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PHYSICS OF THE ATOM

Wehr · Richards · Adair

THIRD EDITION

PHYSICS OF THE ATOM

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Preface

The third edition of *Physics of the Atom* is designed, as were the first two editions, to meet the modern need for a better understanding of the atomic age. It is an introduction suitable for any student with a background in college physics and mathematical competence at the level of calculus. Some parts of the book will be better appreciated by those with a knowledge of chemistry. This book is designed to be an extension of the introductory college physics course into the realm of atomic physics: It should give the student a proficiency in this field comparable to that he or she has in mechanics, heat, sound, light, and electricity.

The approach has been to deal with a logical series of topics leading to the practical conversion of mass-energy into kinetic energy. The development of modern physics is such a logical sequence of discoveries that we have had little difficulty in deciding what topics to include. The order of presentation is usually chronological. Mechanics can be presented in a from-simple-to-complex manner because mechanics is an organization of observations with which most of us are familiar. Atomic physics, on the other hand, involves concepts that are quite foreign to general experience, and it is both helpful and stimulating for the student to feel that he is growing in understanding as others grew before him. This book capitalizes on the fact that the story has a plot.

This plot is developed as simply and directly as possible. It is difficult to know how a new idea comes into being. Even the person who creates a new idea cannot fully describe that moment when the light dawned. But we, as "Monday-morning quarterbacks," can state the problem, present the relevant information, and, we hope, make the idea that originally required genius appear obvious. With informal discussion and many analogies the student may be led to understand new and difficult concepts. Although any serious student of atomic physics must go on to a more elaborate mathematical treatment, we feel that even at this level the most convincing argument is a careful mathematical development and the presentation of original data. We have not hesitated to use calculus where it is appropriate, and we have clearly indicated the weakness of our argument on those few occasions when the argument is indeed weak.

Many who use this book will not have access to a laboratory. Thus we have described a few projects that most students can do for themselves.

The book is designed for a one-term course in either a liberal arts or an engineering curriculum. Basic physics is basic physics whether the student is motivated by curiosity or possible application. Our preference for the SI system of units is due to the fact that this system is rapidly becoming *the* system in engineering and physics, and because this system includes the units all scientists use to measure electrical quantities. Except in equations that include units peculiar to our subject, like the electron volt, our equations are valid in any consistent rationalized system of units.

The references at the end of each chapter include sources which have been helpful to us in preparing the text and to which students may *profitably* refer. Many of our references to original articles are to reprints of source materials. Our thought is that these compilations and translations are more convenient for students to use. In some cases we have made remarks designed to facilitate the student's choice of reference reading.

A few of the problems at the end of each chapter may involve mere substitution of numbers into formulas. In these cases the purpose is to give the student a feeling for the magnitudes of atomic quantities. Most of the problems, however, require thoughtful analysis. Some are stated in general terms instead of numbers. The order of the problems is the same as the order in which the theory is developed. Some of the problems in the earlier editions have been retained without change, others have been rewritten, and over 100 new problems have been added, bringing the total to 457.

Appendix 1 is a chronology of discoveries important to the atomic view of nature. It was impossible to formulate any sharp criterion for selecting the items to be included, and so, in general, we have taken a broad view. The purpose of this chronology is to convey a sense of the development of a natural science. We think it will also serve to stress the international character of scientific achievement and to emphasize that many of the great scientists did their first important work early in life.

The principal changes in the second edition of this book were the rewriting of the chapters on waves and particles and the addition of a new chapter on matter waves, both prepared by I. A. Miller of Drexel University. In the third edition the principal changes are the addition of numerous new sections—for example, those on laser applications, stellar aberration, general relativity, Miller indices, integrated circuits, superconductivity, the Josephson effect, and conservation of parity. Significant revisions have been made in the sections on blackbody radiation, radiation detectors, reactors, fusion, and elementary particles.

This textbook is dedicated to the students who will use it and to former students whose questions, comments, and reactions have largely determined our presentation. For the first edition, we gratefully acknowledge the assistance of Elliot H. Weinberg of North Dakota State College. We also wish to thank our colleagues at Drexel University, especially Henry S. C. Chen, Dennis H. Le Croissette, and Irvin A. Miller, for their constructive suggestions. For assistance with the second edition we wish to thank A. Capecelatro, D. E. Charlton, E. M. Corson, T. T. Crow, E. I. Howell, A. P. Joblin, G. E. Jones, P. Kaczmarczik, A. Meador, M. W. Minkler, T. J. Parmley, L. E. Peterson, D. J. Prowse, F. W. Sears, F. O. Wooten, and M. W. Zemansky. And for very useful comments about the third edition we are pleased to thank Gordon E. Jones of Mississippi State University, Richard Madey of Kent State University, Philip N. Parks of Michigan Technological University, Kenneth W. Rothe of Bowling Green State University, and R. A. Atneosen of Western Washington State College. In addition, we wish to thank Minnette Bilbo for the typing of the many preliminary drafts and the preparation of the final one.

