NUCLEAR REACTIONS FOR ASTROPHYSICS

Principles, Calculation and Applications of
Low-Energy Reactions

Nuclear processes in stars produce the chemical elements for planets and life. This book shows how similar processes may be reproduced in laboratories using exotic beams, and how these results can be analyzed.

Beginning with one-channel scattering theory, the book builds up to complex reactions within a multi-channel framework. It describes both direct and compound reactions, making the connections to astrophysics. A variety of theories are covered in detail, including the adiabatic model and the CDCC method for breakup, eikonal models for stripping, R-matrix techniques, and the Hauser-Feshbach theory for compound nucleus reactions.

Practical applications are prominent in this book, confronting theory predictions with data throughout. The associated reaction program FRESCO is described, allowing readers to apply the methods to practical cases. Each chapter ends with exercises so that readers can test their understanding of the materials covered. Supplementary materials at www.cambridge.org/9780521856355 include the FRESCO program, input and output files for the examples given in the book, and hints and graphs related to the exercises.

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Preface

It was a rainy day in December and we were sitting in an office at the Nuclear Physics Center in Lisbon deeply involved in a heated discussion about the opening of this book. Should we follow the standard practice, or should we paint the big picture? True to our main motivation, after hours we finally agreed.

The human fascination for a clear starry sky is timeless. It has been around since the early days of mankind and includes the most diverse cultures. Only in the last century, nuclear physics has started to make a very important contribution to our understanding of these phenomena in the sky. And until the present day, many big questions connected to nuclear reactions remain to be answered. One of the prime examples listed amongst the eleven most important physics questions for our century is this: 'How and where are the heavy elements produced?'.

Why another book? For decades we have come across colleagues, including experimentalists, who would like to learn more about reactions. Some have become fluent in running reaction codes, but cannot find a book at the right level to learn the theory associated with the calculations they are performing. Probably the largest push toward embarking on the adventure of writing this book came after several years of teaching reaction theory to graduate students. The reference nuclear reaction books have been around for decades, and even though there have been some more recent efforts, nowhere could we find the appropriate level, detail, connection to the present experimental scene, the guiding motivation of astrophysics, and the content consistent with that motivation. So, five years ago, we convinced ourselves this was something worth doing.

Who is the book for? This book is primarily directed to physics graduate students with an interest in nuclear physics and astrophysics. It should serve as a practical guide to experimentalists that need a better understanding of the reaction theories available for the various processes. We hope it can also be a useful reference book for the experts in the matter.

What is different about this book? It contains the standard direct-reaction theory starting from the two-body scattering problem but, rather than expanding toward theories that have not been implemented, it focuses on those that are in use or are being developed. We have tried to present all derivations so that it is easier for the student to follow. We have also tried to make clear the limits of applicability of specific models, and to show examples that can be directly compared with data.

How is the book organized? The first two chapters were written at an introductory level, where the stage of nuclear astrophysics is set and the basic definitions are introduced. Next there are eighty pages of solid scattering theory, which is by far the biggest hurdle a student will have to overcome. This is the central theory component, together with the next two chapters on coupling potentials and structure models. We have provided a chapter on the most common approximations used in this field. More advanced chapters then cover specific types of reactions. And eventually we bring the reader back to astrophysics, introducing the reaction rates into reaction networks in stars and explosive environments.

Throughout the book, as the various reaction mechanisms are discussed, we provide specific examples of relevance to astrophysics and connect back to the astrophysical scenarios set in our first chapter.

In addition to the astrophysics motivation, we have kept in mind a strong connection to experiment. Here, calculations are important, so there is a chapter dedicated to numerical methods. Data is important, so there is a chapter on experimental details. And the comparison between theory and experiment is important, thus the chapter on fitting data.

Another essential component of this project is the assisted hands-on experience. The book comes with a reaction code (FRESCO), and for many examples addressed in the book we provide the inputs to the reaction code so that the readers can perform the calculation by themselves. An appendix for 'Getting started with FRESCO' is also provided.

What is left out? Although we expanded on the number of pages significantly, it is clear that this book does not cover everything that could be contained in such a title as 'Nuclear Reactions for Astrophysics.' From the start, our decision was to focus on direct reactions, and leave out the whole area on central collisions and the specific field of heavy-ion fusion. For each type of reaction included, we prefer to present in detail a small number of models that are implemented and in common use. In this sense the book is not extensive, and should not be used as a review of the field.

What background is needed? A background in quantum mechanics and angular momentum theory is required, although no previous knowledge in scattering theory or nuclear physics is necessary. We have tried to make this a self-contained book and, in particular, scattering theory is developed from scratch.

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Ian J. Thompson and Filomena M. Nunes
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Where to stop? Writing a book can be a never-ending task. It certainly took us longer than we had originally intended, nor is it in the perfect shape we had first envisaged, specially at the graphical level. However, as with many things in life, one has to know when to stop, and our sense is that in its present form this book can already be very helpful to students and researchers. We hope you can learn with it the techniques and the many interesting aspects of studying nuclear reactions for astrophysics. We will surely come back to our heated discussions on how best to present the material. Be it seen from the Café a Brasileira in Lisbon, the Horticulture Gardens in East Lansing or the Golden Gate Bridge in San Francisco, the sky will present itself with the same fascination as always.

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