Texts and
Monographs
in Physics

Roger Balian

From Microphysics to Macrophysics

Methods and Applications of Statistical Physics

Volume I

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Translated by D. ter Haar and J. F. Gregg

With 39 Figures

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Preface

Although it has changed considerably in both coverage and length, this book originated from lecture courses at the Ecole Polytechnique. It is useful to remind non-French readers of the special place this institution occupies in our education system, as it has few features in common with institutes with a similar name in other parts of the world. In fact, its programme corresponds to the intermediate years at a university, while the level of the students is particularly high owing to their strict selection through entrance examinations. The courses put a stress on giving foundations with a balance between the various natural and mathematical sciences, without neglecting general cultural aspects; specialization and technological instruction follow after the students have left the Ecole. The students form a very mixed population, not yet having made their choice of career. Many of them become high-level engineers, covering all branches of industry, some devote themselves to pure or applied research, others become managers or civil servants, and one can find former students of the Ecole amongst generals, the clergy, teachers, and even artists and Presidents of France.

Several features of the present volume, and in particular its contents, correspond to this variety and to the needs of such an audience. Statistical physics, in the broadest meaning of the term, with its many related disciplines, is an essential element of modern scientific culture. We have given a comprehensive presentation of such topics at the advanced undergraduate or beginning graduate level. The book, however, has to a large extent moved away from the original lecture courses; it is not only intended for students, but should also be of interest to a wider public, including research workers and engineers, both beginning and experienced. A prerequisite for its use is an elementary knowledge of quantum mechanics and general physics, but otherwise it is completely self-contained.

Rather than giving a systematic account of useful facts for specialists in some field or other, we have aimed at assisting the reader to acquire a broad and solid scientific background knowledge. We have therefore chosen to discuss amongst the applications of statistical physics those of the greatest educational interest and to show especially how rich and varied these applications are. This is the reason why, going far beyond the traditional topics of statistical mechanics – thermal effects, kinetic theory, phase transitions, radiation laws – we have dwelt on microscopic explanations of the mechanical, magnetic, electrostatic, electrodynamic, ... properties of the various states

of matter. Examples from other disciplines, such as astrophysics, cosmology, chemistry, nuclear physics, the quantum theory of measurement, or even biology, enable us to illustrate the broad scope of statistical physics and to show its universal nature. Out of a concern for culture, and also in trying to keep engineers and scientists away from too narrow a specialization, we have also included introductions to various physical problems arising in important technological fields, ranging from the nuclear industry to lighting by incandescent lamps, or from solar energy to the use of semiconductors for electronic devices.

Throughout this abundance we have constantly tried to retain a unity of thought. We have therefore stressed the underlying concepts rather than the technical aspects of the various methods of statistical physics. Indeed, one can see everywhere in the book under various guises two main guiding principles: on the one hand, the interpretation of entropy as a measure of disorder or of lack of information and, on the other hand, a stress on symmetry and conservation laws. At a time when excessive specialization tends to hide the unity of science, we have deemed it instructive to present unifying points of view, showing, for instance, that the laws of electrodynamics, of fluid dynamics, and of chemical kinetics all go back to the same underlying, basic ideas.

The French tradition, both in secondary education and in the entrance examinations to the Ecole Polytechnique, has to some extent given pride of place to mathematics. We have tried to benefit from this training by putting our treatment on a strict logical basis and giving our arguments a structured, often deductive, character. Mathematical rigour has, however, been tempered by a wish to present and to explain many facts at an introductory level, to avoid formalistic stiffness, and to discuss the validity of models. We have inserted special sections to present the less elementary mathematical tools used.

A first edition of this book was published in French in 1982. When the idea of publishing an English translation started to take shape, it seemed desirable to adapt the text to a broader, more international audience. The first changes in this direction brought about others, which in turn suggested a large number of improvements, both simplifications and more thorough discussions. Meanwhile it took some time to find a translator. Further lecture courses, especially one given at Yale in 1986, led to further modifications. One way or another, one thing led to another and finally there was little left of the original text, and a manuscript which is for more than eighty per cent new was finally translated; the present book has, in fact, only the general spirit and skeleton in common with its predecessor.

The actual presentation of this book aims at making it easier to use by readers ranging from beginners to experienced researchers. Apart from the main text, many applications are incorporated as exercises at the end of each chapter and as problems in the last chapter of the second volume; these are accompanied by more or less detailed solutions, depending on the difficulty.

At the end of each of the two volumes we give tables with useful data and formulae. Parts of the text are printed in small type; these contain proofs, mathematical sections, or discussions of subjects which are important but lie outwith the scope of the book. For cultural purposes we have also included historical and even philosophical notes: the most fundamental concepts are, in fact, difficult to become familiar with and it is helpful to see how they have progressively developed. Finally, other passages in small type discuss subtle, but important, points which are often skipped in the literature. Many chapters are fairly independent. We have also tried clearly to distinguish those topics which are treated with full rigour and detail from those which are only introduced to whet the curiosity. The contents and organization of the book are described in the introduction.