This book is neither a treatise nor a survey. It is a textbook that bridges the gap between classical physics and the present frontiers of physical investigation.

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December 1977

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1 The Atomic View of Matter

1-1. INTRODUCTION

The ancient Greeks speculated about almost everything. Democritus, for example, theorized that not only matter but also the human soul consists of particles. His statements, made about twenty centuries before the advent of experimental science, can be regarded primarily as demonstrating the fertility of his imagination. Still, it would be a mistake to discredit Democritus completely, for although he was no student of atomic physics, he had characteristics that every student needs.

Because atomic physics is built from big ideas about very small things, its development often leads along paths that run counter to common sense. As we consider things and events that are orders of magnitude removed from everyday experience, the difficulty of understanding their nature increases. Our common sense enables us to understand the relationship between a brick and a house. Conceiving of the earth as round may involve a little uncommon sense, but for most people it presents no great difficulty. However, the relationship between water and a water molecule is more difficult. While we can see the earth, whether flat or round, we cannot see a water molecule even with the best of instruments. All of our information about single water molecules is of an indirect kind, yet it is a very unsophisticated chemist for whom the concept of a single water molecule is not a part of his or her common sense. As a person's knowledge expands, more and more facts assume the aspect of "common sense." Certain velocity relationships are common sense. To an observer in a moving car, the velocity of another moving car appears different than it does to an observer standing beside the highway. In fact, a very young child once observed when the car in which he was traveling was passed by another, "We are backing up from the car ahead." However, the statement made by Albert Einstein that the velocity of light is the same for all observers regardless of their own velocities is very uncommon sense. In a later chapter we will attempt to show that his statement is reasonable and can appropriately be incorporated into our common sense. The conflict between the earth's actual roundness and its apparent flatness is resolved conceptually, i.e., by imaginative understanding, with the realization that the earth is a very big sphere. Somewhat similarly, the apparent conflict between our statements about relative velocities is resolved conceptually with the realization that the velocity of light is a very large velocity. Democritus, who could propose an atomic theory in about 400 B.C., would have the courage and imagination to face the ideas that lie before us.

It is the business of philosophers to discuss the nature of reality. It is the business of physicists (once called natural philosophers) to discuss the nature of physical reality. Philosophy, therefore, includes all of physics and a lot more besides. It is natural, then, that physics should have a continuing influence on philosophy. As physical discovery is quickly put into engineering practice and made to bear on human physical environment, so it also affects the formulation of philosophical theory and bears directly on one's outlook and interpretation of life.

The old or classical physics of Newton was extraordinarily successful in dealing with events observed in his day. Using methods he developed, it is simple to equate the earth's gravitational force on the moon to the centripetal force and obtain verifiable relationships about the behavior of the moon. The same methods can be extended to orbits that cannot be regarded as circular. In fact, three observations of a new comet enable astronomers to foretell with great accuracy the entire future behavior of the comet. Given a certain amount of specific data known as initial or boundary conditions, classical Newtonian mechanics enables us to determine future events in a large number of situations. It is easy to move a step further and argue that what Newton has demonstrated to be true often, is true always, and that given sufficient initial data and boundary conditions, laws may be found which show every future event to be determined. The motion of a falling leaf or the fluctuations in the price of peaches may be very complex phenomena. It may require tremendous amounts of data and the application of very complicated laws that we do not yet understand to be able to make predictions in these cases. The important philosophical consequence of classical mechanics was not that every problem had been solved, but that a point of view had been established. It was felt that each new discovery would fall into the Newtonian mechanistic framework. Philosophical questions like the following became more pressing. Do we humans make decisions that alter the course of our lives or are we, like the bodies of the solar system, acting according to a set of inflexible laws and in accordance with a set of boundary conditions? Are we free or is our apparent ability to make decisions an illusion? Is everything we do beyond our responsibility, having been determined at the time of creation? Although mechanistic philosophy is rather repulsive when applied to ourselves, we nevertheless lean heavily upon it in interpreting things that go on about us. Indeed, the whole argument over whether human behavior is influenced more by heredity or environment is based on the assumption that human behavior is determined by some combination of the two.

To the extent that this mechanistic philosophy is based on classical physics, it is due for revision. Upon examination of events that are either very large or very small, we find that classical physics begins to fail. When a new theory or a modified theory has had to be applied in order to describe experimental observations, it has often resulted that the new theory is very different from classical physics. The method of attack, the mathematical techniques, and the form of the solution are often quite different. At one point we shall show that the observations of natural phenomena are inherently *uncertain*. It becomes evident, then, that if some circumstance had led to the development of atomic physics before classical physics, the influence of atomic physics on philosophy would have been against mechanism rather than for it.

