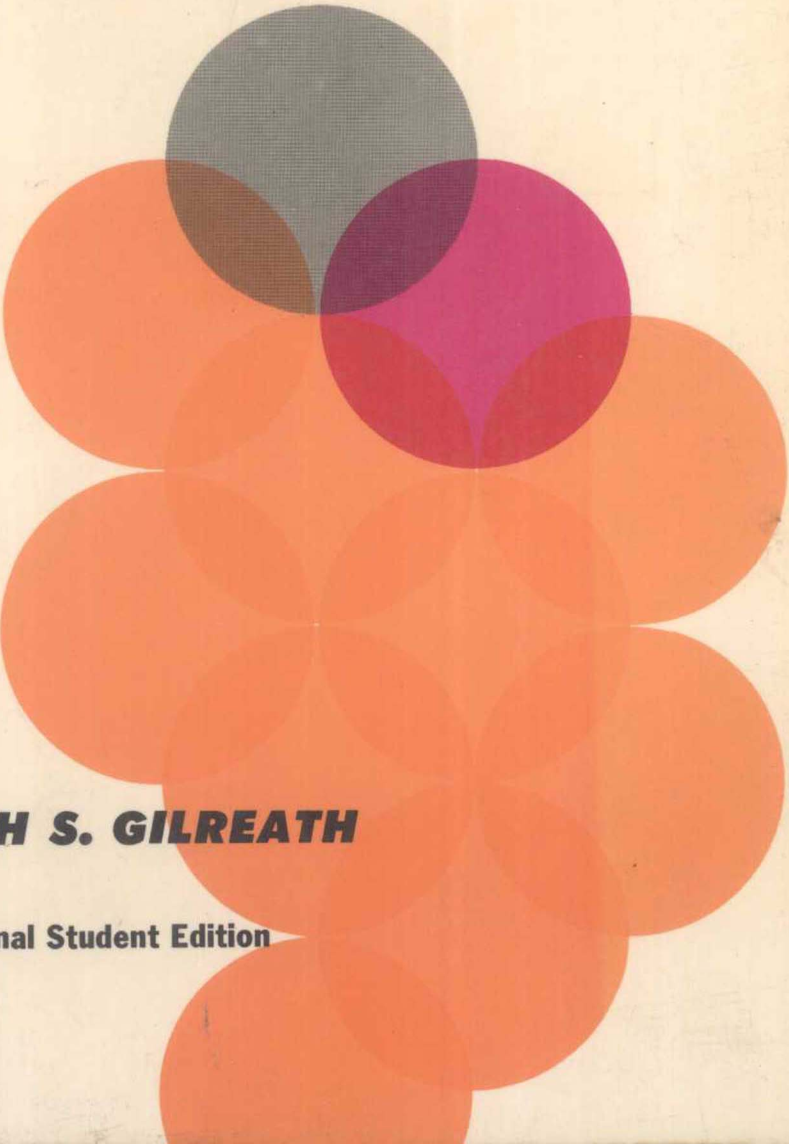
FUNDAMENTAL CONCEPTS OF INORGANIC CHEMISTRY



ESMARCH S. GILREATH

International Student Edition

FUNDAMENTAL CONCEPTS OF Inorganic Chemistry

Esmarch S. Gilreath

PROFESSOR OF CHEMISTRY
WASHINGTON AND LEE UNIVERSITY

INTERNATIONAL STUDENT EDITION

McGRAW-HILL KOGAKUSHA, LTD.
Tokyo Auckland Düsseldorf Johannesburg London
Mexico New Delhi Panama São Paulo Singapore Sydney

FUNDAMENTAL CONCEPTS OF INORGANIC CHEMISTRY

INTERNATIONAL STUDENT EDITION

XIV

Library of Congress Catalog Card Number 57-12898

TOSHO PRINTING CO., LTD.
TOKYO, JAPAN

Preface

This textbook is the outgrowth of several years' experience in the teaching of a course designated as *Advanced Inorganic Chemistry* at Washington and Lee University. The college catalogue describes the course as a one-semester study of special topics in the field of inorganic chemistry for advanced undergraduates. A perusal of other catalogues indicates that a similar study is offered at many other colleges and universities. One irksome task connected with the organization of teaching material has been the yearly preparation of an up-to-date syllabus to serve as a guide for student study. Furthermore the use of such a syllabus has never been quite satisfactory to me or to my students. The present volume is an attempt to remedy the problems resulting from the nonexistence of a suitable textbook.

