CHAPTER I. INTRODUCTION

1.1. The purpose of this report is to describe the scientific and technical developments in this country since 1940 directed toward the military use of energy from atomic nuclei. Although not written as a "popular" account of the subject, this report is intended to be intelligible to scientists and engineers generally and to other college graduates with a good grounding in physics and chemistry. The equivalence of mass and energy is chosen as the guiding principle in the presentation of the background material of the "Introduction."

THE CONSERVATION OF MASS AND OF ENERGY

1.2. There are two principles that have been cornerstones of the structure of modern science. The first--that matter can be neither created nor destroyed but only altered in form--was enunciated in the eighteenth century and is familiar to every student of chemistry; it has led to the principle known as the law of conservation of mass. The second--that energy can be neither created nor destroyed but only altered in form-- emerged in the nineteenth century and has ever since been the plague of inventors of perpetual-motion machines; it is known as the law of' conservation of energy.
1.3. These two principles have constantly guided and disciplined the development and application of science. For all practical purposes they were unaltered and separate until some five years ago. For most practical purposes they still are so, but it is now known that they are, in fact, two phases of a single principle for we have discovered that energy may sometimes be converted into matter and matter into energy. Specifically, such a conversion is observed in the phenomenon of nuclear fission of uranium, a process in which atomic nuclei split into fragments with the release of an enormous amount of energy. The military use of this energy has been the object of the research and production projects described in this report.

THE EQUIVALENCE OF MASS AND ENERGY

1.4. One conclusion that appeared rather early in the development of the theory of relativity was that the inertial mass of a moving body increased as its speed increased. This implied an equivalence between an increase in energy of motion of a body, that is, its kinetic energy, and an increase in its mass. To most practical physicists and engineers this appeared a mathematical fiction of no practical importance. Even Einstein could hardly have foreseen the present applications, but as early as 1905 he did clearly state that mass and energy were equivalent and suggested that proof of this

equivalence might be found by the study of radioactive substances. He concluded that the amount of energy, E, equivalent to a mass, m, was given by the equation

$$E = mc^2$$

where c is the velocity of light. If this is stated in actual numbers, its startling character is apparent. It shows that one kilogram (2.2 pounds) of matter, if converted entirely into energy, would give 25 billion kilowatt hours of energy. This is equal to the energy that would be generated by the total electric power industry in the United States (as of 1939) running for approximately two months. Compare this fantastic figure with the 8.5 kilowatt hours of heat energy which may be produced by burning an equal amount of coal.

1.5. The extreme size of this conversion figure was interesting in several respects. In the first place, it explained why the equivalence of mass and energy was never observed in ordinary chemical combustion. We now believe that the heat given off in such a combustion has mass associated with it, but this mass is so small that it cannot be detected by the most sensitive balances available. (It is of the order of a few billionths of a gram per mole.) In the second place, it was made clear that no appreciable quantities of matter were being converted into energy in any familiar terrestrial processes, since no such large sources of energy were known. Further, the possibility of initiating or controlling such a conversion in any practical way seemed very remote. Finally, the very size of the conversion factor opened a magnificent field of speculation to philosophers, physicists, engineers, and comic-strip artists. For twenty-five years such speculation was unsupported by direct experimental evidence, but beginning about 1930 such evidence began to appear in rapidly increasing quantity. Before discussing such evidence and the practical partial conversion of matter into energy that is our main theme, we shall review the foundations of atomic and nuclear physics. General familiarity with the atomic nature of matter and with the existence of electrons is assumed. Our treatment will be little more than an outline which may be elaborated by reference to books such as Pollard and Davidson's *Applied Nuclear Physics* and Stranathan's *The "Particles" of Modern Physics.*

RADIOACTIVITY AND ATOMIC STRUCTURE

1.6. First discovered by H. Becquerel in 1896 and subsequently studied by Pierre and Marie Curie, E. Rutherford, and many others, the phenomena of radioactivity have played leading roles in the discovery of the general laws of atomic structure and in the verification of the equivalence of mass and energy.

IONIZATION BY RADIOACTIVE SUBSTANCES

1.7. The first phenomenon of radioactivity observed was the blackening of photographic plates by uranium minerals. Although this effect is still used to some

extent in research on radioactivity, the property of radioactive substances that is of greatest scientific value is their ability to ionize gases. Under normal conditions air and other gases do not conduct electricity-otherwise power lines and electrical machines would not operate in the open as they do. But under some circumstances the molecules of air are broken apart into positively and negatively charged fragments, called ions. Air thus ionized does conduct electricity. Within a few months after the first discovery of radioactivity Becquerel found that uranium had the power to ionize air. Specifically he found that the charge on an electroscope would leak away rapidly through the air if some uranium salts were placed near it. (The same thing would happen to a storage battery if sufficient radioactive material were placed near by.) Ever since that time the rate of discharge of an electroscope has served as a measure of intensity of radioactivity. Furthermore, nearly all present-day instruments for studying radioactive phenomena depend on this ionization effect directly or indirectly. An elementary account of such instruments, notably electroscopes, Geiger-Muller counters, ionization chambers, and Wilson cloud chambers is given in Appendix 1.

THE DIFFERENT RADIATIONS OR PARTICLES

1.8. Evidence that different radioactive substances differ in their ionizing power both in kind and in intensity indicates that there are differences in the "radiations" emitted. Some of the radiations are much more penetrating than others; consequently, two radioactive samples having the same effect on an "unshielded" electroscope may have very different effects if the electroscope is "shielded," i.e., if screens are interposed between the sample and the electroscope. These screens are said to absorb the radiation.

1.9. Studies of absorption and other phenomena have shown that in fact there are three types of "radiation" given off by radioactive substances. There are alpha particles, which are high-speed ionized helium atoms (actually the nuclei of helium atoms), beta particles, which are high-speed electrons, and gamma rays, which are electromagnetic radiations similar to X-rays. Of these only the gamma rays are properly called radiations, and even these act very much like particles because of their short wavelength. Such a "particle" or quantum of gamma radiation is called a photon. In general, the gamma rays are very penetrating, the alpha and beta rays less so. Even though the alpha and beta rays are not very penetrating, they have enormous kinetic energies for particles of atomic size, energies thousands of times greater than the kinetic energies which the molecules of a gas have by reason of their thermal motion, and thousands of times greater than the energy changes per atom in chemical reactions. It was for this reason that Einstein suggested that studies of radioactivity might show the equivalence of mass and energy.

THE ATOM

1.10. Before considering what types of atoms emit alpha, beta and gamma rays, and before discussing the laws that govern such emission, we shall describe the current ideas on how atoms are constructed, ideas based partly on the study of radioactivity.

