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Thermal Physics

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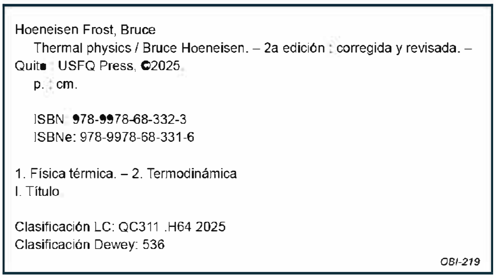

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PREFACE

Thermal physics is a beautiful, subtle and difficult subject. To gain an understanding of thermal physics it is convenient to treat problems with varying degrees of sophistication, and with several complementary approaches. Our emphasis is to illustrate the principles with specific problems, rather than rigorous formalism. Problems are solved from the points of view of kinetic theory (Chapters 1, 7 and 8), statistical mechanics of closed systems (Chapter 2), statistical mechanics of open systems (Chapters 3 and 4), and thermodynamics (Chapter 6). These approaches sometimes lead to the same results, and sometimes lead to results that vary in generality, rigor and predictive power. It is fascinating to discover so many relationships among such different approaches to thermal physics. The relation between entropy and information is remarkable. Applications include superfluidity, semiconductors, cosmology and astrophysics. We have made an effort to make the chapters self contained. These criteria require some repetition which we believe is pedagogical. Handy integrals and formulas are collected in the appendices. A few problems that complement the text are also included.

It is assumed that the reader has some familiarity with calculus, combinatorics and probability theory. We use concepts of modern physics such as "quantum state" and "Planck law". Exposure to modern physics is therefore assumed.

The text contains more material than what can usually be covered in a single term. Chapters may be chosen for an upper undergraduate or a first year graduate course. We hope that the text will also be useful in the personal library of scientists and engineers.

A note on notation. We omit the Boltzmann constant k in all chapters except the first.

This is a text, not a research report. I claim no originality on any of the material covered (except perhaps on parts of the sections on hadron collisions and on dark matter). A brief account of the development of thermal physics is given in Section 1.1. Some problems and data have been adapted from several sources, in particular the excellent texts by Charles Kittel, Landau and Lifshitz, and the awe inspiring Feynman Lectures on Physics.

Thanks are due to Dr. Carlos Montufar and Dr. Santiago Gangotena for reviewing the manuscript. I also thank the help of friends and students in writing and checking formulas, drawing figures and assisting with the computer, in particular Neidy Martén, Marco Guevara, Patricio Larrea and David Cárdenas.

*Sections with a star are relatively difficult and are not required to understand subsequent material. These sections may be omitted on a first reading.

Contents

Chapter 1. INTRODUCTION TO KINETIC THEORY

In this introductory chapter we consider the kinetic theory of gases from a historical point of view. The history of the physics of gases is interesting since it lead to the first reliable determination of the size of atoms, and the discrepancies between the classical theory and experiment contributed to the birth of quantum mechanics at the turn of the century.

1.1 History

With the benefit of hindsight let us briefly recall the main developments that lead to the kinetic theory of gases in its present form. At the time of Galileo (1564–1642) it was well known that water will not raise more than 34 feet when sucked by a pump. Torricelli (1608–1647) filled a glass tube with mercury, put his finger on the end, and inverted the tube into a dish of mercury. The mercury in the glass tube raised about 30 inches above the level of the mercury in the dish. These observations lead eventually to the concept of atmospheric pressure.

Richard Townley and Henry Power discovered in 1653 that the pressure P of a gas varies in proportion to the inverse of its volume V when it is compressed at constant temperature (for example room temperature). The law

$$PV = \text{constant} \qquad \text{at constant temperature}$$

was verified and established by Robert Boyle in 1662 and is generally known as Boyle's law.

Daniel Bernoulli proposed in 1738 the first quantitative kinetic theory. In particular Bernoulli showed that the pressure of the gas is proportional to the square of the molecular velocity v:

$$PV = \frac{1}{3} N M v^2$$

However the equation derived by Bernoulli remained mostly forgotten until 1820 when it was re-derived by Herapath!

The law of thermal expansion of gases in its modern form was established at the end of the 18th century by J.A.C. Charles and J.L. Gay-Lussac:

$$P = C\,(T + T_0) \qquad \text{at constant volume}$$

or

$$V = C'\,(T + T_0) \qquad \text{at constant pressure}$$

where C, C' and T_0 are constants. The universality of T_0 for different gases suggests that there is a lowest temperature $T = -T_0$ for which the pressure or volume drops to zero, as suggested a century earlier by Guillaume Amontons. It is then natural to define $T + T_0$ as an absolute temperature which we will henceforth denote by T.

In 1845 J.J. Waterson gave the first statement of the **equipartition theorem**: the average value of the kinetic energy $\frac{1}{2}Mv^2$ is the same for different types of molecules in a mixture of gases. Another important contribution to the kinetic theory was made by Rudolph Clausius who introduced the concept of **mean free path**.

The modern form of the kinetic theory is a direct outgrowth of the work of James Clerk Maxwell (≈1860) and Ludwig Boltzmann (≈1870).

In 1865 Josef Loschmidt made the first convincing calculation of the size of molecules using the mean free path obtained from viscosity measurements.

The development of the kinetic theory outlined above may suggest that the theory advanced in a regular fashion. Actually the development of the physics of gases was quite erratic and full of confusion. To stress this point it is sufficient to mention here that two key concepts of the