The field of inorganic chemistry is so broad that it would be foolhardy to undertake its coverage in a single volume. Without trying to define the limits of the field, it is possible to divide this branch of chemistry into two approaches, the theoretical and the experimental, neither of which can be thoroughly explored in the duration of a single semester. This book offers only an elementary approach to certain theoretical concepts.

The choice of materials has resulted from a process of elimination. In my teaching I have used a wide range of topics, and I regret that lack of space prevents the inclusion of many of them. The ones retained are those that appear to be essential.

Despite the description of this course as a study of special topics, an examination of the table of contents will disclose that the topics are not only related but more or less dependent upon each other. The first two chapters are devoted to an analysis of the structure of matter, in the form of atomic nuclei and atomic electron shells. The third chapter is concerned with the classification of the elements, and an attempt is made to correlate the various properties of the elements and their compounds. Chapter 4 analyzes the several types of bonds which may exist among atoms, ions, and molecules and makes some prediction as to what conditions are necessary for certain bond formations. Chapter 5 deals with complex ions and coordination compounds, with special emphasis upon the structural aspects of the particles concerned. The problem of solubility, and the reactions of substances in aqueous solution, make up the contents of Chap. 6. The last two chapters are surveys of two growing, and relatively new, branches of inorganic chemistry, namely, inorganic substances in nonaqueous solutions, and radioactivity and nuclear transformations.

Since this book is designed for undergraduate classroom study, a deliberate effort has been made to write it in a language suited to its purpose. Also, I have not hesitated to use elementary explanations for many controversial ideas. It is my belief that the ever-changing nature of chemistry will make many of these concepts obsolete within too short a period of time.

Many persons including various friends, colleagues, and students in chemistry have contributed to this book. It is impossible to give each of them the credit that is due. However, I do wish to express my deep appreciation to those five anonymous individuals who read the whole of the manuscript. Without their searching and helpful criticism many misstatements and ambiguities would have escaped into the final text. Also, it is a pleasant duty to express my indebtedness to my wife, Sally Gilreath, for her help in the preparation of the manuscript. Only through her encouragement and assistance was the completion of the book possible.

E. S. Gilreath

Contents

CHAPTER 1

Atomic Nuclei

The study of inorganic chemistry should involve some exploration into the relationships which exist among the physical properties, the chemical behavior, and the material structure of matter. Furthermore, this exploration should commence with an examination of the structure of matter, and the manner in which it is assembled. Consequently our first chapter is concerned with the particles which make up matter, and their characteristic properties. Although the building blocks of chemistry are the atoms of the several elements, these atoms are not ultimate particles of matter. To approach the possibility of fundamental particles, it is necessary to probe into the internal mechanism of the atoms themselves.

From Ernest Rutherford's experiments and speculations emerged the first modern concept of the atom. Rutherford visualized the atom as a miniature planetary system consisting of a small, heavy core, or *nucleus*, containing all of the atom's positive charge and most of its mass, surrounded by an *electron cloud* composed of negatively charged particles equal in number to the charge on the nucleus. Most of the atom's volume was conceived as empty space, patrolled by the electrons, moving in definite orbits, at relatively great distances from the nucleus and from each other.

Rutherford's picture of the atom presents two structural problems relating to the architecture of the atom. The first of these concerns the arrangement, or probability of position in space, of electrons about the nucleus, and the second pertains to the nature and arrangement of particles within the nucleus. The problem of nuclear structure will be given first consideration, inasmuch as it is in a highly speculative stage of development and, consequently, can be disposed of more quickly.