1.11. According to our present view every atom consists of a smallheavy nucleus approximately 10^{-12} cm in diameter surrounded by a largely empty region 10^8 cm in diameter in which electrons move somewhat like planets about the sun. The nucleus carries an integral number of positive charges, each 1.6×10^{-19} coulombs in size. (See Appendix 2 for a discussion of units.) Each electron carries one negative charge of this same size, and the number of electrons circulating around the nucleus is equal to the number of positive charges on the nucleus so that the atom as a whole has a net charge of zero.

1.12. *Atomic Number and Electronic Structure.* The number of positive charges in the nucleus is called the atomic number, Z. It determines the number of electrons in the extranuclear structure, and this in turn determines the chemical properties of the atom. Thus all the atoms of a given chemical element have the same atomic number, and conversely all atoms having the same atomic number are atoms of the same element regardless of possible differences in their nuclear structure. The extranuclear electrons in an atom arrange themselves in successive shells according to well-established laws. Optical spectra arise from disturbances in the outer parts of this electron structure; X-rays arise from disturbances of the electrons close to the nucleus. The chemical properties of an atom depend on the outermost electrons, and the formation of chemical compounds is accompanied by minor rearrangements of these electronic structures. Consequently, when energy is obtained by oxidation, combustion, explosion, or other chemical processes, it is obtained at the expense of these structures so that the arrangement of the electrons in the products of the process must be one of lowered energy content. (Presumably the total mass of these products is correspondingly lower but not detectably so.) The atomic nuclei are not affected by any chemical process.

1.13. *Mass Number.* Not only is the positive charge on a nucleus always an integral number of electronic charges, but the mass of the nucleus is always *approximately* a whole number times a fundamental unit of mass which is almost the mass of a proton, the nucleus of a hydrogen atom. (See Appendix 2.) This whole number is called the mass number, A, and is always at least twice as great as the atomic number except in the cases of hydrogen and a rare isotope of helium. Since the mass of a proton is about 1,800 times that of an electron, the mass of the nucleus is very nearly the whole mass of the atom.
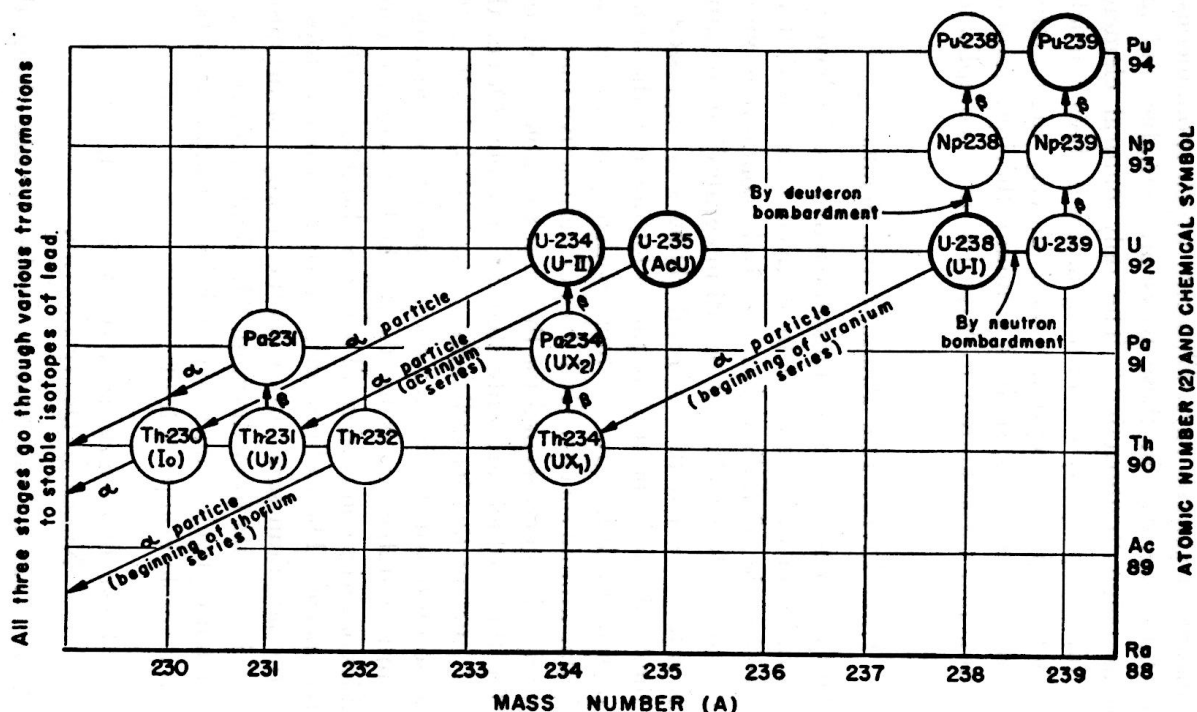
1.14. *Isotopes and Isobars.* Two species of atoms having the same atomic number but different mass numbers are called isotopes. They are chemically identical, being merely two species of the same chemical element. If two species of atoms have the same mass number but different atomic numbers, they are called isobars and represent two different chemical elements.

RADIOACTIVITY AND NUCLEAR CHANGE

1.15. If an atom emits an alpha particle (which has an atomic number of two and a mass of four), it becomes an atom of a different element with an atomic number lower by two and a mass number lower by four. The emission by a nucleus of a beta particle increases the atomic number by one and leaves the mass number unaltered. In some cases, these changes are accompanied by the emission of gamma rays. Elements which spontaneously change or "disintegrate" in these ways are unstable and are described as being "radioactive." The only natural elements which exhibit this property of emitting alpha or beta particles are (with a few minor exceptions) those of very high atomic numbers and mass numbers, such as uranium, thorium, radium, and actinium, i.e., those known to have the most complicated nuclear structures.


HALF-LIVES; THE RADIOACTIVE SERIES

1.16. All the atoms of a particular radioactive species have the same probability of disintegrating in a given time, so that an appreciable sample of radioactive material, containing many millions of atoms, always changes or "disintegrates" at the same rate. This rate at which the material changes is expressed in terms of the "half-life," the time required for one half the atoms initially present to disintegrate, which evidently is constant for any particular atomic species. Half-lives of radioactive materials range from fractions of a second for the most unstable to billions of years for those which are only slightly unstable. Often, the "daughter" nucleus like its radioactive "parent" is itself radioactive and so on down the line for several successive generations of nuclei until a stable one is finally reached. There are three such families or series comprising all together about forty different radioactive species. The radium series starts from one isotope of uranium, the actinium series from another isotope of uranium, and the thorium series from thorium. The final product of each series, after ten or twelve successive emissions of alpha and beta particles, is a stable isotope of lead.

