NUCLEAR TECHNOLOGY FOR ENGINEERS

By R. HOBART ELLIS, Jr.

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Nuclear Technology for Engineers

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Preface

I hope you will like this book. It is written from a conviction that there is a need in its subject area—the broad range of nuclear technology at a beginner's level. Its style is chosen with the intention of making it both easy to read and informative. Moreover I hope that you will find it stimulating and will turn to other books and periodicals to read more deeply in the fascinating new field of nucleonics.

Naturally I have many reasons for hoping you will like this book. But beyond the obvious considerations, it is my feeling that the field of American science and scientific education needs more books, more teachers, and more teaching that students can *like.* It has been my experience that a desire to fill this need is conspicuously absent in our academic communities. I hope that this book can demonstrate that the transfer of information from older minds to younger ones can be highly enjoyable. If this is true, it is the duty of the teacher and writer to make it so.

The subject matter is chosen to be an introduction to nuclear technology. Historically nuclear engineers have had no such introduction to their subject. Most of them have come from other disciplines—physics, chemical engineering, electronics, biology, etc. When the field was new and small, this pattern was all right. But now the field is large in many ways. It has a wide range of subject matter; it employs many men; it has many problems to be solved in the future. It would be no more appropriate for today's nuclear engineer to start his education by acquiring a doctorate in physics than for today's mathematician to master all of the theorems of Euclid before he advanced to differential calculus.

I treat the field of nuclear technology as being made up of four parts: radiotracers, irradiation technology, fission, and fusion. This separation into parts is naturally somewhat artificial, as there is much overlap. That is why this is one book and not four. The introductory chapter is planned as a foundation for the rest of the book. It will remind you of material already covered in earlier courses in physics and chemistry. The next three chapters are directed mostly toward radiotracer technology, the following three toward irradiation, and the next two toward fission reactors. The final chapter on nuclear fusion will give you a brief introduction to the concepts of this important and interesting new field.

In general you will find that this book introduces ideas but does not pursue them deeply in analytical detail. There are few formulas and equations in proportion to the amount of textual material. Mathematics is used mainly to show how calculations can be made rather than to actually make them. However, I hope that you will find enough stimulation in what is presented here to go on into more detailed books and articles.

Several people and organizations have been cooperative in permitting me to copy illustrative material. *Nucleonics* magazine has given me permission to quote a multitude of figures. The people who originally supplied such figures—in most cases the authors of *Nucleonics* articles—have added their approval. Many figures are used with permission of author and publisher from "The Atomic Nucleus," by Robley D. Evans (McGraw-Hill Book Company, Inc., New York, 1955). Another illustration is used with the publisher's permission from "Rayonnements de Particules Atomiques, Électrons et Photons," by André Berthelot (Masson et Cie., Paris, 1956). Several other people have been generous in supplying special illustrations at my request. Acknowledgments for all of these figures are made where they appear in the book.

My particular thanks are due to Miss Susanne Deutsch who has been a generous and competent editorial assistant and advisor.

R. Hobart Ellis, Jr.

Contents

CHAPTER 1

Nature of the Nucleus

For most of us the nuclear age was born in 1945 in an awe-inspiring explosion. Suddenly man had at his disposal a new force, different in nature and greater in magnitude than anything he had been able to use before. This is the force that holds the atomic nucleus together. In this book it is our purpose to explore the technology that is growing out of man's ability to use this force.

From a sophisticated point of view the nuclear age starts some time *before* 1945. As early as 1911 Rutherford asserted that the atom has a nuclear structure. This means that it has a tiny core at the center much, much denser than the material surrounding it. In the following years researchers found out many things about the nucleus. They discovered and explored the particles of which it is made. In 1939 it became evident that a newly discovered phenomenon, nuclear fission, might lead to a chain reaction. A multitude of experimental steps produced the first controlled nuclear chain reaction in 1942, and the first military use of a nuclear explosion occurred in 1945.

Today we stand just inside the threshold of nuclear technology. For purposes of perspective we can compare our position as nuclear engineers with that of power engineers when a rattling tea kettle suggested a steam engine to Watt—with that of chemists when the law of mass action revealed the existence of atoms—and with that of mathematicians when they first began to survey land.

