Foundations of Nuclear and Particle Physics

This textbook brings together nuclear and particle physics, presenting a balanced overview of both fields as well as the interplay between the two. The theoretical as well as the experimental foundations are covered, providing students with a deep understanding of the subject. In-chapter exercises ranging from basic experimental to sophisticated theoretical questions provide an important tool for students to solidify their knowledge. Suitable for upper undergraduate courses in nuclear and particle physics as well as more advanced courses, the book includes road maps guiding instructors on tailoring the content to their course. Online resources including color figures, tables, and a solutions manual complete the teaching package. This textbook will be essential for students preparing for further study or a career in the field who require a solid grasp of both nuclear and particle physics.

Key features

- Contains up-to-date coverage of both nuclear and particle physics, particularly the areas where the two overlap, equipping students for the real-world occasions where aspects of both fields are required for study
- Covers the theoretical as well as the experimental foundations, providing students with a deep understanding of the field
- Exercises ranging from basic experimental to sophisticated theoretical questions provide an important tool for readers to consolidate their knowledge

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Preface

The first question one might ask about this book is: Why do we need another text on the subject of nuclear and particle physics when excellent texts already exist in both of these areas? Indeed, it is true that each sub-discipline has texts that range from elementary to very advanced and cover specific topics in varying degrees of depth that can be used for the appropriate types of courses. For instance, there are fine books on quantum field theory [Bjo64, Pes95, Wei05, Sch14], on the constituent quark model [Clo79], on high-energy physics [Gri08, Hal84], on hadron scattering [Col84], and on nuclear structure [Des74, Wal95, Won98, Pov08, Row10]. However, there are relatively few textbooks that cover several sub-disciplines in a coherent and balanced way, and those that do exist are either more elementary, e.g., Povh et al. [Pov08] than the present book, or are cast at a more theoretical level and are too advanced for the goals we as authors have set for ourselves. Having a book that stresses the interconnections between the two areas of subatomic physics is crucial, since increasingly one finds that the two fields overlap and that it is essential for a graduate student conducting frontier research and preparing for a career in the field to have an understanding of both. An example of this overlap occurs, for instance, in modern neutrino physics wherein experiments utilizing several-GeV neutrinos as probes almost always involve targets/detectors constructed from nuclei and specifics of nuclear structure are unavoidably required to properly interpret such data.

One specific decision we have made in designing this book is to assume that the reader is familiar with the basics of quantum field theory. More elementary texts typically do not make this assumption and thus much of the discussion, for instance, of lepton scattering from hadrons and nuclei, or of the foundations of chiral symmetry and effective field theory is limited and not at the frontier of the field. We realize that many students today do have at least an introductory course in quantum field theory, or are taking one simultaneously with a course that this book covers, and thus we have followed a somewhat more advanced approach than has been customary. We have included in Appendix B an overview of the essential aspects of quantum mechanics and quantum field theory that are needed for the book. Furthermore, the subject of many-body theory underlies much of nuclear physics and the presentation of this subject can also be rather elementary, as is usually the case in texts that cover the two fields, or too advanced for our purposes, focusing on Green's functions, diagrammatic techniques and nonperturbative approximations at a theoretical level. We have chosen a middle course: we have covered the basics of many-body theory, but also have introduced some of the important diagrammatic representations of the nonperturbative approximations employed very widely in quantum physics ranging from atomic and condensed matter physics to the present context of nuclear and hadronic physics.

The book's central focus is to describe the current understanding of the sub-atomic world within the framework of the Standard Model. The layout of the book is summarized as follows: In the first quarter of the book, the Standard Model is developed. The structure of the nucleon and few-body nuclei are discussed in the second quarter. In the third quarter, the structure and properties of atomic nuclei are described. Lepton scattering is the principal tool used in the central narrative of the book to understand hadrons. In the final quarter of the book we present extensions of the earlier focus on EM lepton scattering to include the weak interactions of leptons with nucleons and nuclei. This begins with a chapter on beta-decay and progresses to intermediate-to-high energy neutrino-induced reactions. These two chapters are followed by two more that build on what occurs earlier in the book, namely, on applications to nuclear and particle astrophysics and to studies of the hot, dense phase of matter formed in heavy-ion collisions The book closes with a brief perspective on physics beyond the Standard Model.