The beginnings of the three natural radioactive series and the new transuranic elements, neptunium and plutonium.

FIRST DEMONSTRATION OF ARTIFICIAL NUCLEAR DISINTEGRATION

1.17. Before 1919 no one had succeeded in disturbing the stability of ordinary nuclei or affecting the disintegration rates of those that were naturally radioactive. In 1919 Rutherford showed that high-energy alpha particles could cause an alteration in the nucleus of an ordinary element. Specifically he succeeded in changing a few atoms of nitrogen into atoms of oxygen by bombarding them with alpha particles. The process involved may be written as

$$He^4 + N^{14} \rightarrow O^{17} + H^1$$
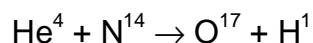
meaning that a helium nucleus of mass number 4 (an alpha particle) striking a nitrogen nucleus of mass number 14 produces an oxygen nucleus of mass number 17 and a hydrogen nucleus of mass number 1. The hydrogen nucleus, known as the "proton," is of special importance since it has the smallest mass of any nucleus. Although protons do not appear in natural radioactive processes, there is much direct evidence that they can be knocked out of nuclei.

The Neutron

1.18. In the decade following Rutherford's work many similar experiments were performed with similar results. One series of experiments of this type led to the discovery of the neutron, which will be discussed in some detail since the neutron is practically the theme song of this whole project.

1.19. In 1930 W. Bothe and H. Becker in Germany found that if the very energetic natural alpha particles from polonium fell on certain of the light elements, specifically beryllium, boron, or lithium, an unusually penetrating radiation was produced. At first this radiation was thought to be gamma radiation although it was more penetrating than any gamma rays known, and the details of experimental results were very difficult to interpret on this basis. The next important contribution was reported in 1932 by Irene Curie and F. Joliot in Paris. They showed that if this unknown radiation fell on paraffin or any other hydrogen-containing compound it ejected protons of very high energy. This was not in itself inconsistent with the assumed gamma-ray nature of the new radiation, but detailed quantitative analysis of the data became increasingly difficult to reconcile with such an hypothesis. Finally (later in 1932) J. Chadwich in England performed a series of experiments showing that the gamma-ray hypothesis was untenable. He suggested that in fact the new radiation consisted of uncharged particles of approximately the mass of the proton, and he performed a series of experiments verifying his suggestion. Such uncharged particles are now called neutrons.

1.20. The one characteristic of neutrons which differentiates them from other subatomic particles is the fact that they are uncharged. This property of neutrons delayed their discovery, makes them very penetrating, makes it impossible to observe them directly, and makes them very important as agents in nuclear change. To be sure, an atom in its normal state is also uncharged, but it is ten thousand times larger than a neutron and consists of a complex system of negatively charged electrons widely spaced around a positively charged nucleus. Charged particles (such as protons, electrons, or alpha particles) and electromagnetic radiations (such as gamma rays) lose energy in passing through matter. They exert electric forces which ionize atoms of the material through which they pass. (It is such ionization processes that make the air electrically conducting in the path of electric sparks and lightning flashes.) The energy taken up in ionization equals the energy lost by the charged particle, which slows down, or by the gamma ray, which is absorbed. The neutron, however, is unaffected by such forces; it is affected only by a very short-range force, i.e., a force that comes into play when the neutron comes very close indeed to an atomic nucleus. This is the kind of force that holds a nucleus together in spite of the mutual repulsion of the positive charges in it. Consequently a free neutron goes on its way unchecked until it makes a "head-on" collision with an atomic nucleus. Since nuclei are very small, such collisions occur but rarely and the neutron travels a long way before colliding. In the case of a collision of the "elastic" type, the ordinary laws of momentum apply as they do in the elastic collision of billiard balls. If the nucleus that is struck is heavy, it acquires relatively little speed, but if it is a proton, which is approximately equal in mass to the neutron, it is projected forward with a large fraction of the original speed of the

neutron, which is itself correspondingly slowed. Secondary projectiles resulting from these collisions may be detected, for they are charged and produce ionization. The uncharged nature of the neutron makes it not only difficult to detect but difficult to control. Charged particles can be accelerated, decelerated, or deflected by electric or magnetic fields which have no effect on neutrons. Furthermore, free neutrons can be obtained only from nuclear disintegrations; there is no natural supply. The only means we have of controlling free neutrons is to put nuclei in their way so that they will be slowed and deflected or absorbed by collisions. As we shall see, these effects are of the greatest practical importance.

THE POSITRON AND THE DEUTERON

1.21. The year 1932 brought the discovery not only of the neutron but also of the positron. The positron was first observed by C. D. Anderson at the California Institute of Technology. It has the same mass and the same magnitude of charge as the electron, but the charge is positive instead of negative. Except as a particle emitted by artificially radioactive nuclei, it is of little interest to us.

1.22. One other major discovery marked the year 1932. H. C.Urey, F. G. Brickwedde, and G. M. Murphy found that hydrogen had an isotope of mass number 2, present in natural hydrogen to one part in 5,000. Because of its special importance this heavy species of hydrogen is given a name of its own, deuterium, and the corresponding nucleus is called the deuteron. Like the alpha particle the deuteron is not one of the fundamental particles but does play an important role in certain processes for producing nuclear disintegration.

NUCLEAR STRUCTURE

1.23. The idea that all elements are made out of a few fundamental particles is an old one. It is now firmly established. We believe that there are three fundamental particles--the neutron, the proton, and the electron. A complete treatise would also discuss the positron, which we have mentioned, the neutrino and the mesotron. The deuteron and alpha particle, which have already been mentioned, are important complex particles.

