INTRODUCTION TO ATOMIC *and* NUCLEAR PHYSICS

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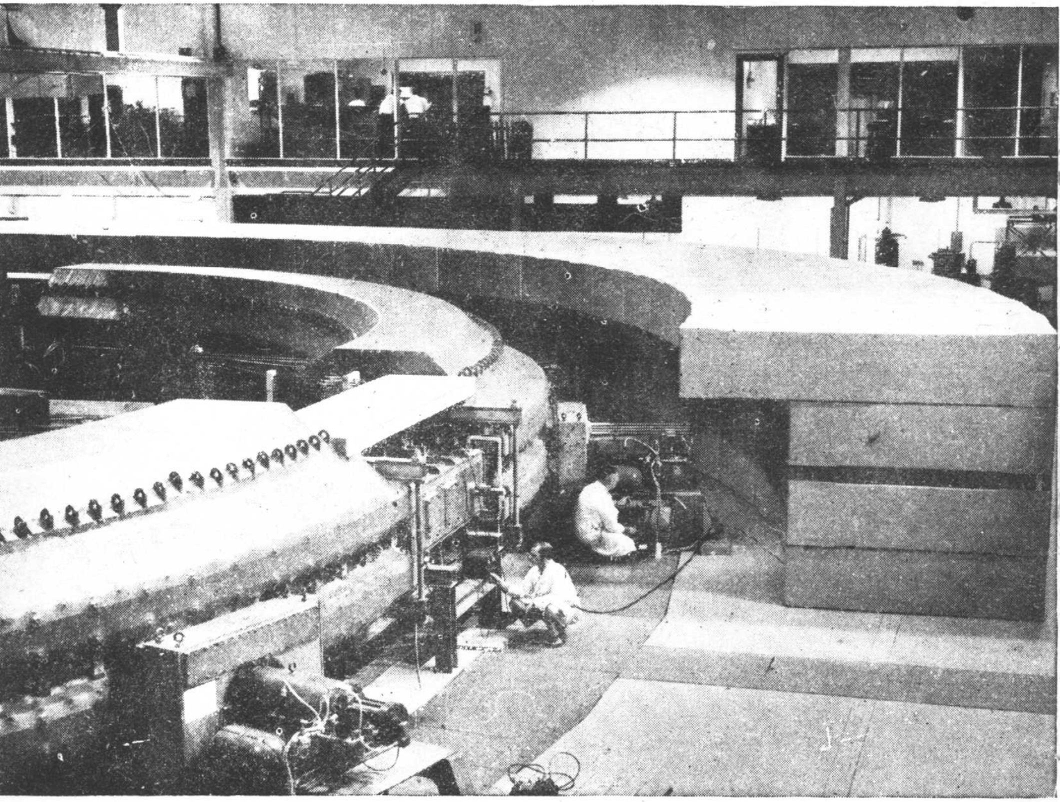

View of the Cosmotron and Its Shielding

(Courtesy of the Brookhaven National Laboratory)

Preface

The first edition of this book, which appeared in 1939 and which was entitled *Introduction to Atomic Physics,* grew out of a course on Modern Physics I had been giving for several years previous. The friendly reception accorded the first edition prompted author and publisher to bring out a revised edition in 1946. The major changes in the second edition were made in the section on the nucleus; other material was, of course, updated, and various improvements and refinements were made at the suggestion of colleagues and critics.

The new title of the third edition, *Introduction to Atomic and Nuclear Physics,* epitomizes the essential difference between this edition and the earlier ones. Nuclear physics is, of course, a part of atomic physics; however, because of the great advances made in this branch of the subject in the past twenty years, beginning with the discoveries of the neutron, of deuterium, and of induced radioactivity nuclear physics has come to be considered as a separate branch of physics. The term atomic physics is now considered by physicists to be concerned mostly with those properties of the atom which depend upon their extranuclear structure. However, the latter is determined by some of the nuclear properties, particularly charge, mass, and spin. Hence, in the development of this book, the foundations are laid in Part 1 for the study of both the nuclear and the extranuclear parts of the atom. These include a brief review of the fundamentals of electricity and magnetism, a description of the methods of determining the fundamental constants of atomic and nuclear physics, the experiments which led to the development of the concept of the nuclear atom, and the fundamental experiments showing the wave and particle aspects of both electromagnetic radiation and matter. Using this foundation, the subject of the extranuclear structure of the atom is treated in Part 2, and that of nuclear physics in Part 3. Approximately equal space in this book is devoted to each of the fields normally encompassed by the respective names of atomic and nuclear physics.