We should also emphasize that the use of word "foundations" in the title of the book is intentional, indicating that this text is not an encyclopedia where one might find material on all of the major topics in the field, albeit at a superficial level. Rather, we have consciously made choices in what and what not to present. We have, for instance, not developed the topic of intermediate-energy hadron scattering, emphasizing lepton scattering instead and have not attempted to cover the lattice approach to the solution of QCD. While the important areas of nuclear structure and the high-energy frontier are covered, we note that excellent, up-to-date, comprehensive textbooks on these important areas are available. Our intent has been to provide the reader with basic material upon which to build by subsequently employing the more advanced sources that exist when it becomes necessary for a more in-depth understanding of specific subjects. In this regard, we have included references to review articles, so that the interested reader can pursue material to a more advanced level. Just what to emphasize and what merely to refer to in passing is, of course, subjective; however, having five co-authors has allowed us to debate the choices we have made.

We view the approximately 120 exercises provided throughout the book and located at the end of each chapter as an important tool for the reader to consolidate their understanding of the material in the book. There exists significant variety in these exercises, ranging from basic experimental issues to sophisticated theoretical questions. Many owe their origins to other sources, but we have tried to tailor them to the material discussed here.

The authors have all taught courses of the type described above at various levels. Specifically, at MIT the book covers the scopes set out for the introductory first-year graduate course in nuclear and particle physics (8.701), together with the second-year graduate courses in nuclear (8.711) and particle (8.811) physics. All graduate students in experimental nuclear/particle physics at MIT are required to take the latter two, with the former being a prerequisite. Additionally, at MIT there is an advanced undergraduate course in nuclear/particle physics (8.276), as well as more advanced courses in many-body theory (8.361), nuclear theory (8.712) and electroweak interactions (8.841) – all taught by one of the authors (TWD) – for which at least some of this text is appropriate.

We acknowledge that the derivation of the QCD Lagrangian in Chapter 5 owes its origins to Professor Frank Wilczek. We acknowledge that Chapter 19 was shaped by the work of Professor Berndt Müller and his colleagues. We thank the Super-Kamiokande Collaboration for permission to use their image on the cover.

The book's evolution profited from its use in draft form as a resource for the MIT course 8.711 taught by one of us (RGM) and Dr. Stephen Steadman in the spring semesters of 2014, 2015, and 2016. We acknowledge the constructive feedback from the MIT graduate students in those classes. Further, we acknowledge careful and critical reading of drafts by Dr. Jan Bernauer, Charles Epstein, Dr. Douglas Hasell, Dr. Rebecca Russell, Dr. Axel Schmidt, Dr. Stephen Steadman, Reynier Cruz Torres and Constantin Weisser at MIT, Professor James Napolitano, Dr. Matt Posik, Devika Gunarathne, Amani Kraishan and Daniel Olvitt at Temple University, Rosi Reed at Lehigh University and Rosi Esha at UCLA. We are grateful to Dr. Brian Henderson for a careful reading of all of the exercises. We thank Connor Dorothy-Pachuta for his considerable expertise in creating many of the figures in the book. There are, of course, many others to thank who, over the years, have been our collaborators – we cannot list them all, but they will find their efforts reflected in many of our choices for what to present. We do, however, wish to acknowledge three who directly played roles in developing some of the figures in Chapters 16 and 18, namely, Professors Maria Barbaro and Juan Caballero, and Guillermo Megias.

In addition to being an integrated text, there are other aspects of this presentation that we feel are important. Specifically, we have attempted to make strong connections with contemporary experiments and have tried, whenever possible, to help the reader become aware of the relevant frontier experimental facilities available and planned worldwide. Doing so is, of course, time dependent; but we have tried to be as up to date as possible. We have also made liberal use of the Particle Data Group website [PDG14] as a resource with which we encourage all students to become familiar. Finally, in Appendix A we have collected information that we believe will be useful to readers.