1.24. According to our present views the nuclei of all atomic species are made up of neutrons and protons. The number of protons is equal to the atomic number, Z. The number of neutrons, N , is equal to the difference between the mass number and the atomic number, or A - Z. There are two sets of forces acting on these particles, ordinary electric coulomb forces of repulsion between the positive charges and very short-range, forces between all the particles. These last forces are only partly understood, and we shall not attempt to discuss them. Suffice it to say that combined effects of these attractive and repulsive forces are such that only certain combinations of neutrons and protons are stable. If the neutrons and protons are few in number, stability occurs when their numbers are about equal. For larger nuclei, the proportion of neutrons

required for stability is greater. Finally, at the end of the periodic table, where the number of protons is over 90 and the number of neutrons nearly 150, there are no completely stable nuclei. (Some of the heavy nuclei are almost stable as evidenced by very long half-lives.) If an unstable nucleus is formed artificially by adding an extra neutron or proton, eventually a change to a stable form occurs. Strangely enough, this is not accomplished by ejecting a proton or a neutron but by ejecting a positron or an electron; apparently within the nucleus a proton converts itself into a neutron and positron (or a neutron converts itself into a proton and electron), and the light charged particle is ejected. In other words, the mass number remains the same but the atomic number changes. The stability conditions are not very critical so that for a given mass number, i.e., given total number of protons and neutrons, there may be several stable arrangements of protons and neutrons (at most three or five) giving several isobars. For a given atomic number, i.e., given number of protons, conditions can vary still more widely so that some of the heavy elements have as many as ten or twelve stable isotopes. Some two hundred and fifty different stable nuclei have been identified, ranging in mass number from one to two hundred and thirty-eight and in atomic number from one to ninety-two.

1.25. All the statements we have been making are based on experimental evidence. The theory of nuclear forces is still incomplete, but it has been developed on quantum-mechanical principles sufficiently to explain not only the above observations but more detailed empirical data on artificial radioactivity and on differences between nuclei with odd and even mass numbers.

ARTIFICIAL RADIOACTIVITY

1.26. We mentioned the emission of positrons or electrons by nuclei seeking stability. Electron emission (beta rays) was already familiar in the study of naturally radioactive substances, but positron emission was not found in the case of such substances. In fact, the general discussion presented above obviously was based in part on information that cannot be presented in this report. We shall, however, give a brief account of the discovery of "artificial" radioactivity and what is now known about it.

1.27. In 1934, Curie and Joliot reported that certain light elements (boron, magnesium, aluminum) which had been bombarded with alpha particles continued to emit positrons for some time after the bombardment was stopped. In other words, alpha-particle bombardment produced radioactive forms of boron, magnesium, and aluminum. Curie and Joliot actually measured half-lives of 14 minutes, 2.5 minutes, and 3.25 minutes, respectively, for the radioactive substances formed by the alpha-particle bombardment.

1.28. This result stimulated similar experiments all over the world. In particular, E. Fermi reasoned that neutrons, because of their lack of charge, should be effective in penetrating nuclei, especially those of high atomic number which repel protons and alpha particles strongly. He was able to verify his prediction almost immediately, finding that the nucleus of the bombarded atom captured the neutron and that there was thus produced an unstable nucleus which then achieved stability by emitting an

electron. Thus, the final, stable nucleus was one unit higher in mass number and one unit higher in atomic number than the initial target nucleus.

1.29. As a result of innumerable experiments carried out since 1934, radioactive isotopes of nearly every element in the periodic table can now be produced. Some of them revert to stability by the emission of positrons, some by the emission of electrons, some by a process known as K-electron capture which we shall not discuss, and a small number (probably three) by alpha-particle emission. Altogether some five hundred unstable nuclear species have been observed, and in most cases their atomic numbers and mass numbers have been identified.

1.30. Not only do these artificially radioactive elements play an important role throughout the project with which we are concerned, but their future value in medicine, in "tracer" chemistry, and in many other fields of research can hardly be overestimated.

ENERGY CONSIDERATIONS

NUCLEAR BINDING ENERGIES

1.31. In describing radioactivity and atomic structure we have deliberately avoided quantitative data and have not mentioned any applications of the equivalence of mass and energy which we announced as the guiding principle of this report. Now when we must speak of quantitative details, not merely of general principles.

1.32. We have spoken of stable and unstable nuclei made up of assemblages of protons and neutrons held together by nuclear forces. It is a general principle of physics that work must be done on a stable system to break it up. Thus, if an assemblage of neutrons and protons is stable, energy must be supplied to separate its constituent particles. If energy and mass are really equivalent, then the total mass of a stable nucleus should be less than the total mass of the separate protons and neutrons that go to make it up. This mass difference, then, should be equivalent to the energy required to disrupt the nucleus completely, which is called the binding energy. Remember that the masses of all nuclei were "approximately" whole numbers. It is the small differences from whole numbers that are significant.

1.33. Consider the alpha particle as an example. It is stable; since its mass number is four and its atomic number two it consists of two protons and two neutrons. The mass of a proton is 1.00758 and that of a neutron is 1.00893 (see Appendix 2), so that the total mass of the separate components of the helium nucleus is

$$2 \times 1.00758 + 2 \times 1.00893 = 4.03302$$

whereas the mass of the helium nucleus itself is 4.00280. Neglecting the last two decimal places we have 4.033 and 4.003, a difference of 0.030 mass units. This, then, represents the "binding energy" of the protons and neutrons in the helium nucleus. It looks small, but recalling Einstein's equation, $E = mc^2$, we remember that a small amount of mass is equivalent to a large amount of energy. Actually 0.030 mass units is equal to 4.5×10^{-5} ergs per nucleus or 2.7×10^{19} ergs per gram molecule of helium. In

units more familiar to the engineer or chemist, this means that to break up the nuclei of all the helium atoms in a gram of helium would require 1.62×10^{11} gram calories or 190,000 kilowatt hours of energy. Conversely, if free protons and neutrons could be assembled into helium nuclei, this energy would be released.

1.34. Evidently it is worth exploring the possibility of getting energy by combining protons and neutrons or by transmuting one kind of nucleus into another. Let us begin by reviewing present-day knowledge of the binding energies of various nuclei.

MASS SPECTRA AND BINDING ENERGIES

1.35. Chemical atomic-weight determinations give the average weight of a large number of atoms of a given element. Unless the element has only one isotope, the chemical atomic weight is not proportional to the mass of individual atoms. The mass spectrograph developed by F. W. Aston and others from the earlier apparatus of J. J. Thomson measures the masses of individual isotopes. Indeed, it was just such measurements that proved the existence of isotopes and showed that on the atomic-weight scale the masses of all atomic species were very nearly whole numbers. These whole numbers, discovered experimentally, are the mass numbers which we have already defined and which represent the sums of the numbers of the protons and neutrons; their discovery contributed largely to our present views that all nuclei are combinations of neutrons and protons.

