in Chemistry for his work on isotopes.