An understanding of nuclear technology begins with a knowledge of the atom. In this chapter, therefore, we turn to the atom as we know it, made up of three kinds of fundamental particles: electrons, protons, and neutrons. Three kinds of forces act among these particles—gravitational forces, electrical forces, and nuclear forces. An atom is a combination of these fundamental particles held together by the forces acting among them.

In this chapter our principal concern is stable atoms—in which the nuclei will remain unchanged throughout eternity unless external influences change them. Among external influences that can cause changes are those that are chemical in nature. In this case the atoms change their associations with one another, but their nuclei remain unchanged. In nuclear technology, however, there are also nuclear reactions in which the nucleus itself changes. Because of their particular importance to all of the later chapters, nuclear reactions and the probabilities of the occurrence of these reactions are discussed at the end of this chapter.

A. ELEMENTARY PARTICLES

The three fundamental particles—electrons, protons, and neutrons—are the building blocks from which every atom is made. A combination of protons and neutrons forms a dense core or nucleus at the center of every atom. Such a nucleus is about 10^{-13} cm in diameter. In other words, if one could line up 10^{13} (10,000,000,000,000) atomic nuclei side by side, they would form a row 1 cm long.

Around the nucleus is a cloud of electrons that gives the complete atom a diameter of about 10^{-8} cm. Thus the total diameter of the atom is about 100,000 times the diameter of its nucleus. Moreover, the density of the nucleus is such that it contains almost all of the mass or weight of the atom. The electron cloud on the outside contains about 1/4,000 of the total atomic mass.

For the purposes of comparison, Table 1-1 lists the principal properties of the three fundamental atomic particles.

Electrons. Best known of the fundamental particles is the negatively charged electron. This is because electrons have their places on the outside of the atom, and man has, by necessity, explored the atom from the outside in.

In its natural, undisturbed state, each electron occupies a distinct place in an atom. Later on we shall call this "place" a "state." By the laws of physics only one electron can occupy a state at a time. Yet each electron may have close neighbors, for each neutral uncharged atom has a number of electrons equal to its atomic number. Thus a

Table 1-1. Characteristics of the Three Fundamental Particles

Particle	Mass, amu *	Mass, grams	Charge (units of electron charge)	Charge, coulombs
Electron	5.49×10^{-4}	9.11×10^{-28}	-1	-1.59×10^{-19}
Proton	1.008	1.672×10^{-24}	$+1$	$+1.59 \times 10^{-19}$
Neutron	1.009	1.675×10^{-24}	0	0

* The atomic mass unit is $\frac{1}{16}$ the weight of the oxygen-16 isotope. This is slightly smaller than the unit of the chemist's atomic-weight scale, defined as $\frac{1}{16}$ the average weight of an oxygen atom in a natural mixture of oxygen isotopes.

hydrogen atom has one electron; helium has two; oxygen has eight; and so on.

As atoms are joined together to form molecules, the electrons form the bonds that hold them together. Under these conditions the outermost electrons can no longer be specified as belonging to a particular atom. Some belong rather to the molecule as a unit. They are shared between two atoms or among several.

This state of electron sharing reaches an extreme in situations where many atoms are combined into a crystal. In metals, for example, the outermost electrons of the atoms are shared among so many atoms that they are essentially free. They move about among the metal atoms like gas molecules in an air-filled bottle. It is the motion of electrons of this kind that forms electric currents. When a metal is heated enough, the electrons acquire enough energy to leave the surface. These electrons produce the currents in electronic vacuum tubes.

Protons. Balancing the negative charge of the electron in the atom is the positively charged proton. This is a particle that has a charge of the same magnitude as the electron but of opposite sign. Thus any system that has an equal number of protons and electrons is electrically neutral.

Besides the difference in the signs of their electrical charges, the proton and electron differ in another important way. As shown in Table 1-1, the proton is about 1,840 times as heavy as the electron.

The protons in the atom are contained in the nucleus. There are as many protons in the nucleus as there are electrons in the surrounding cloud. Since there are no other charged particles in the atom, and since there are no electrons in the nucleus, the normal, undisturbed atom is electrically neutral. That is, it is neither positive nor negative as far as its electrical nature is concerned.