1.36. Improved mass spectrograph data supplemented in a few cases by nuclear reaction data have given accurate figures for binding energies for many atomic species over the whole range of atomic masses. This binding energy, B, is the difference between the true nuclear mass, M, and the sum of the masses of all the protons and neutrons in the nucleus. That is,

$$B = (ZM_p + NM_n) - M$$

where M_p and M_n are the masses of the proton and neutron respectively, Z is the number of protons, $N = A - Z$ is the number of neutrons, and M is the true mass of the nucleus. It is more interesting to study the binding energy per particle, B/A, than B itself. Such a study shows that, apart from fluctuations in the light nuclei, the general trend of the binding energy per particle is to increase rapidly to a flat maximum around A = 60 (nickel) and then decrease again gradually. Evidently the nuclei in the middle of the periodic table--nuclei of mass numbers 40 to 100--are the most strongly bound. Any nuclear reaction where the particles in the resultant nuclei are more strongly bound than the particles in the initial nuclei will release energy. Speaking in thermochemical terms, such reactions are exothermic. Thus, in general, energy may be gained by combining light nuclei to form heavier ones or by breaking very heavy ones into two or three smaller fragments. Also, there are a number of special cases of exothermic nuclear disintegrations among the first ten or twelve elements of the periodic table, where the binding energy per particle varies irregularly from one element to another.

1.37. So far we seem to be piling one supposition on another. First we assumed that mass and energy were equivalent; now we are assuming that atomic nuclei can be rearranged with a consequent reduction in their total mass, thereby releasing energy which can then be put to use. It is time to talk about some experiments that convinced physicists of the truth of these statements.

EXPERIMENTAL PROOF OF THE EQUIVALENCE OF MASS AND ENERGY

1.38. As we have already said, Rutherford's work in 1919 on artificial nuclear disintegration was followed by many similar experiments. Gradual improvement in high-voltage technique made it possible to substitute artificially produced high-speed ions of hydrogen or helium for natural alpha particles. J. D. Cockcroft and E. T. S. Walton in Rutherford's laboratory were the first to succeed in producing nuclear changes by such methods. In 1932 they bombarded a target of lithium with protons of 700 kilovolts energy and found that alpha particles were ejected from the target as a result of the bombardment. The nuclear reaction which occurred can be written symbolically as

$$_3Li^7 + {_1}H^1 \rightarrow {_2}He^4 + {_2}He^4$$
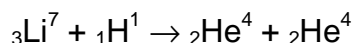
where the subscript represents the positive charge on the nucleus (atomic number) and the superscript is the number of massive particles in the nucleus (mass number). As in a chemical equation, quantities on the left must add up to those on the right; thus the subscripts total four and the superscripts eight on each side.

1.39. Neither mass nor energy has been included in this equation. In general, the incident proton and the resultant alpha particles will each have kinetic energy. Also, the mass of two alpha particles will not be precisely the same as the sum of the masses of a proton and a lithium atom. According to our theory, the totals of mass and energy taken together should be the same before and after the reaction. The masses were known from mass spectra. On the left ($Li^7 + H^1$) they totalled 8.0241, on the right ($2He^4$) 8.0056, so that 0.0185 units of mass had disappeared in the reaction. The experimentally determined energies of the alpha particles were approximately 8.5 million electron volts each, a figure compared to which the kinetic energy of the incident proton could be neglected. Thus 0.0185 units of mass had disappeared and 17 Mev of kinetic energy had appeared. Now 0.0185 units of mass is 3.07 X 10^{26} grams, 17 Mev is 27.2 X 10^{-6} ergs and c is 3 X 10^{10} cm/sec. (See Appendix 2.) If we substitute these figures into Einstein's equation, $E = mc^2$, on the left side we have 27.2 X 10^{-6} ergs and on the right side we have 27.6 X 10^{-6} ergs, so that the equation is found to be satisfied to a good approximation. In other words, these experimental results prove that the equivalence of mass and energy was correctly stated by Einstein.

NUCLEAR REACTIONS

METHODS OF NUCLEAR BOMBARDMENT

1.40. Cockcroft and Walton produced protons of fairly high energy by ionizing gaseous hydrogen and then accelerating the ions in a transformer-rectifier high-voltage apparatus. A similar procedure can be used to produce high-energy deuterons from deuterium or high-energy alpha particles from helium. Higher energies can be attained by accelerating the ions in cyclotrons or Van de Graaff machines. However, to obtain high-energy gamma radiation or--most important of all--to obtain neutrons, nuclear reactions themselves must be used as sources. Radiations of sufficiently high energy come from certain naturally radioactive materials or from certain bombardments. Neutrons are commonly produced by the bombardment of certain elements, notably beryllium or boron, by natural alpha particles, or by bombarding suitable targets with protons or deuterons. The most common source of neutrons is a mixture of radium and beryllium where the alpha particles from radium and its decay products penetrate the Be^9 nuclei, which then give off neutrons and become stable C^{12} nuclei (ordinary carbon). A frequently used "beam" source of neutrons results from accelerated deuterons impinging on "heavy water" ice. Here the high-speed deuterons strike the target deuterons to produce neutrons and He^3 nuclei. Half a dozen other reactions are also used involving deuterium, lithium, beryllium, or boron as targets. Note that in all these reactions the total mass number and total charge number are unchanged.
1.41. To summarize, the agents that are found to initiate nuclear reactions are--in approximate order of importance--neutrons, deuterons, protons, alpha particles, gamma rays and, rarely, heavier particles.

RESULTS OF NUCLEAR BOMBARDMENT

1.42. Most atomic nuclei can be penetrated by at least one type of atomic projectile (or by gamma radiation). Any such penetration may result in a nuclear rearrangement in the course of which a fundamental particle is ejected or radiation is emitted or both. The resulting nucleus may be one of the naturally available stable species, or--more likely--it may be an atom of a different type which is radioactive, eventually changing to still a different nucleus. This may in turn be radioactive and, if so, will again decay. The process continues until all nuclei have changed to a stable type. There are two respects in which these artificially radioactive substances differ from the natural ones: many of them change by emitting positrons (unknown in natural radioactivity) and very few of them emit alpha particles. In every one of the cases where accurate measurements have been made, the equivalence of mass and energy has been demonstrated and the mass-energy total has remained constant. (Sometimes it is necessary to invoke neutrinos to preserve mass-energy conservation.)

NOTATION

1.43. A complete description of a nuclear reaction should include the nature, mass and energy of the incident particle, also the nature (mass number and atomic number), mass and energy (usually zero) of the target particle, also the nature, mass and energy of the ejected particles (or radiation), and finally the nature, mass and energy of the remainder. But all of these are rarely known and for many purposes their complete specification is unnecessary. A nuclear reaction is frequently described by a notation that designates first the target by chemical symbol and mass number if known, then the projectile, then the emitted particle, and then the remainder. In this scheme the neutron is represented by the letter n, the proton by p, the deuteron by d, the alpha particle by α, and the gamma ray by γ. Thus the radium-beryllium, neutron reaction can be written $Be^9(\alpha, n)C^{12}$ and the deuteron-deuteron reaction $H^2(d, n)He^3$.