Atomic physics has given us electronics and all that that word implies, including radio, radar, television, computers, etc. Atomic physics has given us nuclear energy. The new physics is as successful with submicroscopic events as classical physics was with large-scale events. But it may be that the most important benefits that can result from the study of atomic physics are philosophical rather than technical.

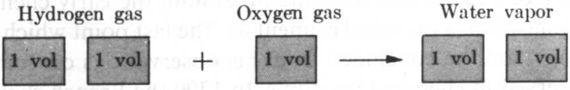
1-2. CHEMICAL EVIDENCE FOR THE ATOMIC VIEW OF MATTER

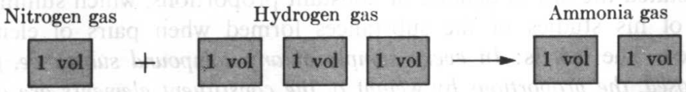
The speculations of Democritus and of the Epicurean school, whose philosophy was based on atomism, were not the generally accepted views of matter during the Middle Ages and the Renaissance. The prevailing concepts were those of Aristotle and the Stoic philosophers, who held that space, matter, and so on were continuous, and that all matter was one primordial stuff which was the habitat of four elementary principles—hotness, coldness, dryness, and wetness. Different materials differed in the degree of content of these principles. The hope of changing the amount of these principles in the various kinds of matter was the basis of alchemy. Not until the development of quantitative chemistry in the last half of the eighteenth century did the experimental evidence needed for evaluating the conflicting speculations about the constitution of matter begin to appear.

Antoine Lavoisier of France was outstanding among the early chemists. He evolved the present concept of a chemical element as "the last point which analysis is capable of reaching"; and he concluded from his observations on combustion that matter was conserved in chemical reactions. In 1799 the French chemist J. L. Proust stated the law of definite or constant proportions, which summed up the results of his studies of the substances formed when pairs of elements are combined. The law is: *In every sample of any compound substance, formed or decomposed, the proportions by weight of the constituent elements are always the same.* This statement actually defines chemical compounds, because it differentiates them from solutions, alloys, and other materials that do not have definite composition.

The principal credit for founding the modern atomic theory of matter goes to John Dalton, a teacher in Manchester, England. His concern with atoms seems to have originated with his speculations about the solubilities of gases in water and with his interest in meteorology, which led him to try to explain the fact that the atmosphere is a homogeneous mixture of gases. Eventually, he believed that an element is composed of atoms that are both *physically* and *chemically* identical, and that the atoms of different elements differ from one another. In a paper he read at a meeting of the Manchester Literary and Philosophical Society in 1803, Dalton gave the first indication of the quantitative aspect of his atomic theory. He said, “An enquiry into the relative weights of the ultimate particles of bodies is a subject, as far as I know, entirely new: I have lately been prosecuting this enquiry with remarkable success.” This was followed by his work on the composition of such gases as methane (CH_4), ethylene (C_2H_4), carbon monoxide (CO), carbon dioxide (CO_2), and others which led him to propose the law of multiple proportions in 1804. This law states: *If substance A combines with substance B in two or more ways, forming substances C and D, then if mass A is held constant, the masses of B in the various products will be related in proportions which are the ratios of small integers.* The only plausible interpretation of this law is that when elementary substances combine, they do so as discrete entities or atoms. Dalton emphasized the importance of relative weights of atoms to serve as a guide in obtaining the composition of other substances, and stressed that a chemical symbol means not only the element but also a fixed mass of that element. The introduction of the concept of atomic weights (strictly, atomic masses) was Dalton’s greatest contribution to the theory of chemistry, because it gave a precise quantitative basis to the older vague idea of atoms. This concept directed the attention of quantitative chemistry to the determination of the relative masses of atoms.

An important law pertaining to volumes of gases was announced by Gay-Lussac in 1808. He said that *if gas A combines with gas B to form gas C, all at the same temperature and pressure, then the ratios of the volumes of A, B, and C will all be ratios of simple integers.* Two examples of this law are (a) the combining of two volumes of hydrogen and one volume of oxygen to form two volumes of water vapor, and (b) the union of one volume of nitrogen and three volumes of hydrogen to produce two volumes of ammonia. The following are symbolic forms of these reactions:





It is obvious that Gay-Lussac’s law, like the law of multiple proportions, implies that the substances which participate in these reactions participate in discrete or corpuscular amounts. The ratio between the number of shoes worn to the number of people wearing them is almost an exact integer, namely two, showing that both people and shoes are discrete entities. The ratio of the number of tomatoes used per serving of tomato soup is quite a different kind of situation, and if the ratio is integral it is only by coincidence.

Gay-Lussac’s law supported the work of Dalton, but it also raised difficult questions about the composition of an element in the gaseous state. In the case of