SUBATOMIC PARTICLES

The idea that matter is constructed of ultimately indivisible particles is as old as natural philosophy. From the Greeks came the beginning of the atomic theory; Democritus taught that atoms are hard, small objects—so small as to render them invisible—with form, size, and weight. This old atomic hypothesis was placed on a useful scientific basis by John Dalton, who in 1803 developed the concept of atomic weights. Dalton's atomic theory contained the famous postulate that atoms of the same elements are similar to one another and equal in weight. This led Prout, an Edinburgh physician, to suggest in 1815 that all atoms are made of the same primordial atoms of a substance which he called "protyle" and which he attempted to identify as hydrogen. However, Prout's hypothesis was short-lived since accurate atomic-weight determinations by Berzelius and by Stas proved that atomic weights of many elements were not integral multiples of the weight of the hydrogen atom. Despite this early deathblow to the Prout hypothesis the idea of an ultimate particle or particles has lingered in the minds of physicists and chemists since its inception. Even at present there is much speculation among top-flight scientists that the composition of matter may yet be resolved into a few fundamental particles.

1·1 The Enigma of Fundamental Particles. The problem of breaking the atom down into its component particles has progressed from what appeared at first to be a simple, logical solution involving only three fundamental particles, namely, electrons, protons, and neutrons, into an entangled, obscure situation, embodying a multiplicity of particles. The known and probable particles coming from the atom total at least 20, with others likely to be added before some resolution is made of the present number. In the analysis of mass particles it is also necessary to account for particles of energy; however, the border line between mass and energy is not always clear-cut. Despite the fact that twenty or more particles have been observed as products of nuclear reactions of various types, this does not necessarily mean that the nucleus is a mixture of these particles. It is unlikely, for example, that photons are constituent particles. Photons, which are units of high-frequency electromagnetic radiation, e.g., gamma rays, may result from internal stresses within the nucleus, in which mass is converted into energy. It is also quite possible that mass particles such as electrons, positrons, and mesons do not exist as components but are created by stresses in which energy is converted into mass. It is much easier to return to an earlier hypothesis in which the nucleus is considered as being composed of two building blocks, protons and neutrons, which are collectively called nucleons. Perhaps all the other particles coming from the nucleus are by-products created by interaction of the two types of nucleons. Various theories as to the structure of the nucleus will be discussed in more detail later in this chapter.

No particles are necessarily immutable, and therefore none can be considered as truly fundamental. All the known particles existing in nature have been found to undergo various types of reactions, either with other particles and radiation or by decay. For the purpose of this study we shall classify particles existing outside the atom into two types: those which are stable, and those which are unstable. The term *stable*, or *stability*, denotes an absence of decay but does not necessarily imply long life; e.g., the positron is a stable particle, but usually short-lived because it is rapidly destroyed by interaction with an electron.

Before listing and describing the various stable and unstable particles which are believed to be fundamental, it seems pertinent to examine certain general properties which are more or less common to all particles.

1·2 Properties of Nuclear Particles. The most important properties of nuclear particles are their charge, mass, and spin. One or more of these properties may be absent in a given particle; e.g., the neutron has zero charge, the neutrino has zero mass, and the various mesons are supposed to have zero spins. Certain conventions have been adopted for indicating as many of these properties as possible in the symbolic representations of the particles. First of all, each particle has an identifying abbreviation or symbol; these are listed in Tables 1·1 and 1·2. The charge, if any, is shown as a subscript to the symbol of the particle, and the mass, to the nearest whole number, is written as a superscript. Thus the correct representation for the neutron is ${}_0n^1$, indicating that this particle has zero charge and a mass number of 1. The alpha particle, although not considered as a fundamental nuclear particle, may be used as another illustration. This nuclear fragment is written as ${}_2He^4$, signifying that it is a helium nucleus, with a charge of +2 and a mass of 4. Still another illustration is that for the electron, ${}_{-1}e^0$, which denotes the particle as having zero mass and a charge of −1.