TYPES OF REACTION

1.44. Considering the five different particles (n, p. d, α, γ) both as projectiles and emitted products, we might expect to find twenty-five combinations possible. Actually the deuteron very rarely occurs as a product particle, and the photon initiates only two types of reaction. There are, however, a few other types of reaction, such as (n, 2n), (d, H^3), and fission, which bring the total known types to about twenty-five. Perhaps the (n, γ) reaction should be specifically mentioned as it is very important in one process which will concern us. It is often called "radiative capture" since the neutron remains in the nucleus and only a gamma ray comes out.

PROBABILITY AND CROSS SECTION

1.45. So far nothing has been said about the probability of nuclear reactions. Actually it varies widely. There is no guarantee that a neutron or proton headed straight for a nucleus will penetrate it at all. It depends on the nucleus and on the incident particle. In nuclear physics, it is found convenient to express probability of a particular event by a "cross section." Statistically, the centers of the atoms in a thin foil can be considered as points evenly distributed over a plane. The center of an atomic projectile striking this plane has geometrically a definite probability of passing within a certain distance (r) of one of these points. In fact, if there are n atomic centers in an area A of the plane, this probability is $n*\pi*r^2/A$, which is simply the ratio of the aggregate area of circles of radius r drawn around the points to the whole area. If we think of the atoms as impenetrable steel discs and the impinging particle as a bullet of negligible diameter, this ratio is the probability that the bullet will strike a steel disc, i.e., that the atomic projectile will be stopped by the foil. If it is the fraction of impinging atoms getting *through* the foil which is measured, the result can still be expressed in terms of the equivalent stopping cross section of the atoms. This notion can be extended to any interaction between the impinging particle and the atoms in the target. For example, the probability that an alpha particle striking a beryllium target will produce a neutron can be expressed is the equivalent cross section of beryllium for this type of reaction.

1.46. In nuclear physics it is conventional to consider that the impinging particles have negligible diameter. The technical definition of cross section for any nuclear process is therefore:

```
     number of
processes occurring
------------------- = (number of target nuclei per cm²) X (nuclear
     number of                                      cross section in cm²)
incident particles
```

It should be noted that this definition is for the cross section per nucleus. Cross sections can be computed for any sort of process, such as capture scattering, production of neutrons, etc. In many cases, the number of particles emitted or scattered in nuclear processes is not measured directly; one merely measures the attenuation produced in a parallel beam of incident particles by the interposition of a known thickness of a particular material. The cross section obtained in this way is called the total cross section and is usually denoted by a σ.

1.47. As indicated in paragraph 1.11, the typical nuclear diameter is of the order of 10^{-12} cm. We might therefore expect the cross sections for nuclear reactions to be of the order of $\pi^* d^2/4$ or roughly 10^{-24} cm^2 and this is the unit in which they are usually expressed. Actually the observed cross sections vary enormously. Thus for slow neutrons absorbed by the (n, γ) reaction the cross section in some cases is as much as $1,000 \times 10^{-24}$ cm^2, while the cross sections for transmutations by gamma-ray absorption are in the neighborhood of $(1/1,000) \times 10^{-24}$ cm^2.

PRACTICABILITY OF ATOMIC POWER IN 1939

SMALL SCALE OF EXPERIMENTS

1.48. We have talked glibly about the equivalence of mass and energy and about nuclear reactions, such as that of protons on lithium, where energy was released in relatively large amounts. Now let us ask why atomic power plants did not spring up all over the world in the 'thirties. After all, if we can get 2.76×10^5 ergs from an atom of lithium struck by a proton, we might expect to obtain approximately half a million kilowatt hours by combining a gram of hydrogen with seven grams of lithium. It looks better than burning coal. The difficulties are in producing the high-speed protons and in controlling the energy produced. All the experiments we have been talking about were done with very small quantities of material, large enough in numbers of atoms, to be sure, but in terms of ordinary masses infinitesimal--not tons or pounds or grams, but fractions of micrograms. The amount of energy used up in the experiment was always far greater than the amount generated by the nuclear reaction.

1.49. Neutrons are particularly effective in producing nuclear disintegration. Why weren't they used? If their initial source was an ion beam striking a target, the limitations discussed in the last paragraph applied. If a radium and beryllium source was to be used, the scarcity of radium was a difficulty.
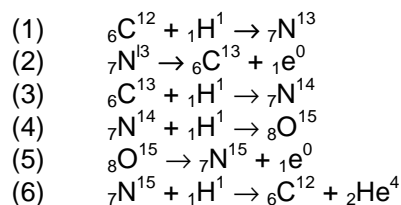
THE NEED OF A CHAIN REACTION

1.50. Our common sources of power, other than sunlight and water power, are chemical reactions--usually the combustion of coal or oil. They release energy as the result of rearrangements of the outer electronic structures of the atoms, the same kind of process that supplies energy to our bodies. Combustion is always self-propagating; thus lighting a fire with a match releases enough heat to ignite the neighboring fuel, which releases more heat which ignites more fuel, and so on. In the nuclear reactions we have described this is not generally true; neither the energy released nor the new particles formed are sufficient to maintain the reaction. But we can imagine nuclear reactions emitting particles of the same sort that initiate them and in sufficient numbers to propagate the reaction in neighboring nuclei. Such a self-propagating reaction is called a "chain reaction" and such conditions must be achieved if the energy of the nuclear reactions with which we are concerned is to be put to large-scale use.

PERIOD OF SPECULATION

1.51. Although there were no atomic power plants built in the 'thirties, there were plenty of discoveries in nuclear physics and plenty of speculation. A theory was advanced by H. Bethe to explain the heat of the sun by a cycle of nuclear changes involving carbon, hydrogen, nitrogen, and oxygen, and leading eventually to the formation of helium.* This theory is now generally accepted. The discovery of a few (n, 2n) nuclear reactions (i.e., neutron-produced and neutron-producing reactions) suggested that a self-multiplying chain reaction might be initiated under the right conditions. There was much talk of atomic power and some talk of atomic bombs. But the last great step in this preliminary period came after four years of stumbling. The effects of neutron bombardment of uranium, the most complex element known, had been studied by some of the ablest physicists. The results were striking but confusing. The story of their gradual interpretation is intricate and highly technical, a fascinating tale of theory and experiment. Passing by the earlier inadequate explanations, we shall go directly to the final explanation, which, as so often happens, is relatively simple.