The plan and spirit of the original book have not undergone any essential changes. The text is still intended for use at the undergraduate level with students who have had a one-year physics course and a course in the calculus. Part 1, Foundations of Atomic and Nuclear Physics, and Part 2, The Extranuclear Structure of the Atom, have undergone minor revisions since the second edition, mostly to improve them from a pedagogical standpoint and to bring the subject matter up to date. Some of the longer chapters have been subdivided, some new topics as well as diagrams and photographs have been added, and additional problems and references included.

The major change is in Part 3, Nuclear Physics. Chapter 10, on natural radioactivity, has been brought up to date, and several new sections have been added to it. Chapter 11 describes a large variety of experiments on the disintegration of nuclei, and Chapter 12 discusses, in an elementary way, some of the theory of these nuclear processes. Chapter 13, Nuclear Fission, is devoted almost entirely to the physical aspects of fission rather than to the technical aspects. Chapter 14, Elementary Particles, is devoted mostly to the newer particles, the mesons and V-particles, with a brief discussion of the older elementary particles. Chapter 15 discusses the production of new elements and isotopes. Chapter 16 contains a description of the different types of particle accelerators which are used in atomic and nuclear physics. Part 3 contains many new diagrams and photographs as well as a large number of suitable problems.

Throughout the preparation of the various versions of this text I have received invaluable assistance from my colleagues, from teachers who have used the book in one or more editions, and from physicists who have read the manuscripts in whole or in part. I should, therefore, like to extend my sincere thanks to the following: Professor E. F. Barker, University of Michigan; Dr. Dixon Callihan, Oak Ridge National Laboratory; Professor Joseph H. Dexter, College of the City of New York; Mr. H. H. Goldsmith, late of the College of the City of New York; Professor J. M. B. Kellogg, Los Alamos Scientific Laboratory; Professor Paul Kirkpatrick, Stanford University; Dr. Sidney Millman, Bell Telephone Laboratories; Professor Hans Mueller, Massachusetts Institute of Technology; Dr. Edson R. Peck, Northwestern University; Dr. John R. Platt, University of Chicago; Professor Robert L. Weber, The Pennsylvania State University; Professor Lawrence A. Wills, College of the City of New York; Professor Hugh C. Wolfe, Cooper Union; Professor Mark W. Zemansky, College of the City of New York; Dr. Walter H. Zinn, Argonne National Laboratory.

Further, in the preparation of the third edition I have received invaluable help from many physicists in the form of photographs, graphs, and diagrams. These are acknowledged at the appropriate places in the text. In particular, I wish to thank Dr. Maurice M. Shapiro of the Naval Research Laboratory both for supplying me with a large number of photographs and for several helpful discussions on the subject of mesons. I also wish to thank Dr. Charlotte E. Moore of the National Bureau of Standards for supplying me with a corrected list of the first ionization potentials of the elements, and Professor K. B. Newbound of the University of Alberta for his list of problems in nuclear physics, some of which have been incorporated in the text.

I am deeply grateful to Professor Bernard T. Feld of Massachusetts Institute of Technology and to Professor R. L. Sproull of Cornell University, who read the original manuscript of the third edition, for their many valuable criticisms and suggestions, most of which have been incorporated in the book. I also wish to thank my colleague, Professor Harry Soodak, for having read Part 3 and in particular for his many valuable suggestions for Chapter 13 on nuclear fission, and Professor Leo Lederman of Columbia University for having read Chapter 14 on elementary particles and for his many valuable suggestions on the subject of mesons.

Finally, I wish to express my thanks and appreciation to my wife, Ray K. Semat, for typing the manuscripts and for the many other chores involved in the preparation of all three editions.

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June, 1954

H. S.

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part 1

FOUNDATIONS of ATOMIC and NUCLEAR PHYSICS

chapter 1

Elements of Electricity and Magnetism

1-1. Introduction

The decade from 1895 to 1905 may be termed the beginning of modern physics. During this period, J. J. Thomson succeeded in demonstrating the existence of the electron, a fundamental unit of negative electricity having very small mass. Becquerel discovered the phenomenon of natural radioactivity and Roentgen discovered x-rays. To these discoveries must be added the bold hypothesis put forth by Planck, that radiant energy, in its interaction with matter, behaves as though it consists of corpuscles or quanta of energy. This led to the development of the quantum theory of radiation and ultimately to quantum mechanics. It was also during this period that Einstein re-examined the fundamental concepts of physics and was led to the development of the special theory of relativity.

It is the aim of this book to present the important experimental data upon which are based our present ideas of the structure of the atom. An atom is to be regarded not as a static structure composed of particles in fixed positions, but rather as a dynamic structure changing in response to outside agencies, affecting them and, in turn, being affected by them. It is by examining the phenomena that occur during these changes that we get our information concerning the structure of the atom as well as an insight into the nature of those quantities which produce or are the result of these changes.

