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Quantum Optics

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The field of quantum optics has witnessed significant developments in recent years, from the laboratory realization of counter-intuitive concepts such as lasing without inversion and micromasers, to the investigation of fundamental issues in quantum mechanics, such as complementarity and hidden variables. This book provides an in-depth and wide-ranging introduction to the subject of quantum optics, emphasizing throughout the basic principles and their applications.

The book begins by developing the basic tools of quantum optics, and goes on to show the application of these tools in a variety of quantum optical systems, including resonance fluorescence, lasers, micromasers, squeezed states, and atom optics. The final four chapters are devoted to a discussion of quantum optical tests of the foundations of quantum mechanics, and particular aspects of measurement theory.

Assuming only a background of standard quantum mechanics and electromagnetic theory, and containing many problems and references, this book will be invaluable to graduate students of quantum optics, as well as to established researchers in this field.

Quantum optics

Marlan O. Scully has received numerous honors as a result of his many pioneering contributions as a researcher and educator on both sides of the Atlantic. These include: the Adolph Lomb Medal of the Optical Society of America, the Elliot Cresson Medal of the Franklin Society, Guggenheim Fellowship, and the Alexander von Humboldt Award. He is an elected member of the Max-Planck Society and a Fellow of the American Physical Society, the Optical Society of America, and the American Association of the Advancement of Science. He has held the faculty positions at Yale, MIT, University of Arizona, University of New Mexico and is currently Burgess Distinguished Professor of Physics, Director of the Center for Theoretical Physics at Texas A&M University, Co-Director of the Texas Laser Lab., and Auswrtiges Wissenschaftliches Mitglied at the Max-Planck Institut für Quantenoptik.

M. Suhail Zubairy received his PhD degree from the University of Rochester in 1978. He held research and faculty positions at the University of Rochester, University of Arizona, and the University of New Mexico before joining the Quaid-i-Azam University, Islamabad in 1984 where he is presently a Professor and founding Chairman of the Department of Electronics. He has held visiting appointments at the Max-Planck Institut für Quantenoptik, Universität Ulm, University of New Mexico, and the University of Campinas. He has been an Associate Member of the International Centre for Theoretical Physics, Trieste. He was awarded the Order of Sitara-e-Imtiaz by the President of Pakistan in 1993. He has received the Salam Prize for Physics and a Gold Medal from the Pakistan Academy of Sciences. He is a Fellow of the Pakistan Academy of Sciences and the Optical Society of America.

To

Thelma T. Scully and Naseem Fatima Zubairy

and to the memory of

Orvil O. Scully and Muhibul Islam Zubairy

Preface

Quantum optics, the union of quantum field theory and physical optics, is undergoing a time of revolutionary change. The subject has evolved from early studies on the coherence properties of radiation like, for example, quantum statistical theories of the laser in the sixties to modern areas of study involving, for example, the role of squeezed states of the radiation field and atomic coherence in quenching quantum noise in interferometry and optical amplifiers. On the one hand, counter intuitive concepts such as lasing without inversion and single atom (micro) masers and lasers are now laboratory realities. Many of these techniques hold promise for new devices whose sensitivity goes well beyond the standard quantum limits. On the other hand, quantum optics provides a powerful new probe for addressing fundamental issues of quantum mechanics such as complementarity, hidden variables, and other aspects central to the foundations of quantum physics and philosophy.

The intent of this book is to present these and many other exciting developments in the field of quantum optics to students and scientists, with an emphasis on fundamental concepts and their applications, so as to enable the students to perform independent research in this field. The book (which has developed from our lectures on the subject at various universities, research institutes, and summer schools) may be used as a textbook for beginning graduate students with some background in standard quantum mechanics and electromagnetic theory. Each chapter is supplemented by problems and general references. Some of the problems rely heavily on the treatment given in a research paper, leading students directly to the scientific literature. The role of the references is to identify original papers, and to refer the reader to review articles and related papers for in-depth study. No attempt is made to give an exhaustive list of references.

