

# Preface

During the last years of the nineteenth century, the development of new techniques and the refinement of measuring apparatuses provided an abundance of new data whose interpretation implied deep changes in the formulation of physical laws and in the development of new phenomenology.

Several experimental results lead to the birth of the *new physics*. A brief list of the most important experiments must contain those performed by H. Hertz about the photoelectric effect, the measurement of the distribution in frequency of the radiation emitted by an ideal oven (the so-called *black body* radiation), the measurement of specific heats at low temperatures, which showed violations of the Dulong–Petit law and contradicted the general applicability of the equipartition of energy. Furthermore, we have to mention the discovery of the electron by J.J. Thomson in 1897, A. Michelson and E. Morley’s experiments in 1887, showing that the speed of light is independent of the reference frame, and the detection of line spectra in atomic radiation.

From a theoretical point of view, one of the main themes pushing for new physics was the failure in identifying the ether, i.e., the medium propagating electromagnetic waves, and the consequent Einstein–Lorentz interpretation of the Galilean *relativity principle*, which states the equivalence among all reference frames having a linear uniform motion with respect to fixed stars.

In the light of the electromagnetic interpretation of radiation, of the discovery of the electron and of Rutherford’s studies about atomic structure, the anomaly in black body radiation and the particular line structure of atomic spectra lead to the formulation of *quantum theory*, to the birth of *atomic physics* and, strictly related to that, to the quantum formulation of the *statistical theory of matter*.

*Modern Physics*, which is the subject of these notes, is well distinct from *Classical Physics*, developed during the XIX century, and from *Contemporary Physics*, which was started during the Thirties (of XX century) and deals with the nature of *Fundamental Interactions* and with the physics of matter under extreme conditions. The aim of this introduction to Modern Physics is that of presenting a quantitative, even if necessarily also concise and schematic, account of the main

features of *Special Relativity*, of *Quantum Physics* and of its application to the *Statistical Theory of Matter*. In usual textbooks these three subjects are presented together only at an introductory and descriptive level, while analytic presentations can be found in distinct volumes, also in view of examining quite complex technical aspects. This state of things can be problematic from the educational point of view.

Indeed, while the need for presenting the three topics together clearly follows from their strict interrelations (think for instance of the role played by special relativity in the hypothesis of de Broglie's waves or of that of statistical physics in the hypothesis of energy quantization), it is also clear that this unitary presentation must necessarily be supplied with enough analytic tools so as to allow a full understanding of the contents and of the consequences of the new theories.

On the other hand, since the present text is aimed to be introductory, the obvious constraints on its length and on its prerequisites must be properly taken into account: it is not possible to write an introductory encyclopedia. That imposes a selection of the topics which are most qualified from the point of view of the physical content/mathematical formalism ratio.

In the context of special relativity, after recalling the classical analysis of the ether hypothesis, we introduce Lorentz's transformations and their action on Minkowski space-time, discussing the main consequences of the new interpretation of space and time. Then we introduce the idea of covariant formulation of the laws of nature, considering in particular the new formulation of energy-momentum conservation. Finally, we discuss the covariant formulation of electrodynamics and its consequences on field transformation laws and Doppler effect.

Regarding Schrödinger quantum mechanics, after presenting with some care the origin of the wave equation and the nature of the wave function together with its main implications, like *Heisenberg's Uncertainty Principle*, we have emphasized its qualitative consequences on energy levels. The main analysis begins with one-dimensional problems, where we have examined the origin of discrete energy levels and of band spectra as well as the tunnel effect. Extensions to more than one dimension have been limited to very simple examples in which the Schrödinger equation is easily separable, like the case of central forces. Among the simplest separable cases we discuss the three-dimensional harmonic oscillator and the cubic well with completely reflecting walls, which are however among the most useful systems for their applications to statistical physics. In a further section we have discussed a general solution to the three-dimensional motion in a central potential based on the harmonic homogeneous polynomials in the Cartesian particle coordinates. This method, which simplifies the standard approach based on the analysis of the Schrödinger equation in spherical coordinates, is shown to be perfectly equivalent to the standard one. It is applied in particular to the study of bound states in spherical wells, of the hydrogen atom spectrum, of that of the isotropic harmonic oscillator and, finally, of elastic scattering.

Going to the last subject, which we have discussed, as usual, on the basis of Gibbs construction of the statistical ensemble and of the related distribution, we have chosen to consider those cases which are more meaningful from the point of view of quantum effects, like degenerate gases, focusing in particular on

distribution laws and on the equation of state. In order to put into evidence the strict connection between the statistical results and thermodynamics, we have extended Gibbs construction to the classical gases, considering also the real gas case. We have then presented the statistical meaning of entropy and of the thermodynamic potentials, concluding the chapter with the discussion of the phase transition in the van der Waals real gas model.

In order to accomplish the aim of writing a text which is introductory and analytic at the same time, the inclusion of significant collections of problems associated with each chapter has been essential. We have possibly tried to avoid mixing problems with text complements; however, moving some relevant applications to the exercise section has the obvious advantage of streamlining the general presentation. Therefore in a few cases we have chosen to insert relatively long exercises, taking the risk of dissuading the average student from trying to give an answer before looking at the suggested solution scheme. On the other hand, we have tried to limit the number of those (however necessary) exercises involving a mere analysis of the order of magnitudes of the physical effects under consideration. The resulting picture, regarding problems, should consist of a sufficiently wide series of applications of the theory, being simple but technically nontrivial at the same time: we hope that the reader will feel that this result has been achieved.

Going to the chapter organization, the one about *Special Relativity* is divided into five sections, dealing respectively with Lorentz transformations, with the covariant form of Maxwell's equations, and with relativistic kinematics. The chapter on *Wave Mechanics* is made up of nine sections, going from an analysis of the photoelectric effect to the Schrödinger equation and from the potential barrier to the analysis of band spectra and to the Schrödinger equation in central potentials. Finally, the chapter on the *Statistical Theory of Matter* is divided into seven sections, going from Gibbs distribution, to the equation of state, to perfect quantum gases and to the classical real ones. The statistical results are interpreted in thermodynamical terms, introducing the thermodynamic potentials and giving a simple example of a phase transition.

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## Suggestion for Introductory Reading

- K. Krane: *Modern Physics*, 2nd edn (John Wiley, New York 1996)

## Physical Constants

- Speed of light in vacuum:  $c = 2.998 \times 10^8 \text{ m/s}$
- Planck's constant:  $h = 6.626 \times 10^{-34} \text{ J s} = 4.136 \times 10^{-15} \text{ eV s}$
- $\hbar \equiv h/2\pi = 1.055 \times 10^{-34} \text{ J s} = 6.582 \times 10^{-16} \text{ eV s}$
- Boltzmann's constant:  $k = 1.381 \times 10^{-23} \text{ J/}^\circ\text{K} = 8.617 \times 10^{-5} \text{ eV/}^\circ\text{K}$
- Electron charge:  $e = 1.602 \times 10^{-19} \text{ C}$
- Electron mass:  $m_e = 9.109 \times 10^{-31} \text{ Kg} = 0.5110 \text{ MeV}/c^2$
- Proton mass:  $m_p = 1.673 \times 10^{-27} \text{ Kg} = 0.9383 \text{ GeV}/c^2$
- Electric permittivity of free space:  $\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$
- Magnetic permeability of free space:  $\mu_0 = 4\pi \times 10^{-7} \text{ N/A}^2$

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