INVITATION TO CONTEMPORARY PHYSICS

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PREFACE

This book deals with seven of the most exciting areas of modern physics: lasers, superconductivity, chaos, symmetry, stars, particles, and cosmology. Together, these topics cover a large spectrum of physical concepts and phenomena — from the tiniest objects to the whole universe, from the hottest to the coldest systems, from abstract principles to ideas with immediate practical implications, from the beauty of symmetries in Nature to the baffling aspects of complex systems. We hope, from this mosaic, a picture will emerge that can convey to the reader all the richness and the enchantment of modern physics. The choice of these seven areas is necessarily subjective to some extent, but multiple authorship has reduced this risk to an acceptable level.

Our goal is to make some parts of physics comprehensible to the general reader not having much prior training in physics, yet intellectually alert and armed with a keen interest in science. We are motivated to write because of a shortage of books of this kind. Quite often we ourselves would like to learn about some area of contemporary intellectual activity outside our own field, but find it difficult to locate a suitable and convenient source of reading material. Textbooks and scientific review articles tend to be too technical, while popular books and magazine articles are often long on facts and short on explanations, as such they might act like analgesics merely to dull the pain of incomprehension. We realize from our own experience that we want to know the essential facts and ideas in the area of interest, short of all the nitty-gritty technical details that a specialist in the field must worry about. But most of all, we want to *understand* the basic principles behind these facts and ideas, the logic in the organization of concepts and in the working of things. In other words, we would like to be told in plain English *why*, and not just *what* and *how*. We believe that the greatest joy in learning a subject is to *understand* what is really going on, rather than simply to register all the relevant facts. We have attempted to transmit our own joy in learning physics through this book, by exploring with the reader a variety of physical phenomena and trying to understand them in terms of a few basic physical ideas.

Since we feel that such a book is of use to all those who love physics and to all those who are more than just simply curious about science, we have written for a diverse readership. The book can be used as a reference text for a university course aiming at a general survey of modern physics; in fact this book grew partially out of a course one of us (QHK) teaches. On the other hand, it can also be read by an individual who wants to understand the essence of one of the topics treated without having to be bothered by the detailed formalisms. Each of the seven chapters can be read independently. Each starts from the very beginning, then progresses into more modern and, perhaps deeper, areas in the field.

This *Invitation to Contemporary Physics* is therefore an invitation to an excursion into a marvelously varied country. There are many roads, some easier than others; but the traveler willing to take unfamiliar paths, to climb hills and mountains will be amply rewarded by beautiful sights. A novice at a first reading may find some of the later sections of a chapter rather difficult to master, and a more mature reader may find the earlier sections far too elementary. In other words, although the book has been written in such a way that any intelligent reader with a determination can understand, it is not to say that some of these topics can be understood without some effort on the part of the reader. If such difficulties are encountered, we advise the reader to skip the section or the rest of the chapter, and come back to it at a later date when some of the new concepts have sunk in. On the other hand, the more mature reader would perhaps prefer to gloss over some parts and concentrate mostly on those sections or chapters of interest to her or him. Footnotes are sometimes used to explain finer points or to give quantitative results. The more complex sections are recapitulated in short summaries. Finally, some of the fundamental concepts and facts of physics commonly used in the main text are described in three Appendices.

We are indebted to a great number of people for their valuable suggestions and comments. In particular, we wish to thank our friends and colleagues at McGill University: Abdelhamid Bougourzi, Cliff Burgess, John Crawford, Subal Das Gupta, Al-Amin Dhirani, Charles Gale, Terry Gannon, Noureddine Hambli, David Hanna, Jonathan Lee, Zhishun Li, Rob Myers, Bob Sharp, and Douglas Stairs; at Université Laval: Sea Leang Chin, Veronique François, Michel Gagnon, Eduardo Hardy, Roger Lessard, and Serge Pineault; and at the Indian Institute of Science: N. Mukunda, T.V. Ramakrishnan, Rahul Pandit, Sriram Ramaswamy, and H.R. Krishnamurthy.

Quang Ho-Kim
Narendra Kumar
Chi-Sing Lam

May 1991

TABLE OF CONTENTS

CHAPTER I

LASERS AND PHYSICS

CONTENTS

1. INVITATION TO THE NEW OPTICS

The laser may turn out to be one of the most significant inventions of our times. A product of modern quantum mechanics, it generates a light endowed with many remarkable properties and qualitatively very different from the light hitherto available to us from conventional sources. This form of light, which gives us a completely new tool for probing Nature, already transforms and broadens to an extraordinary extent the ancient science of optics. It gives us a radically new power of control of light that opens up seemingly limitless applications in arts and sciences, in medicine and technology. Physicists have used lasers to study minute details of the structure of atoms and molecules, to catch atoms in flight, and to perform delicate experiments to test the very foundations of quantum mechanics. Biologists have used lasers to study the structure and the degree of aggregation of various biomolecules, to probe their dynamic behavior, or still to detect constituents of cells. Mathematicians actively involved with nonlinear complex systems have been intrigued by the possibility that their ideas could be tested by observing the dynamical instabilities exhibited by some lasers. And not only scientists or engineers — artists and dentists, soldiers and spies have also been touched by this invention.