Accumulation of experimental data, particularly from the study of electrochemistry and the discharge of electricity through gases, indicates clearly that the atom is essentially electrical in nature. It will therefore be of value to discuss briefly those fundamental concepts of electricity and magnetism which have been found essential in studying the structure of the atom.

1-2. Coulomb's Law of Force between Electric Charges

If a glass rod is rubbed with a piece of silk, both the glass and the silk become electrified. When two glass rods which have been rubbed with silk are placed near each other. a force of repulsion will be found to exist between them. In a similar manner, if two rubber rods which have been rubbed with wool or cat's fur are placed near each other, there will be a force of repulsion between them. But if one of these rubber rods is brought near one of the electrified glass rods, a force of attraction is found to exist between them. All other electrified bodies can be compared with such glass and rubber rods. *Those electrified bodies which repel the charged glass rod are said to be positively charged or charged with positive electricity, while those electrified bodies which repel the charged rubber rod are said to be negatively charged or charged with negative electricity.* This arbitrary sign convention is adhered to throughout the realm of physics including the atomic domain. The ultimate determination of the sign of any electric charge must rest on a comparison with the charge on a glass rod which has been rubbed with silk or that on a rubber rod which has been rubbed with wool.

Coulomb (1789) made a study of the quantitative law of force between charged bodies. He found that the force between two charged bodies, whose dimensions are small in comparison with the distance between them, is given by

$$\boxed{F = \frac{q_1 q_2}{kr^2},} \tag{1}$$

where q_1 is the magnitude of the electric charge on one body, q_2 the magnitude of the charge on the second body, and r is the distance between them. The force F between the two charges also depends upon the nature of the medium between them; this is expressed by the factor k, called the *dielectric constant*, or the *specific inductive capacity* of the medium. The numerical value of k depends not only upon the nature of the medium but also upon the system of units used in expressing the other quantities in equation (1). In the cgs *electrostatic system of units*, k is set equal to unity when the charges are placed in a vacuum, F is measured in dynes, and r in centimeters. The charge q is then said to be expressed in electrostatic units (esu) of charge. The definition of a unit charge now follows directly from equation (1): *an electrostatic unit charge (1 esu) is one which, when placed in a vacuum one centimeter away from a like equal charge, will repel it with a force of one dyne.* The electrostatic unit of charge is sometimes called the *statcoulomb*. The electrostatic unit of charge is very small; hence, in the practical system of electrical units, a much larger charge is taken as the unit and is called a *coulomb*. A coulomb is equivalent to 3×10^9 esu of charge.

In the cgs electrostatic system of units defined above, the dielectric constant k is a pure numerical constant. For nonconductors or insulators, k is generally greater than unity.

1-3. Intensity of the Electric Field

The fact that a charged body will experience a force when placed at any point in the neighborhood of another body containing a charge Q suggests the idea that an *electric field* exists in the space around the charge Q. This electric field may be explored by placing a very small positive charge q at different points and measuring the force F experienced by it at each point. The *intensity of the electric field* E at any point P is defined as the ratio of this force F to the magnitude of the small positive charge q placed at this point, that is,

$$\boxed{E = \frac{F}{q}\cdot} \tag{2}$$

The test charge q must be sufficiently small so that the electric field is not materially altered by the introduction of this test charge. If F is measured in dynes and q in esu of charge, then E is expressed in dynes per esu of charge.

The intensity of the electric field E at any point is a vector quantity whose direction is that of the force experienced by a *positive* charge placed at that point. A negative charge placed in an electric field will experience a force whose direction is opposite to that of the electric field.

The intensity of the electric field can be evaluated mathematically in many cases. For example, the intensity of the electric field in the space around a point charge Q can be found by imagining a small positive charge q placed at any point P a distance r from the point charge Q. The force F experienced by this positive charge q is, from Coulomb's law,

$$F = \frac{Qq}{kr^2}\cdot \tag{3}$$

Substituting this value of F in equation (2), we get

$$\boxed{E = \frac{Q}{kr^2}} \tag{4}$$

for the intensity of the electric field E at a distance r from the charge Q. In the cgs electrostatic system of units, E is expressed in dynes per esu of charge, or dynes per statcoulomb.

There is a convenient method for mapping the electric field in any region of space to show at a glance its magnitude and direction. If the intensity of the electric field is known at any point, we can imagine a unit area drawn perpendicular to the direction of the electric field at this point and a sufficient number of lines drawn perpendicularly through this unit area so that the number of lines per unit area will represent the magnitude of the intensity of the electric field at this point, and the direction of these lines will represent the direction of this electric field. For example, the electric field around a point charge Q is radial, as shown in Figure 1-1. It can be shown that if one line of force per square centimeter is to represent an intensity of one dyne per esu of charge, then $4\pi Q$ lines will have to be drawn radiating from the point charge Q. If the electric field is uniform throughout a given region of space, that is, if the intensity of the electric field has the same value throughout this region, then it would be represented by a series of parallel, equally spaced lines as shown in Figure 1-2.