The mass of nuclear particles may be described by either of two systems. One system is based on the unit of the physical atomic-weight scale. In this system the unit of mass, frequently referred to as *mass unit*, is one-sixteenth the mass of the ${}_8O^{16}$ atom of oxygen. In other words, the unit of mass is one-sixteenth the atomic mass of the O^{16} isotope of oxygen. This particular isotope has been selected as the standard for the physical atomic-weight scale, and the unit of this scale is usually designated as amu (atomic mass unit). A discussion of isotopes and the physical atomic-weight scale is given later in this chapter in Secs. 1·18 and 1·16.

Another system of designating mass for nuclear particles is based on the charge of the electron. The apparent mass of an electron depends upon the speed with which it is traveling. For an electron moving with small velocity the ratio of the charge to mass, e/m, is 5.274×10^{17} esu (electrostatic units)/g. Since the charge of the electron, e, has been determined as 4.803×10^{-10} esu, the mass may be calculated as

$$m = \frac{4.803 \times 10^{-10}}{5.274 \times 10^{17}} = 9.107 \times 10^{-28}\ \text{g}$$

The value 9.107×10^{-28} g is referred to as the *rest mass* of the electron, and if this value is arbitrarily designated as unity, then the masses of other particles may be assigned values relative to that of the electron. To illustrate, the mass of the proton, on this scale, is 1,836.14, indicating that this particle has a mass over 1,800 times greater than that of the electron.

In Tables 1·1 and 1·2 the masses of known particles are listed in the units of both the systems just described.

All bodies in space—the sun, the earth, and even nuclear particles—manifest the property of angular momentum, usually called *spin*. For simplicity it is easier to think of a particle as spinning like a top around its own axis; however, physicists usually prefer to think of spin as a mathematical notation rather than an actual physical rotation. This property can be measured, and the unit of spin is Planck's constant, h, divided by 2π. Since the laws of quantum mechanics require that the spin of any particle or system of particles be quantized, the value of the spin is always an integral or half-integral multiple of $h/2\pi$. Most fundamental particles, such as an electron or a proton, have spins in units of $+\frac{1}{2}$ or $-\frac{1}{2}$. The combination of the spins of these or other fundamental particles in an atomic nucleus results in systems with spins of 0, $\frac{1}{2}$, 1, $\frac{3}{2}$, 2, etc., but never in intermediate values such as $\frac{3}{4}$. When the atomic weight of an atom is an even number, the number of particles in the nucleus will also be even in number and the nuclear spin will be zero or a whole number, usually 1.

The spin numbers of all particles in a nuclear reaction must be balanced on both sides of the nuclear equation. This provides a convincing argument for postulating the neutrino particle, which is needed to balance the nuclear equation when an electron is emitted from a radioactive nucleus in beta decay. The need for postulating this hypothetical particle is described in the next section.

1·3 Stable Particles. Four mass particles and three energy particles have been either identified or postulated which are not subject to decay. The mass particles are the electron, the proton, the antiproton, and the positron; the energy particles are the neutrino, the photon, and the graviton. The general characteristics of these particles are summarized in Table 1·1.

The Electron. This was the first particle to be recognized as a constituent of all atoms. The first evidence of its existence dates back to Michael Faraday, who, in 1833, while studying the conduction of electricity by solutions, reached the conclusion that a flow of electricity was due to a movement of discrete particles. In 1879 Sir William Crookes showed that cathode rays could be bent by an electromagnetic field, indicating that cathode rays are particles of matter. In 1895 Jean Perrin showed that the charge on these particles is negative. As early as 1874 G. Johnston Stoney had recognized the need for the particle, and after its discovery it was he who suggested the name *electron* for this unit of matter. It was in 1897 that Sir J. J. Thomson assigned the first value for the ratio of the charge of the electron to its mass. By observing the deflections of cathode rays in magnetic and electrical fields of known strengths he was able to determine the velocities of the particles and the ratio of their charge e to their mass m. The value he obtained for e/m was 1.77×10^7 emu (electromagnetic units)/g, which was far from the correct value as shown by more precise measurements in subsequent determinations. However, the true importance of his work lay in his observation that the value of e/m was independent of the metal used as the cathode and the nature of the gas in the tube, indicating that the nature of the particles from various metallic cathodes was the same.