The term *laser*, which is an acronym for *light amplification by stimulated emission of radiation*, is an apt description of the device. The principle on which the laser is based can be traced back to a work by Albert Einstein who showed in 1917 that 'stimulated', or induced, radiation could be obtained from an atom under certain conditions. But the actual invention of the laser did not come until 1960 when Arthur Schawlow and Charles Townes demonstrated that it was possible to amplify this kind of radiation in the optical and infrared regions of the spectrum. Soon thereafter, the first laser beam was obtained.

The laser is a device for producing a very tight beam of extremely bright and highly coherent light. To appreciate these remarkable properties of laser light that make the laser the unique tool it has come to be for research and applications, we will begin by considering light as it is normally found and discuss its characteristic features, with the view of contrasting them with the distinctive properties of laser light. There exist now many types of lasers, which use different substances as active media, achieve atomic excitations through different pumping techniques, and generate light at widely different wavelengths. They all share, however, the same basic principles. We will describe many applications of lasers, not only in technology, but also in basic research in many branches of physics where the use of this tool has led us to new directions, taken us to new frontiers.

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2. CONVENTIONAL LIGHT SOURCES

2.1 Light and Electromagnetic Radiation

Light is ordinarily produced in hot matter. In 1704, in his second great work, *Opticks*, Isaac Newton wrote:

> Do not all fix'd Bodies, when heated beyond a certain degree,
> emit Light and shine; and is not this Emission perform'd by
> the vibrating motions of their parts?

Light can be described as a perturbation of space of the kind one may observe in the vicinity of two electrically charged plates or near the path of a rapidly moving charged particle. Once we have observed how iron filings spread around the plates shift about to align themselves into a regular pattern, or watched a small probe charge attached to the end of a very thin thread respond to the particle's motion, we are left in no doubt that space nearby is pervaded with a certain distribution of force that is called *electromagnetic field*. The precise way in which this field varies in space and time is described concisely by a set of differential equations, due to James Clerk Maxwell (1873), which replaced and generalized all previous empirical laws of electricity and magnetism. According to the theory encapsulated in these equations and later confirmed by experiments, the electromagnetic field is a disturbance that propagates from point to point in all accessible directions and behaves at large distances from the source as a wave. For this reason we may refer to it simply as an *electromagnetic wave*. One of its basic properties is that it can convey energy through empty space without the transfer

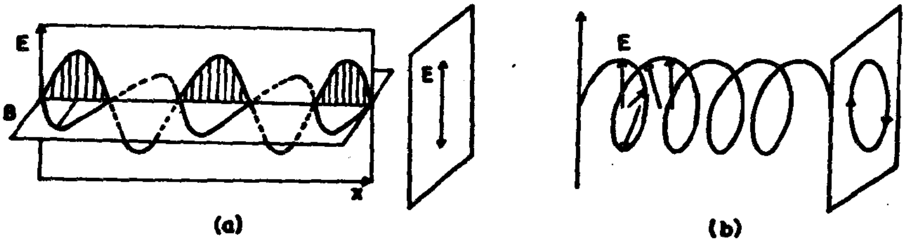

FIG. I.1 *Representation of an electromagnetic wave as space and time variations of electric field* E *and magnetic field* B. *In (a)* E *stays at all times in a plane passing by the propagation line, and the polarization is said to be planar. In (b)* E *changes direction as it evolves, and the polarization is nonplanar.*

of matter and that it is always moving at high speed, indeed at the speed of light ($c = 300000\,\mathrm{km\,s^{-1}}$ in empty space), and when it stops moving, it ceases to exist. We implicitly refer to this kind of energy transfer whenever we use the term '*electromagnetic radiation*'. An electromagnetic wave has all the characteristics, except visibility, of light: it can be reflected, refracted, or diffracted. Light, in effect, is the *visible* form of electromagnetic radiation.

A light wave, like any other electromagnetic wave, is described by the variations in space and time of two vectorial quantities, namely, an electric field **E** and a magnetic field **B**. These vectors remain at all times perpendicular to each other and perpendicular to the direction of propagation. Thus, the wave in question is a traveling transverse wave, much like the ripples on a disturbed water surface. The direction of the electric field is called the direction of the *polarization* of the wave. Over a period of time, the electric field vector defines a vibration pattern which may be projected in the **E**-**B** plane as a line segment, a circle, or an ellipse (Fig. I.1). The states of polarization of a light wave can be easily discovered: let light pass through a polarizer — a tourmaline crystal or a Polaroid filter — and observe the