Neutrons. The remaining member of our fundamental-particle trio is the neutron. Unlike the proton and electron it has no electrical charge; it is electrically neutral. It has a mass almost equal to the proton mass, and in many ways it behaves much like the proton.

One is tempted at this point to suggest that the neutron is a combination of an electron and a proton. However, powerful physical reasons show that a single-particle combination of a proton and an electron cannot exist.

Like the proton, the neutron has its place in the atomic nucleus. Because it is electrically neutral, it is difficult to detect. For this reason it was the last of the atomic particles to be discovered. It has been known only since 1932.

Short-lived Particles. The normal, stable, everyday atom is made up of the three kinds of particles just described. It is not to be inferred, however, that no other particles exist in nature. There are others, and new ones are being discovered. These other particles have short lives. They are created in the moment of a nuclear reaction and disappear almost immediately thereafter. Some of them exist long enough and in large enough numbers to have some significance to nuclear technology. The positive electron and the neutrino will make their entrances later in the book. As of this writing most other particles are mainly of academic interest to physicists. But it would constitute a sad lack of imagination not to assume that they may be of important engineering interest when more is known about them.

B. FORCES

Three kinds of forces act on these particles that make up our universe. There may be more kinds of forces that have not yet been discovered, but for the moment we are safe in assuming that there are three: gravitational, electric, and nuclear.

Gravitational force acts between any two masses. It is the force that keeps the earth in its orbit about the sun, satellites in their orbits about the earth, and you in your chair. Such forces are important in considerations that involve large masses. In atomic phenomena they play no important part. For the purposes of this book we can safely forget them.

Electric Forces. Between any two electric charges there is a force of repulsion or attraction. If the charges are alike—both positive or both negative—the force is a repulsion. If they are unlike—one negative and one positive—it is an attraction. This is the so-called "coulomb force," which is proportional to the product of the magnitudes of the charges and inversely proportional to the square of their separation.

If charges are in motion, another kind of force acts on them. Moving charges create magnetic fields, and if other charges move in these fields, they experience forces. However, in nuclear considerations magnetic forces are usually much smaller than coulomb forces. One is usually justified in treating the magnetic forces as small perturbing influences on the coulomb forces.

Nuclear Forces. It is plain that with only the forces that have been mentioned so far there would be no nuclei made up of neutrons and protons. Protons repel one another strongly. Neutrons are uncharged and therefore not subject to coulomb forces. Gravitational forces are much too small in magnitude to hold a nucleus together.

The force that holds particles in the nucleus is a short-range force of attraction. Unlike the coulomb forces it does not operate at all distances but only when two nucleons—protons or neutrons—are within nuclear distances of one another. Nuclear distances are of an order of magnitude equal to the nuclear diameter—10^{-13} cm. It is now believed that the nuclear force between any two nuclear particles is independent of their charge; two protons, two neutrons, or a proton-neutron pair are held together by the same nuclear force when they are close enough. In the case of the proton pair the coulomb repulsion is acting *in addition* to the nuclear force, but the nuclear force itself is independent of charge.

An important quality of nuclear forces is their truly gigantic magnitude. They must be greater than coulomb forces just to hold the protons in the nucleus. In reality they are greater by a large factor.

One measure of the difference in magnitude is a comparison of chemical-bond energies with the energy represented by a particle in the nucleus. Chemical bonds are formed by associations among electrons. These electrons are held to the nucleus by coulomb forces, and a typical energy involved in forming or breaking a bond is a few electron-volts. On the other hand, the binding energy of a particle in the nucleus is typically several million electron volts in spite of the reduction of this energy by the repulsion between the protons of the nucleus.

C. QUANTUM STATES

There are particles in the universe and forces that act among them. The question that naturally follows is, how are these particles associated to form atoms?

A simple picture of the atom will serve for most of our purposes. In this model the particles are all represented as spheres. At the center is a configuration of protons and neutrons called a nucleus. The nucleus can have as few as one particle, in which case it is the nucleus of a hydrogen atom, a single proton. It can have as many as 256 particles, with neutrons comprising a bit more than half of the number. This nucleus is much like a drop of liquid. It has a volume proportional to the number of particles in it.