The history of the identification of the electron, and the determination of its properties, is replete with the famous names of science; however, it is not proposed to reproduce this history here. It will suffice to note a few of the most important constants which have been determined for the electron.

Its charge e is 4.8024×10^{-10} esu, or about 1.60×10^{-19} coulomb. The most reliable measurements of e/m for the electron, at low velocity, is 5.274×10^{17} esu. Its mass is 9.106×10^{-28} g, 1,836 times less than the proton, or 0.0005486 on the physical scale of isotopic weight. (This scale is designated in Sec. 1·4 and described in Sec. 1·16.)

The Proton. The discovery of the electron stimulated a search for the corresponding unit of positive charge. In 1886 Eugene Goldstein, using a perforated metal disk as a cathode, in a cathode-ray tube, observed luminous rays emerging in straight lines from the holes in the disk and moving in a direction opposite to the cathode rays. In 1898 W. Wien showed that these rays were deflected in a magnetic and in an electric field, but in opposite direction to the deflection of electrons in the same fields, indicating that they were streams of positively charged particles. The rays were originally called *canal rays* since they passed through channels in the cathode, but in 1907 J. J. Thomson proposed the more appropriate name of *positive rays.* A determination of the ratio of charge to mass, e/m, of the particles making up the positive rays showed that they were much heavier than electrons. The lightest of these particles had a mass approximately that of the hydrogen atom; consequently it was assumed that such a particle was merely a hydrogen (protium) atom stripped of its lone electron. The name *proton,* coming from the Greek word for *first,* was suggested for it by Sir Ernest Rutherford in 1920.

The mass of the proton in the free state, as determined from mass spectrum measurements, is 1.007581 on the physical scale, or 1.6725×10^{-24} g.

The Positron. Up to 1932 the only unit of positive charge recognized was the hydrogen positive ray of mass 1, which is the hydrogen nucleus, or hydrogen ion. However, in 1930, the existence of positive electrons, as distinct from protons, was predicted theoretically by Paul A. M. Dirac, the English mathematical physicist, on the basis of his relativistic quantum theory of the electron. Proof of the existence of the positive electron, now called the *positron*, was obtained by Carl D. Anderson, an American physicist, during his study of cosmic rays. From its path in a cloud chamber Anderson proved the positive charge of the positron. When this particle passes through a lead plate, it loses some of its energy and this loss of energy affects the degree of curvature in a magnetic field and the intensity of the track itself. Thus measurements made on the track of a particle before and after it had passed through a lead plate enabled Anderson to evaluate the mass of the particle and the magnitude of its electric charge.

The Antiproton. For many years theoretical physicists have speculated upon the probable existence in nature of particles as pairs possessing similar but opposite characteristics. This concept is sometimes termed the *electric-charge symmetry in nature* and predicts that for each fundamental mass particle occurring in nature there should exist a similar particle of opposite electrical charge. The occurrence and characteristics of the electron-positron pair illustrates the idea embodied in this concept. Furthermore physicists have predicted that comparable symmetry may exist in other characteristics. According to the broader theory, not only should a negatively charged proton, called an *antiproton*, exist, but there should also occur in nature a symmetrical companion to the uncharged neutron, called the *antineutron*. Such a theory would also predict the probable existence of the *antineutrino*.

The concept of electric-charge symmetry predicted the possible existence of the antiproton, with a mass equal to the proton, but with a negative charge. Such a particle could not be expected to exist free in nature because it would be annihilated rapidly upon contact with other matter. In fact its existence is possible only at a distance from the earth's crust and atmosphere or momentarily as a newly created particle in a powerful proton accelerator.