I am indebted to John Gregg and Dirk ter Haar for the translation. The former could only start on this labour, and I am particularly grateful to the main translator, Dirk ter Haar, for his patience (often sorely tried by me) and for the care bestowed on trying to present my ideas faithfully. I have come to appreciate how difficult it is to find exact equivalents for the subtleties of the French language, and to discover some of the subtleties of the English language. He has also accomplished the immense task of producing a text, including all the mathematical formulae, which could be used directly to produce the book, and which, as far as I can see, should contain hardly any misprints.

The Service de Physique Théorique de Saclay, which is part of the Commissariat à l'Energie Atomique, Direction des Sciences de la Matière, and in which I have spent the major part of my scientific research career, has always been like a family to me and has been a constant source of inspiration. I am grateful to all my colleagues who through many discussions have helped me to elaborate many of the ideas presented here in final form. They are too numerous to be thanked individually. I wish to express my gratitude to Jules Horowitz for his suggestions about the teaching of thermodynamics. As indicated in the preface to the first edition, I am indebted to the teaching staff who worked with me at the Ecole Polytechnique for various contributions brought in during a pleasant collaboration; to those mentioned there, I should add Laurent Baulieu, Jean-Paul Blaizot, Marie-Noëlle Bussac, Dominique Grésillon, Jean-François Minster, Patrick Mora, Richard Schaeffer, Heinz Schulz, Dominique Vautherin, Michel Voos, and Libero Zuppiroli, who to various degrees have helped to improve this book. I also express my thanks to Marie-Noëlle Bussac, Albert Lumbroso, and Marcel Vénéroni, who helped me in the tedious task of reading the proofs and made useful comments, and to Dominique Bouly, who drew the figures. Finally, Lauris and the other members of my family should be praised for having patiently endured the innumerable evenings and weekends at home that I devoted to this book.

Paris, April 1991 *Roger Balian*

Preface to the Original French Edition

The teaching of statistical mechanics at the Ecole Polytechnique used for a long time to be confined to some basic facts of kinetic theory. It was only around 1969 that Ionel Solomon started to develop it. Nowadays it is the second of the three physics "modules", courses aimed at all students and lasting one term. The first module is an introduction to quantum mechanics, while the last one uses the ideas and methods of the first two for treating more specific problems in solid state physics or the interaction of matter with radiation. The students then make their own choice of optional courses in which they may again meet with statistical mechanics in one form or another.

There are many reasons for this development in the teaching of physics. Enormous progress has been made in statistical physics research in the last hundred years and it is now the moment not only to reflect this in the teaching of future generations of physicists, but also to acquaint a larger audience, such as students at the Ecole Polytechnique, with the most useful and interesting concepts, methods, and results of statistical physics. The spectacular success of microscopic physics should not conceal from the students the importance of macroscopic physics, a field which remains very much alive and kicking. In that it enables us to relate the one to the other, statistical physics has become an essential part of our understanding of Nature; hence the desirability of teaching it at as basic a level as possible. It alone helps to unravel the meaning of thermodynamic concepts, thanks to the light it sheds on the nature of irreversibility, on the connections between information and entropy, and on the origin of the qualitative differences between microscopic and macroscopic phenomena. Despite being a many-faceted and expanding discipline with ill-defined boundaries, statistical physics in its modern form has an irreplaceable position in the teaching of physics; it unifies traditionally separate sciences such as thermodynamics, electromagnetism, chemistry, and mechanics. Last and not least its numerous applications cover a wide range of macroscopic phenomena and, with continuous improvements in the mathematical methods available, its quantitative predictions become increasingly accurate. The growth of micro-electronics and of physical metallurgy indicates that in future one may hope to "design" materials with specific properties starting from first principles. Statistical physics is thus on the way to becoming one of the most useful of the engineering sciences, sufficient justification for the growth of its study at the Ecole Polytechnique.

This book has evolved from courses given between 1973 and 1982 in the above spirit. The contents and teaching methods have developed considerably during that period; some subjects were occasionally omitted or were introduced as optional extras, intended only for a section of the class. Most of the major threads of statistical mechanics were reviewed, either in the course itself, or in associated problems. Nevertheless, on account of their difficulty, it has been possible to treat some important topics, such as irreversible processes or phase transitions, only partially, and to mention some of them, like superconductivity, only in passing. The published text contains all the material covered, suitably supplemented and arranged. It has been organized as a basic text, explaining first the principles and methods of statistical mechanics and then using them to explain the properties of various systems and states of matter. The work is systematic in its design, but tutorial in its approach; it is intended both as an introductory text to statistical physics and thermodynamics and as a reference book to be used for further applications.

Even though it goes far beyond the actual lecture programme, this is the text circulated to the students. Its style being half way between a didactic manual and a reference book, it is intended to lead the student progressively away from course work to more individual study on chosen topics, involving a degree of literature research. Typographically, it is designed to ease this transition and to help the first-time reader by highlighting important parts through italics, by framing the most important formulae, by numbering and marking sections to enable selective study, by putting items, supplementary to the main course, and historical notes in small type, and by giving summaries at the end of each chapter so that the students can check whether they have assimilated the basic ideas. However, the very structure of the book departs from the order followed in the lecture course, which, in fact, has changed from year to year; this is the reason why some exercises involve concepts introduced in later chapters.