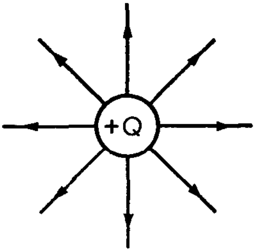

FIG. 1-1. Radial electric field around a small charge.

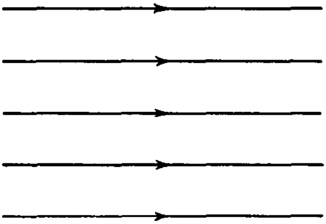

FIG. 1-2. A uniform electric field.

1-4. Potential Difference; Potential

A charge q situated at any point in an electric field will experience a force $F = Eq$ where E is the electric field intensity at that point. If this charge is moved from any point A to any other point B, in general work will have to be done in moving it against the forces of the electric field. The *difference of potential* V between A and B is defined as *the ratio of the work done* W *to the positive charge* q *that is moved from* A *to* B, thus

$$\boxed{V = \frac{W}{q}.} \tag{5}$$

It follows directly from the principle of conservation of energy that the difference of potential between two points in an electrostatic field is independent of the path traversed in going from A to B.

In the es system of units, the work W is expressed in ergs, and the charge q in es units of charge or statcoulombs. Hence the difference of potential V will be expressed in ergs per esu of charge. This is sometimes called a *statvolt.* In the practical system of units, W is expressed in joules and q in coulombs; V in this system is expressed in volts. Thus

$$1 \text{ volt} = 1 \text{ joule/coulomb}.$$

Since

$$1 \text{ joule} = 10^7 \text{ ergs}$$

and

$$1 \text{ coul} = 3 \times 10^9 \text{ statcoulombs},$$

$$300 \text{ volts} = 1 \text{ statvolt}.$$

If point A is taken as the zero level of potential, then the difference of potential between A and B is also the *potential of point B.* In practice, the ground is taken as the zero level of potential; the potential of any point is then its difference of potential with respect to ground potential. The potential of a point may be either positive or negative, since V is defined in terms of the work done in moving a positive charge from one point to another.

Of particular interest is the evaluation of the potential at a point A in the neighborhood of a positive charge Q. The electric field intensity E at a distance r from Q is, from equation (4),

$$E = \frac{Q}{kr^2}\cdot \tag{4}$$

If a small positive charge q is moved through a distance dr against the forces of the electric field, the work done per unit charge, which is the difference of potential dV, is, from equation (5),

$$dV = \frac{dW}{q},$$

and since

$$dW = -Fdr,$$

$$dV = \frac{-F}{q}dr = -Edr.$$

Substituting the value of E from equation (4),

we get

$$dV = -\frac{Q}{kr^2}dr\,.$$

Let us take a point at infinity as our zero level of potential and imagine the small charge q brought from infinity to point A at a distance a from charge Q. The potential at A is then

$$V_A = -\frac{Q}{k}\int_{\infty}^{a}\frac{dr}{r^2},$$

from which

$$\boxed{V_A = \frac{Q}{ka}.} \tag{6}$$

If we were to determine the potential at any other point B at a distance b from charge Q in a similar manner, we would get

$$V_B = \frac{Q}{kb}.$$

The difference of potential V between points A and B is

$$V = V_B - V_A$$

so that

$$\boxed{V = \frac{1}{k}\left(\frac{Q}{b} - \frac{Q}{a}\right).} \tag{7}$$

If the space around the charge Q is a vacuum, then $k = 1$ in the cgs electrostatic system of units and equation (7) becomes

$$\boxed{V = \frac{Q}{b} - \frac{Q}{a}.} \tag{7a}$$

The work done in bringing a charge q to point A where the potential is V_A is, from the definition of potential, simply

$$W = V_A q.$$

Using the value of V_A from equation (6) yields

$$\boxed{W = \frac{Qq}{ka}} \tag{8}$$

for the work done in bringing two charges Q and q to within a distance a of each other. This work produces a *change in the electrostatic potential energy of the system;* hence equation (8) is also the expression for the potential energy $\mathcal{E}_p$ of this system, with the zero level of potential energy taken when the distance $a = \infty$. In general, if r is the distance between two point charges Q and q, the potential energy of the system is

$$\boxed{\mathcal{E}_p = \frac{Qq}{kr}.} \tag{9}$$