In 1955 the existence of the antiproton was confirmed by scientists at the Universities of California and of Rome. The creation of the antiproton was accomplished at the University of California by means of a powerful proton synchrotron called a *Bevatron*. This accelerator, as the name implies, is capable of accelerations above a billion electron volts

(Bev). In the Bevatron chamber protons accelerated to 6.2 Bev were directed upon a copper target. When a proton with this acceleration hits a neutron in a copper atom, two new particles are produced—a proton and an antiproton. In such a collision a part of the proton's energy is converted to mass in accordance with Einstein's equation, and the remaining energy produces motion in all particles remaining or created by the collision. In this experiment nearly 1 Bev of the original 6.2 was required to create each antiproton.

The mass of the antiproton is equal to that of the proton. It is stable in a vacuum and does not decay spontaneously; however, as has been said before, it is annihilated upon contact with either neutrons or protons. The particle bears a negative charge and has a spin of $\frac{1}{2}h$. These characteristics are listed in Table 1·1.

The Neutrino. The emission of an electron from a radioactive (unstable) nucleus, called *beta decay,* is evidently due to the transformation of a neutron into a proton and an electron.

$$\text{Neutron} \rightarrow \text{proton} + \text{electron}$$

In beta decomposition the energy of the neutron should be equal to the energy of the products, but it has been found that the beta particles (electrons) which are emitted have a range of values of kinetic energy. This would appear to be a contradiction of the law of conservation of energy. In the same process another conservation principle, the law of conservation of angular momentum, seems to have been violated. In Sec. 1·2 it was stated that the spins of fundamental particles, such as neutrons, protons, and electrons, are either $+\frac{1}{2}h$ or $-\frac{1}{2}h$. In this transformation the neutron with a spin of $\pm\frac{1}{2}h$ gives rise to two particles, the proton and the electron, each with a spin of $\pm\frac{1}{2}h$. Since the spin numbers must be balanced on both sides of the equation for the nuclear reaction, an extra $\frac{1}{2}$-spin unit must be accounted for. Either a $\frac{1}{2}$-spin unit is gained in the production of two new particles, or, if there is a balancing of opposite spins, there is a loss of a $\frac{1}{2}$-spin unit.

The *neutrino* was a theoretical particle postulated by Wolfgang Pauli in 1931 to preserve the conservation of energy and angular momentum in beta decay. With the addition of this new particle the creation of an electron in the nucleus could be represented as

$$\text{Neutron} \rightarrow \text{proton} + \text{electron} + \text{neutrino}$$

in which the proton is retained in the nucleus and two particles, the electron and the neutrino, are emitted. Assuming the neutrino has a spin of $\pm\frac{1}{2}h$, the unbalanced angular momentum is restored, inasmuch as the neutron with a half-integral spin is transformed into three particles, the sum of whose spins is a half-integral.

Existence of the free neutrino was established experimentally in 1956 by a group of Los Alamos scientists working with a complex detecting system set up near a powerful reactor at the Savannah River plant of the Atomic Energy Commission. The late discovery of the neutrino particle may be attributed to the fact that its charge is zero and its mass is either zero or very close to zero. Some physicists postulate the existence of an antineutrino to distinguish between β^- and β^+ decay. However, there appears to be no definable difference between the two particles.

The Photon. It is fairly easy to think of matter as composed of fundamental particles, but it requires considerable imagination to visualize

TABLE 1·1 CHARACTERISTICS OF CERTAIN STABLE ELEMENTARY PARTICLES

Particle	Symbol	Charge	Mass*	Mass†	Spin‡
Electron	e, β^-	−	0.0005486	1	½
Proton	p	+	1.00758	1,836	½
Positron	e^+, β^+	+	0.0005486	1	½
Neutrino	v	0	<0.00002	<0.04	½
Photon	γ	0	0	0	1
Graviton	G	0	0	0	2
Antiproton	$\bar{p}$	−	1.00758	1,836	½