Around the nucleus but far away from it are the electrons. According to the simple picture they whirl in orbits like satellites around a planet. Only certain orbits are available, and only one electron can occupy each orbit. The number of electrons whirling in orbits is equal to the number of protons in the nucleus. Thus the available orbits are filled up to the number required to hold all of the electrons, the first filled being the orbit of lowest energy.

The periodic table of chemistry results from the arrangement of the orbits in groups or "shells," as they are called. The first two orbits complete the first of these shells. The next eight orbits form the second shell, and so on. As one progresses along the periodic table, he finds that every time a shell is filled, the resulting element is an inert element. The inert elements include helium with 2 electrons, neon with 10, argon with 18, etc. Another set of similar elements can be found by taking the ones that have one more electron than the number that fills a shell. These include lithium with 3 electrons, sodium with 11, potassium with 19. By similar reasoning it is possible to build up the entire periodic table of the elements. It is important to realize that chemical properties depend only on the electron configuration.

This simple model of the atom is sufficient for many purposes and contains much of the truth about the atom as we know it. However, it fails in several important ways when we take a closer look. These failures led to the development of quantum mechanics, which provides a more detailed and more useful model.

Need for Quantum Mechanics. The concept of an electron in an orbit around the nucleus like a moon whirling around a planet contradicts one of the fundamental principles of modern physics—the Heisenberg uncertainty principle. Applied to the electron orbit the argument goes like this: It is impossible by any physical means for anything as small as an electron to manifest precise values for both its position and velocity at the same moment. Consequently it is meaningless to ascribe precise values to these quantities at the same time. Any description of the electron that contains an implication of simultaneous, precise values of position and velocity is to this extent inadequate and requires modification.

To see how this argument comes about, imagine an electron that is traveling along a straight line. Suppose that an experimenter plans to observe where it is and how fast it is going at the same moment. Any observation that he makes to determine position must affect the velocity in an indeterminate way. Likewise any observation of velocity will disturb the position.

As an example, suppose that by some means the experimenter has determined the velocity precisely. He now plans to determine position precisely. He might plan to observe reflected light from the electron. Then he will know that the light comes from the position of the electron, and he will know both position and velocity. However, the experiment is impossible. The electron is so small that the light used to determine position will exert a pressure and change the velocity. Thus in finding position, the experimenter must sacrifice his precise knowledge of the velocity. Moreover, if the experimenter demands more and more precise information about position, he must use light of shorter and shorter wavelength. Shorter wavelength means photons of greater and greater energy; the light will exert more and more pressure on the electron; and the uncertainty introduced in the value of the velocity will become greater and greater.

We must emphasize that the language we are using here is that of a "thought experiment." It does not matter whether equipment is actually available to perform such an experiment. The limitations that apply are not in the experimental apparatus but in the physical nature of the universe. Thus if the hypothetical experimenter in a thought experiment cannot determine a property, the conclusion is that the property has no physical manifestation. If it has no physical manifestation, it is meaningless to ascribe to it any physical reality.

Physicists have used many thought experiments to examine the required uncertainty in position and velocity. The conclusion is that the product of the uncertainty in position and the uncertainty in the momentum—the product of mass and velocity—of any particle must be at least as great as a quantity called "Planck's constant," h, which has a value of 6.62×10^{-27} erg-sec. Other variables stand in the same relationship as position and momentum. Among them are time and energy. The energy of any system can have a precise value only if it has an infinite time to establish itself.

How does all of this affect our model of the atom? To say that an electron is whirling about the nucleus establishes a picture in which the electron has a precise position and a precise velocity. Computation, on the other hand, indicates that the uncertainty that must be allowed in these two quantities is such that this picture of an orbit disappears. If the electron is to have a known velocity within limits corresponding to measurements that can be made on the atom, the uncertainty that must be allowed in its position has a magnitude comparable to the diameter of the orbit.