The book is divided roughly into three parts. In the first six chapters, we develop the 'tools' of quantum optics. In the next eleven chapters, these 'tools' are applied to various quantum optical systems. In the last four chapters, we consider the application of modern quantum optical physics to testing the foundations of quantum mechanics.

The book opens with the presentation of the quantization of the radiation field by associating each mode of the field with a quantized harmonic oscillator. The strong motivation to quantize the radiation field in many quantum optical systems comes from phenomena such as quantum beats, two-photon interferometry, and the generation of nonclassical states of the radiation field, e.g., Fock states. Some of these phenomena shed new light on our understanding of the elusive concept of the photon. In the first part of the book, we discuss the various states of the radiation field, e.g., coherent and squeezed states, and introduce the distribution functions of the field which form a correspondence between the quantum and the classical theories of radiation. We then develop a quantum theory of coherence in terms of the correlation functions of the field, which provides a framework for discussing the outcome of interferometric experiments. We proceed to develop the semiclassical and quantum theories of the interaction of the radiation field with matter, with an emphasis on formulating a theoretical framework directed toward understanding the many faceted problems of modern quantum optics.

In the second part, we use this theoretical framework to develop theories of atomic and field damping, resonance fluorescence, laser and micromaser operation, and the study of the quantum noise properties of such nonlinear optical processes as parametric amplification and four-wave mixing. Atomic coherence effects in many novel systems are discussed in detail. For example, the role of atomic coherence in suppressing absorption leads to interesting effects such as lasing without inversion and electromagnetically induced transparency. Atomic coherence can also play a role in quenching Schawlow–Townes spontaneous emission noise in lasers, as in the correlated emission laser (CEL). Such CEL systems have potential applications in, e.g., laser gyro physics and 'noise-free' amplification.

In the third part, we move on to the application of modern quantum optical physics to fundamental questions related to the foundation of quantum mechanics. These include Bell's theorem, quantum nondemolition measurements, 'which-path' detectors, and two-photon interferometry.

We have benefited greatly from our interaction with many of our colleagues, friends, and students in the preparation of this book. They are too numerous to be individually acknowledged and we are able to express our gratitude to only a few of them here.

We would especially like to thank Stephen Harris, Willis Lamb, Julian Schwinger, and Herbert Walther, who have strongly influenced our thinking through their profound contributions to physics in general and many fruitful collaborations in particular. Their imprint on this book is evident: but for them, entire chapters would be missing. We are grateful to Peter Knight for providing the encouragement for writing this book. Critical comments from and helpful discussions with him and with Girish Agarwal, Richard Arnowitt, Chris Bednar, Janos Bergou, Leon Cohen, Jonathan Dowling, Joe Eberly, Michael Fleischhauer, Edward Fry, Julio Gea-Banacloche, Roy Glauber, Trung-Dung Ho, Hwang Lee, Lorenzo Narducci, Robert O'Connell, Norman Ramsey, Ulrich Rathe, Wolfgang Schleich, Krzysztof Wodkiewicz, Bernand Yurke, and Shi-Yao Zhu provided invaluable assistance concerning many subtle points. One of us (MSZ) would like to express his gratitude to the Pakistan Atomic Energy Commission for the financial support over the years, and particularly its Chairman, Ishfaq Ahmad, for his deep interest and commitment that played a vital role in the completion of this project. MOS would like to acknowledge the support of the Office of Naval Research, and particularly Herschel Pilloff, whose wisdom and dedication to scientific excellence have resulted in many successful joint projects and conferences which have had a marked impact on this book. The support of the Houston Advanced Research Center (HARC), and the Welch Foundation is also deeply appreciated. We thank Jeanne Williams for the careful typing in TEX, and Jim and Andrey Bailey for the hospitality of the Bailey ranch, where the manuscript was completed.

Finally, we are grateful to our family members, Judith, James, Debra, Robert, Steven, and Jacquelyn, and Parveen, Sarah, Sahar, and Raheel, for their support, and understanding, especially during the extended absences in the course of the last decade, when this book was contemplated, planned, and written.

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