* The unit is the physical atomic weight; ${}_8O^{16} = 16.00000$.
† Mass relative to e, where $e = 9.11 \times 10^{-28}$ g.
‡ In units of $h/2\pi$.

energy as made up of ultimate particles. However, according to the quantum theory, energy, as well as matter, is made up of discrete units. The photon is the unit of electromagnetic radiation. The history of the photon goes back to Max Planck, who in 1901 pointed out that the distribution of energy in black-body radiation could not be reconciled with the wave theory of light and suggested the hypothesis that energy is emitted or absorbed discontinuously in multiplies of a certain unit, or *quantum*. Furthermore, the magnitude of this unit, or quantum, is hv, where v is the frequency of the radiation and h is a constant, which has become known as *Planck's constant.*

In 1905 Albert Einstein suggested that not only was radiation absorbed and emitted in whole numbers of energy quanta but that it was also propagated through space in definite quanta, moving with the speed of light. The term *photon*, coming from the Greek word for *light*, was introduced in 1928 by A. H. Compton. Earlier, in 1923, Compton had discovered (Sec. 2·12) that, when X rays fall on any material of low atomic weight, the scattered rays consisted of two frequencies, one equal to and the other less than that of the primary rays. To account for the change in frequency in the scattered rays, Compton deduced mathematical equations which accounted perfectly for this frequency change in terms of body collisions. According to these equations the frequency change is due to the collision of an X-ray photon with an electron in the material on which it impinges, producing, in the recoil, another photon (the scattered X ray) of longer wavelength.

The Graviton. The elementary particle corresponding to the gravitational field, more aptly described as the *unit of gravitational energy*, is the *graviton*. This particle has never been observed, but the postulation of its existence is necessary in certain mathematical equations relating to quantum mechanics. Gravitational forces are extremely weak, the weakest of all the physical forces, and, for this reason, gravitational effects are observed only in large masses. In such masses the number of gravitons must be quite large, but since the particle itself is postulated as having zero mass and zero charge, it is doubtful that the individual graviton will ever be observed.

1·4 Unstable Particles. Any estimate as to the number of unstable elementary particles that may exist would be an extremely unsafe guess, inasmuch as new particles are being discovered at a rate somewhat discomforting to most scientists. This discomfort arises not from the actual discoveries of the new particles but from the fact that the problem of nuclear structure is increasing in complexity, with any possible solution being pushed further into the future. Not only is there the problem of new additions to the number of known particles, but the fact that so many change from one type to another is quite disconcerting.

Among the unstable elementary particles that will be described are the *neutron*, the family of particles known as *mesons*, and the V *particles*. The general characteristics of these particles are summarized in Tables 1·2 and 1·3.

The Neutron. Of all the particles that have been, or will be, discussed, the neutron is the most intriguing. Our knowledge of the properties and behavior of the neutron is extensive; our lack of knowledge of the role it plays within the nucleus is abysmal. Undoubtedly it is one of the fundamental building blocks of nature, and for that reason we shall cite all its known properties and shall later explore some of the speculative theories as to its function in the nucleus.

Atoms of the same element may vary in their atomic masses. Among the most popular of the earlier explanations for this variation was the theory that the nucleus consisted of protons and electrons and that weight differences in atoms were due to different numbers of proton-electron combinations in the nucleus. However, theoretical difficulties of dealing with electrons as nuclear building stones led to the prediction by Sir

Ernest Rutherford, in his Bakerian Lecture to the Royal Society in 1920, of the existence in the nucleus of a neutral, uncharged particle, having a mass of unity on the atomic-weight scale.

