Remarkable recent developments in the field of quantum optics have given rise to experimental techniques, of unprecedented sensitivity, and theoretical tools which are being used to investigate the fundamental concepts of quantum mechanics, and to perform extremely sophisticated measurements of important physical parameters. This book provides an introduction to this exciting area of physics by giving a comprehensive account of the basic theory of the interaction between atoms and electromagnetic fields.

The first four chapters describe the different forms of the interaction between atoms and radiation fields. The rest of the book deals with how these interactions lead to the formation of dressed states, in the presence of vacuum fluctuations, as well as in the presence of external fields. Also covered are the role of dressed atoms in quantum measurement theory, and the physical interpretation of vacuum radiative effects.

Treating a key field on the boundary between quantum optics and quantum electrodynamics, the book will be of great use to graduate students, as well as to established experimentalists and theorists, in either of these areas.

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Atom-Field Interactions and Dressed Atoms

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Preface

Quantum Optics is a branch of physics which has developed recently in different directions relevant to fundamental physics as well as to highly sophisticated technological applications. The scientific roots of quantum optics, however, originate from the broader subject of Quantum Electrodynamics and, more generally, from quantum field theory. Thus the boundary between quantum optics and quantum field theory is a particularly delicate conceptual ground which should be properly mastered by any prospective quantum optician, theorist or experimentalist alike. This book is intended to foster understanding and knowledge of this boundary region by presenting in a pedagogical fashion the basic theory of dressed atoms, which has been established as a concept of central importance in quantum optics, since it is capable of shedding light on such diverse physical phenomena as resonance fluorescence, the Lamb shift and van der Waals forces.

Coherently with the aims outlined above, the first part of this book, consisting of the first four chapters, is dedicated to the foundations of atom-field interactions. Both radiation and matter are treated from the quantum field theory point of view, and the coupling between matter and the electromagnetic field is derived using the principle of gauge invariance. The atom-photon Hamiltonian is obtained by specializing this general treatment to a nonrelativistic electron field describing the electrons around an atomic nucleus. It should be noted that these first four chapters are specifically aimed at deriving the atom-photon interaction from general principles of quantum field theory, and are not in the form of a balanced compendium of QED.

The impossibility of separating atoms and radiation leads naturally to the second part of the book and to the concept of atoms dressed by the radiation field. Actually, the expression “dressed atom” in nonrelativistic

QED is used with reference to two physical situations which, broadly speaking, are different with respect to the photon number of occupancy. In the first situation an atom is in the presence of real photons, such as those produced by an external source, coherent or incoherent. Then the atom-photon coupling admixes, shifts and splits the levels of the system constituted by the atom and the field. The resulting atom-field energy levels display correlations between bare atom and field states, which are interpreted as states of a new composite object, namely the dressed atom. This kind of dressed atom is the subject of the fifth chapter. In the second situation one has a ground-state bare atom interacting with the vacuum electromagnetic field. Taking the total atom-field system to be in the lowest possible energy state, the zero-point quantum fluctuations of the field induce virtual absorption and re-emission processes of photons by the atom. Since these processes take place continuously they create a cloud of virtual photons around the bare atom. The complex object, bare atom plus cloud of virtual photons, is what one calls a dressed atom in this second physical situation. Naturally this concept of dressed atom is a specialization of the much more general concept of dressed source in quantum field theory, which finds application in diverse branches of physics as solid state or elementary particles, and it is discussed from this general point of view in Chapters 6 and 7. The final chapter of the book is dedicated to some general features of the theory of dressed atoms relevant for the quantum theory of measurement and for the theory of self-reaction. Chapters 6 to 8 summarize investigations by different authors and attempt to present them in a systematic way, with an emphasis on the conceptual QED foundations. On the whole, the last four chapters of the book are aimed at deriving and describing the properties of dressed atoms and are inevitably more specific than the first four. However, the presentation of the subject in the more general context of quantum fields, using models taken from the theory of the electron-phonon and of the nucleon-meson interactions, is intended to smooth out discontinuities in the treatment as far as possible. The appendices are intended to complement or to generalize the topics discussed in the text.

In view of the rather broad scope of the book, no attempt has been made to provide the reader with a complete set of references. The general criterion has been to refer to an easily available book wherever possible, or to a review article. Reference to normal papers has been done only in the case of historic and fundamental papers or when the information contained in the paper has been deemed necessary and not available in a book or in a review article. Furthermore, in order to avoid divergence of citation lists we have also made recourse to the well-known formula "and papers cited therein". Thus the reference lists at the end of each chapter cannot be used to assess priority of a discovery, of a new idea or of a suggestion.

The book is a theoretical text, but it is not intended for theoreticians only. It has been assumed that the reader is a postgraduate student specializing in quantum optics or in nonrelativistic QED possessing a working knowledge of quantum mechanics and classical electrodynamics. The derivation of the main results, however, is displayed in a rather complete fashion and the mathematics involved should be well within the grasp of theorists and experimentalists alike. We also hope that the book may interest more senior scientists working in quantum optics, in QED and in neighbouring fields where a knowledge of the basis of quantum optics is useful or even necessary.

The system of units throughout the book is the Gauss system. A recipe for translating all expressions and formulae quickly and efficiently into SI units is presented in Appendix E.

This book owes much to our collaboration with E. A. Power, from whom we have learned most of the QED we know. We are particularly grateful to P. L. Knight for suggesting and encouraging the project. P. L. Knight, E. A. Power and T. Thirunamachandran have read the complete manuscript and have spent long hours with us in discussions relating to this book. S. M. Barnett has made useful comments on Chapters 5 and 6. L. de la Peña has volunteered a thorough debugging of the manuscript as well as interesting remarks on the structure of the book. We feel indebted to these friends and colleagues who have generously dedicated a substantial part of their time to improve our book and to purify it from a large number of what pudic authors usually call misprints. We thank P. W. Milonni for reading the manuscript, for suggesting changes and for encouragement, and we gratefully acknowledge a much appreciated conversation on the contents of the book with C. Cohen-Tannoudji, who in addition has generously sent us useful material on dressed atoms.

Most of the discussions on the manuscript with S. M. Barnett, P. L. Knight, E. A. Power and T. Thirunamachandran have taken place in the pleasantly stimulating environment of the International Centre for Theoretical Physics in Trieste, and we are grateful to the ICTP organizers for liberal hospitality and collaboration. Finally we wish to thank Mr. S. Pappalardo for helpful assistance with the figures.