Classes at the Ecole Polytechnique tend to be mixed, different students having different goals, and some compromises have been necessary. It is useful to take advantage of the mathematical leanings of the students, as they like an approach proceeding from the general to the particular, but it is equally essential that they are taught the opposite approach, the only one leading to scientific progress. The first chapter echoes this sentiment in using a specific example in order to introduce inductively some general ideas; it is studied at the Ecole as course work in parallel with the ensuing chapters, which provide a solid deductive presentation of the basis of equilibrium statistical mechanics. Courses at the Ecole Polytechnique are intended to be complemented later on by specialized further studies. When we discuss applications we have therefore laid emphasis on the more fundamental aspects and we have primarily selected problems which can be completely solved by students. However, we have also sought to satisfy the curiosity of those interested in more difficult questions with major scientific or technological impli-

cations, which are only qualitatively discussed. Conscious of the coherence of the book as a whole, we have tried to maintain a balance between rigour and simplicity, theory and fact, general methods and specific techniques. Finally, we have tried to keep the introductory approach of the book in line with modern ideas. These are based upon quantum statistical mechanics, richer in applications and conceptually simpler than its classical counterpart, which is commonly the first topic taught, upon the entropy as a measure of information missing because of the probabilistic nature of our description, and upon conservation laws.

Capable of being read at various different levels, and answering to a variety of needs, this course should be useful also outside the Ecole Polytechnique. Given its introductory nature and its many different purposes, it is not intended as a substitute for the more advanced and comprehensive established texts. Nevertheless, the latter are usually not easy reading for beginners on account of their complexity or because they are aimed at particular applications and techniques, or because they are aimed at an English-speaking audience. The ever increasing part played by statistical physics in the scientific background essential for engineers, researchers, and teachers necessitates its dissemination among as large an audience as possible. It is hoped that the present book will contribute to this end. It could be used as early as the end of undergraduate studies at a university, although parts are at the graduate level. It is equally well geared to the needs of engineering students who require a scientific foundation course as a passport to more specialized studies. It should also help all potential users of statistical physics to learn the ideas and skills involved. Finally, it is hoped that it will interest readers who wish to explore an insufficiently known field in which immense scientific advances have been made, and to become aware of the modern understanding of properties of matter at the macroscopic level.

Physics teaching at the Ecole Polytechnique is a team effort. This book owes much to those who year after year worked with me on the statistical mechanics module: Henri Alloul, Jean Badier, Louis Behr, Maurice Bernard, Michel Bloch, Edouard Brézin, Jean-Noël Chazalviel, Henri Doucet, Georges Durand, Bernard Equer, Edouard Fabre, Vincent Gillet, Claudine Hermann, Jean Iliopoulos, Claude Itzykson, Daniel Kaplan, Michel Lafon, Georges Lampel, Jean Lascoux, Pierre Laurès, Guy Laval, Roland Omnès, René Pellat, Yves Pomeau, Yves Quéré, Pierre Rivet, Bernard Sapoval, Jacques Schmitt, Roland Sénéor, Ionel Solomon, Jean-Claude Tolédano, and Gérard Toulouse, as well as our colleagues Marcel Fétizon, Henri-Pierre Gervais, and Jean-Claude Guy from the Chemistry Department. I have had the greatest pleasure in working with them in a warm and friendly environment, and I think they will excuse me if I do not describe their individual contributions down the years. Their enthusiasm has certainly rubbed off onto the students with whom they have been in contact. Several of them have given excellent lectures on special topics for which there has regrettably not been room in this book; others have raised the curiosity of students with the help of in-

genious and instructive experiments demonstrated in the lecture theatre or classroom. This book has profited from the attention of numerous members of the teaching staff who have corrected mistakes, simplified the presentation, and thought up many of the exercises to be found at the end of the chapters. Some have had the thankless task of redrafting and correcting examination problems; the most recent of those have been incorporated in the second volume. To all of them I express my heartfelt thanks. I am especially indebted to Ionel Solomon: it is thanks to his energy and dedication that the form and content of the course managed to evolve sufficiently rapidly to keep the students in contact with live issues. On the practical side, the typing was done by Mmes Blanchard, Bouly, Briant, Distinguin, Grognet, and Lécuyer from the Ecole's printing workshop, efficiently managed by M. Deyme. I am indebted to them for their competent and patient handling of a job which was hampered by the complexity of the manuscript and by numerous alterations in the text. Indeed, it is their typescript which, with some adjustments by the publisher, was reproduced for the finished work. The demanding and essential task of proofreading was performed by Madeleine Porneuf from our group at Saclay. I also thank the staffs of the Commissariat à l'Energie Atomique and of the Ecole Polytechnique, in particular, MM. Grison, Giraud, Servières, and Teillac for having facilitated publication. Finally, I must not forget the many students who have helped to improve my lectures by their criticism, questions, and careful reading, and from whose interest I have derived much encouragement.

Roger Balian

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