* The series of reactions postulated was

(1) $_6C^{12} + {}_1H^1 \rightarrow {}_7N^{13}$
(2) $_7N^{l3} \rightarrow {}_6C^{13} + {}_1e^0$
(3) $_6C^{13} + {}_1H^1 \rightarrow {}_7N^{14}$
(4) $_7N^{14} + {}_1H^1 \rightarrow {}_8O^{15}$
(5) $_8O^{15} \rightarrow {}_7N^{15} + {}_1e^0$
(6) $_7N^{15} + {}_1H^1 \rightarrow {}_6C^{12} + {}_2He^4$

The net effect is the transformation of hydrogen into helium and positrons (designated as $_1e^0$) and the release of about thirty million electron volts energy.

DISCOVERY OF URANIUM FISSION

1.52. As has already been mentioned, the neutron proved to be the most effective particle for inducing nuclear changes. This was particularly true for the elements of highest atomic number and weight where the large nuclear charge exerts strong repulsive forces on deuteron or proton projectiles but not on uncharged neutrons. The results of the bombardment of uranium by neutrons had proved interesting and puzzling. First studied by Fermi and his colleagues in 1934, they were not properly interpreted until several years later.

1.53. On January 16, 1939, Niels Bohr of Copenhagen, Denmark, arrived in this country to spend several months in Princeton, N. J., and was particularly anxious to discuss some abstract problems with Einstein. (Four years later Bohr was to escape from Nazi-occupied Denmark in a small boat.) Just before Bohr left Denmark two of his colleagues, O. R. Frisch and L. Meitner (both refugees from Germany), had told him their guess that the absorption of a neutron by a uranium nucleus sometimes caused that nucleus to split into approximately equal parts with the release of enormous quantities of energy, a process that soon began to be called nuclear "fission." The occasion for this hypothesis was the important discovery of O. Hahn and F. Strassmann in Germany (published in *Naturwissenschaften* in early January 1939) which proved that an isotope of barium was produced by neutron bombardment of uranium. Immediately on arrival in the United States Bohr communicated this idea to his former student J. A. Wheeler and others at Princeton, and from them the news spread by word of mouth to neighboring physicists including E. Fermi at Columbia University. As a result of conversations among Fermi, J. R. Dunning, and G. B. Pegram, a search was undertaken at Columbia for the heavy pulses of ionization that would be expected from the flying fragments of the uranium nucleus. On January 26, 1939, there was a conference on theoretical physics at Washington, D. C., sponsored jointly by the George Washington University and the Carnegie Institution of Washington. Fermi left New York to attend this meeting before the Columbia fission experiments had been tried. At the meeting Bohr and Fermi discussed the problem of fission, and in particular Fermi mentioned the possibility that neutrons might be emitted during the process. Although this was only a guess, its implication of the possibility of a chain reaction was obvious. A number of sensational articles
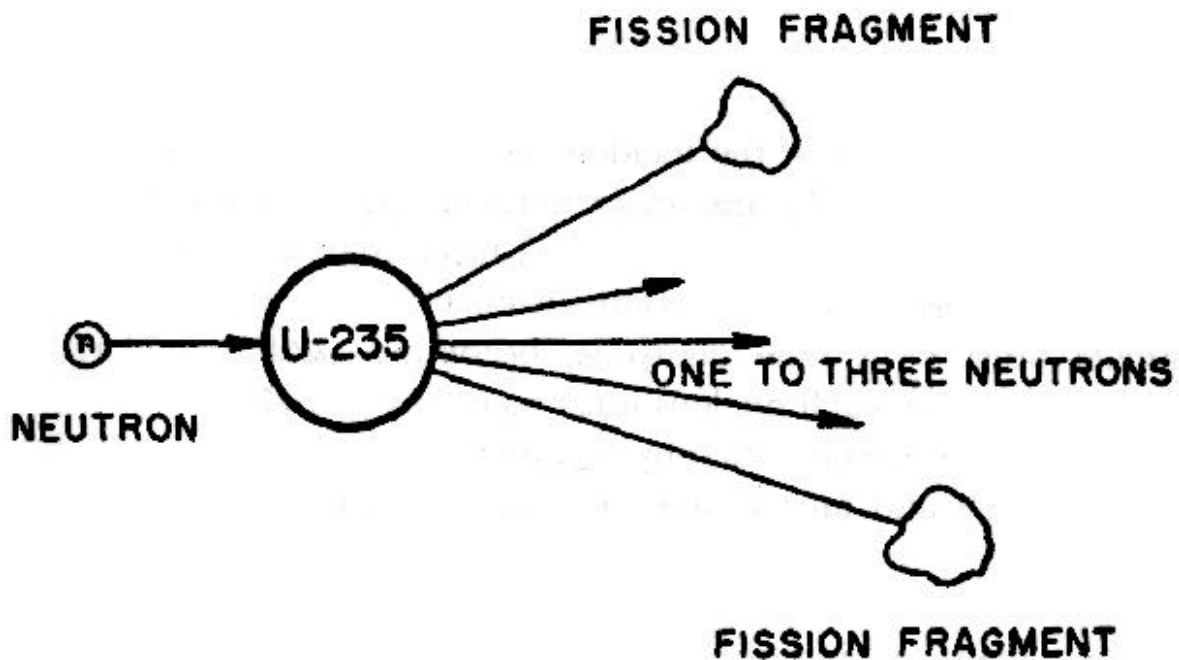
were published in the press on this subject. Before the meeting in Washington was over, several other experiments to confirm fission had been initiated, and positive experimental confirmation was reported from four laboratories (Columbia University, Carnegie Institution of Washington, Johns Hopkins University, University of California) in the February 15, 1939, issue of the *Physical Review*. By this time Bohr had heard that similar experiments had been made in his laboratory in Copenhagen about January 15. (Letter by Frisch to *Nature* dated January 16, 1939, and appearing in the February 18 issue.) F. Joliot in Paris had also published his first results in the *Comptes Rendus* of January 30, 1939. From this time on there was a steady flow of papers on the subject of fission, so that by the time (December 6, 1939) L. A. Turner of Princeton wrote a review article on the subject in the *Reviews of Modern Physics* nearly one hundred papers had appeared. Complete analysis and discussion of these papers have appeared in Turner's article and elsewhere.