The brilliant prediction of Rutherford remained unverified for 12 years. Among the first attempts to produce such particles was the passage of an electric discharge through hydrogen, with the hope of causing the union of electrons with protons, but experiments of this nature were unsuccessful. In 1930 Bothe and Becker of Germany bombarded targets of lithium, beryllium, and boron with alpha particles from the natural radioactive element polonium and found that an uncharged radiation with an unusually high penetrating power was produced. These results were confirmed in 1931 by Frédéric Joliot and Irène Joliot-Curie in France. The Joliots made the additional observation that, when a screen of paraffin was interposed in the path of the new radiation, high-speed protons were ejected. This effect might possibly be produced by gamma rays of very short wavelength, and for some time this explanation was accepted. Finally, in 1932, James Chadwick of Cambridge University repeated these experiments, using beryllium as a target for the alpha particles, but directed the new radiation into a Wilson cloud chamber filled with nitrogen. The ionization produced in the chamber was measured and then the experiment repeated with a sheet of paraffin in the path of the secondary radiation, before its entrance into the cloud chamber. The interposition of the paraffin sheet increased considerably the ionization within the cloud chamber. Such an increase was due to protons produced in the paraffin by the secondary radiation from the beryllium. Moreover the production of protons was little affected by placing a lead screen between the beryllium source and the paraffin. The events in the cloud chamber could be interpreted only as body collisions of particles too massive to be caused by weightless gamma radiation. The approximate mass of the new particles emanating from the beryllium target was determined by Chadwick through a comparison of the maximum velocities of protons and nitrogen nuclei produced by the impacts of the new particles in hydrogen and nitrogen, respectively. The new particles were called *neutrons* since they were electrically neutral, and consequently their paths were not visible in a cloud chamber. Despite the foregoing statements concerning the behavior of neutrons in a cloud chamber they produce no primary ionization but may be detected by the fact that in collisions with charged nuclei (nitrogen atoms, in this case) they will impart energy to them, and these secondary moving nuclei will ionize and be detectable.

The specific properties of the neutron may be listed as: zero electric charge, a mass of 1.00893 on the physical atomic-weight scale, and a spin of ½. It has a half life of approximately 20 min, undergoing spontaneous destruction, with the formation of a proton, an electron, and a neutrino according to the equation

$$\text{Neutron} \rightarrow \text{proton} + \text{electron} + \text{neutrino}$$

This is the reaction that was postulated as taking place in beta decay (Sec. 1·3), making necessary the invention of the neutrino particle, even before its discovery, to preserve the conservation of angular momentum. Direct experimental proof for this decay has been obtained only recently owing to the fact that free neutrons are captured so rapidly by nuclei that the average life of a free neutron is short in comparison with its expected radioactive half-life period.

The neutron has zero electric charge, but the statement that it is a neutral particle should have some qualification. It is true that no deflection can be observed in the slowest of neutrons with the strongest electric fields. Also true is the fact that the neutron, in itself, causes no ionization in a cloud chamber. On the other hand the neutron has magnetic properties which seem contrary to what might be expected of a totally neutral particle. A neutron will align itself in the fashion of a small magnet when placed in a magnetic field. It has also been observed that slow neutrons are deflected from their course by passing them through magnetized iron. Moreover the electrically neutral neutron possesses a magnetic moment equivalent to that of a spinning negative charge. As might be expected, the magnetic moment of the neutron is negative and opposite in sign to the magnetic moment of the proton, which is a spinning positive charge.

The magnetic moment of the neutron would indicate that it possesses some type of charge-bearing structure, although it is neutral over-all. Recent experiments have explored this possibility, and there seems a likelihood that the neutron consists of a positively charged core surrounded by a thin shell containing an equal quantity of negative charge. In fact there is some experimental evidence that neutrons may interact slightly with electrons—a behavior quite contrary to what would be expected of a neutral particle.

Mesons. From the time of the discovery of the neutron in 1932, scientists have felt that the essential building blocks of the nucleus are neutrons and protons. Beginning with that date, they have struggled to assemble some sort of theory to explain the extremely powerful forces that are necessary to hold together these heavy particles in the very small nucleus. Theorizing along this line led the Japanese physicist Hideki Yukawa to suggest in 1935 that a kind of field, consisting of quanta of energy which could take the form of particles of a certain mass, might account for the nuclear binding forces. Although the speculative theories regarding nuclear structure will be given in more detail later in this