The foregoing argument is surely a difficult one if you have not met it before. Quite abruptly it contradicts one's everyday sense of what things are and how they behave. Unfortunately there is not time or space to develop it fully here. The reader must go to introductory texts in quantum mechanics or wave mechanics for a fuller treatment.

Let us summarize briefly the argument thus far before going on to see how modern physics meets the problem it poses. (1) The elementary particles are so small that by no physical interaction can they manifest precise velocities of both position and momentum simultaneously. (2) Anything that has no physical manifestation has no physical existence. (3) Thus there is no reality in a description of the electron, for example, that requires values of both position and momentum more precise than are permitted by the Heisenberg uncertainty principle. (4) The concept of an electron moving in a path around a nucleus violates the Heisenberg principle. (5) Therefore one must find a new way to describe the existence of an electron.

In brief, we must give up the intuitive concept that nuclear particles behave just as baseballs do but in much smaller dimensions. A new set of laws governs their behavior; so we must be prepared for some unusual phenomena.

Quantum physics—the physics of very-small-dimension phenomena—has found a solution for this problem in the concept of the wave function.

Significance of the Wave Function. The refusal of atomic particles to accept the kind of description that applies to baseballs presents a serious problem, but it is probably not as difficult as it appears at first. *Similar situations are familiar in everyday life.*

Imagine, for example, that someone telephones and asks the whereabouts of a friend who has recently left your house. You know the road he is traveling, but you do not know exactly when he left or exactly how fast he is driving. You feel, perhaps, that he is probably 10 miles away. Certainly he must have gone at least 5 miles, and it is unlikely that he has gone as far as 15. If the reasoning is extended you can plot a function to represent your friend's position. It would be a probability function with a peak 10 miles away and a descent to zero near the 5- and 15-mile points. The width of the function would depend on the accuracy that you assign to your estimates of speed and the moment of departure.

The wave function that describes an electron has a significance like the probability function that describes the friend's position. It is a more complicated function, and it contains more information.

In fact it is possible to define a function that includes all of the information that is available. Through mathematical operations we can, as it were, interrogate the function to get answers to such questions as these: Where is the electron? How fast is it moving? What is its angular momentum? What is its energy?

In each situation the answer is a probability function. Depending on the state of the electron and the nature of the question, the answer is a wide or narrow probability function. In agreement with the uncertainty principle, an electron that has a *narrow* probability function defining its position has a broad one defining its velocity, and so on.

Electron Orbitals. It becomes plain that the simple picture of an electron as a tiny speck tracing a closed path around a nucleus will not hold up in a wave-function model. An electron that is a tiny speck has a precise position. A speck that is tracing a path has a precise velocity. It is necessary to substitute a wave function that contains this kind of information: The electron is in the vicinity of the nucleus. If a measurement is made to determine its position there is a high probability that it will be found at point *A* and a low probability that it will be found at point *B*. A measurement to determine its velocity will be most likely to result in such and such a value, and so on.

The reader should recognize that the qualitative language of the last few paragraphs is intended to represent something that can be made accurately quantitative. Physicists can compute wave functions for particles with high precision. The wave function can be verified by making quantitative experiments. One cannot, indeed, examine the wave function of a *particular* electron in detail. The first observation that one makes will change the function so much that further measurements no longer apply to the original. However, one can examine a multitude of identical systems—for example, many hydrogen molecules—and determine statistically what kind of wave function properly represents each of the systems.

In this way a wave-function orbital replaces the orbits of the simpler model of the atom. Each orbital represents a state in which an electron can be. Only one electron can occupy an orbital. Other electrons of the atom must occupy their own orbitals. The orbitals are arranged in shells, and the shells have the same significance as the shells of the simpler model.

Nuclear States. Nuclear particles, like the electron, are described by quantum-mechanical wave functions. Because they are much heavier than the electron, the uncertainty that must be allowed in their positions is smaller, and there is no violation of physical laws in assuming that they are bound within the tiny volume of the nucleus.

The states available to nuclear particles are considerably different from the ones occupied by electrons in the outer shells of the atom. We have seen that the nuclear particles are more massive. More important is the fact that the strongest forces that act upon them are short-range forces—like hooks or glue—forces that act only when the particles are close to one another, and not at all when they are distant.