GENERAL DISCUSSION OF FISSION

1.54. Consider the suggestion of Frisch and Meitner in the light of the two general trends that had been discovered in nuclear structure: first, that the proportion of neutrons goes up with atomic number; second, that the binding energy per particle is a maximum for the nuclei of intermediate atomic number. Suppose the U-238 nucleus is broken exactly in half; then, neglecting the mass of the incident neutron, we have two nuclei of atomic number 46 and mass number 119. But the heaviest stable isotope of palladium (Z = 46) has a mass number of only 110. Therefore to reach stability each of

these imaginary new nuclei must eject nine neutrons, becoming $_{46}Pd^{110}$ nuclei; or four neutrons in each nucleus must convert themselves to protons by emitting electrons, thereby forming stable tin nuclei of mass number 119 and atomic number 50; or a combination of such ejections and conversions must occur to give some other pair of stable nuclei. Actually, as was suggested by Hahn and Strassmann's identification of barium (Z = 56, A = 135 to 140) as a product of fission, the split occurs in such a way as to produce two unequal parts of mass numbers about 140 and 90 with the emission of a few neutrons and subsequent radioactive decay by electron emission until stable nuclei are formed. Calculations from binding-energy data show that any such rearrangement gives an aggregate resulting mass considerably less than the initial mass of the uranium nucleus, and thus that a great deal of energy must be released.

1.55. Evidently, there were three major implications of the phenomenon of fission: the release of energy, the production of radioactive atomic species and the possibility of a neutron chain reaction. The energy release might reveal itself in kinetic energy of the fission fragments and in the subsequent radioactive disintegration of the products. The possibility of a neutron chain reaction depended on whether neutrons were in fact emitted--a possibility which required investigation.

1.56. These were the problems suggested by the discovery of fission, the kind of problem reported in the journals in 1939 and 1940 and since then investigated largely in secret. The study of the fission process itself, including production of neutrons and fast fragments, has been largely carried out by physicists using counters, cloud chambers, etc. The study and identification of the fission products has been carried out largely by chemists, who have had to perform chemical separations rapidly even with submicroscopic quantities of material and to make repeated determinations of the half-lives of unstable isotopes. We shall summarize the state of knowledge as of June 1940. By that time the principal facts about fission had been discovered and revealed to the scientific world. A chain reaction had not been obtained, but its possibility--at least in principle--was clear and several paths that might lead to it had been suggested.

STATE OF KNOWLEDGE IN JUNE 1940
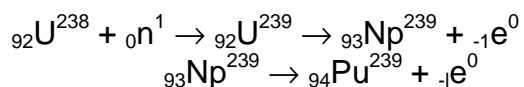

DEFINITE AND GENERALLY KNOWN INFORMATION ON FISSION

1.57. All the following information was generally known in June 1940, both here and abroad:

(1) That three elements--uranium, thorium, and protoactinium --when bombarded by neutrons sometimes split into approximately equal fragments, and that these fragments were isotopes of elements in the middle of the periodic table, ranging from selenium (Z = 34) to lanthanum (Z = 57).

(2) That most of these fission fragments were unstable, decaying radioactively by successive emission of beta particles through a series of elements to various stable forms.

(3) That these fission fragments had very great kinetic energy.
(4) That fission of thorium and protoactinum was caused only by fast neutrons (velocities of the order of thousands of miles per second).
(5) That fission in uranium could be produced by fast or slow (so-called thermal velocity) neutrons; specifically, that thermal neutrons caused fission in one isotope, U-235, but not in the other, U-238, and that fast neutrons had a lower probability of causing fission in U-235 than thermal neutrons.
(6) That at certain neutron speeds there was a large capture cross section in U-238 producing U-239 but not fission.
(7) That the energy released per fission of a uranium nucleus was approximately 200 million electron volts.
(8) That high-speed neutrons were emitted in the process of fission.
(9) That the average number of neutrons released per fission was somewhere between one and three.
(10) That high-speed neutrons could lose energy by inelastic collision with uranium nuclei without any nuclear reaction taking place.
(11) That most of this information was consistent with the semi-empirical theory of nuclear structure worked out by Bohr and Wheeler and others; this suggested that predictions based on this theory had a fair chance of success.

SUGGESTION OF PLUTONIUM FISSION

1.58. It was realized that radiative capture of neutrons by U-238 would probably lead by two successive beta-ray emissions to the formation of a nucleus for which Z = 94 and A = 239. Consideration of the Bohr-Wheeler theory of fission and of certain empirical relations among the nuclei by L. A. Turner and others suggested that this nucleus would be a fairly stable alpha emitter and would probably undergo fission when bombarded by thermal neutrons. Later the importance of such thermal fission to the maintenance of the chain reaction was foreshadowed in private correspondence and discussion. In terms of our present knowledge and notation the particular reaction suggested is as follows:

$$_{92}U^{238} + _{0}n^{1} \rightarrow _{92}U^{239} \rightarrow _{93}Np^{239} + _{-1}e^{0}$$
$$_{93}Np^{239} \rightarrow _{94}Pu^{239} + _{-1}e^{0}$$

where Np and Pu are the chemical symbols now used for the two new elements, neptunium and plutonium; $_{0}n^{1}$ represents the neutron, and $_{-1}e^{0}$ represents an ordinary (negative) electron. Plutonium 239 is the nucleus rightly guessed to be fissionable by thermal neutrons. It will be discussed fully in later chapters.

GENERAL STATE OF NUCLEAR PHYSICS

1.59. By 1940 nuclear reactions had been intensively studied for over ten years. Several books and review articles on nuclear physics had been published. New techniques had been developed for producing and controlling nuclear projectiles, for studying artificial radioactivity, and for separating submicroscopic quantities of chemical elements produced by nuclear reactions. Isotope masses had been measured accurately. Neutron-capture cross sections had been measured. Methods of slowing down neutrons had been developed. Physiological effects of neutrons had been observed; they had even been tried in the treatment of cancer. All such information was generally available; but it was very incomplete. There were many gaps and many inaccuracies. The techniques were difficult and the quantities of materials available were often submicroscopic. Although the fundamental principles were clear, the theory was full of unverified assumptions and calculations were hard to make. Predictions made in 1940 by different physicists of equally high ability were often at variance. The subject was in all too many respects an art, rather than a science.

SUMMARY

1.60. Looking back on the year 1940, we see that all the prerequisites to a serious attack on the problem of producing atomic bombs and controlling atomic power were at hand. It had been proved that mass and energy were equivalent. It had been proved that the neutrons initiating fission of uranium reproduced themselves in the process and that therefore a multiplying chain reaction might occur with explosive force. To be sure, no one knew whether the required conditions could be achieved, but many scientists had clear ideas as to the problems involved and the directions in which solutions might be sought. The next chapter of this report gives a statement of the problems and serves as a guide to the developments of the past five years.