FOREWORD

THE story of the development of the atomic bomb by the combined efforts of many groups in the United States is a fascinating but highly technical account of an enormous enterprise. Obviously military security prevents this story from being told in full at this time. However, there is no reason why the administrative history of the Atomic Bomb Project and the basic scientific knowledge on which the several developments were based should not be available now to the general public. To this end this account by Professor H. D. Smyth is presented.

All pertinent scientific information which can be released to the public at this time without violating the needs of national security is contained in this volume. No requests for additional information should be made to private persons or organizations associated directly or indirectly with the project. Persons disclosing or securing additional information by any means whatsoever without authorization are subject to severe penalties under the Espionage Act.

The success of the development is due to the many thousands of scientists, engineers, workmen and administrators—both civilian and military—whose prolonged labor, silent perseverance, and whole-hearted cooperation have made possible the unprecedented technical accomplishments here described.

L. R. Groves
Major General, USA

War Department
Washington, D. C.
August 1945

PREFACE

THE ultimate responsibility for our nation's policy rests on its citizens and they can discharge such responsibilities wisely only if they are informed. The average citizen cannot be expected to understand clearly how an atomic bomb is constructed or how it works but there is in this country a substantial group of engineers and scientific men who can understand such things and who can explain the potentialities of atomic bombs to their fellow citizens. The present report is written for this professional group and is a matter-of-fact, general account of work in the United States since 1939 aimed at the production of such bombs. It is neither a documented official history nor a technical treatise for experts. Secrecy requirements have affected both the detailed content and general emphasis so that many interesting developments have been omitted.

References to British and Canadian work are not intended to be complete since this is written from the point of view of the activities in this country.

The writer hopes that this account is substantially accurate, thanks to cooperation from all groups in the project; he takes full responsibility for such errors as may occur.

H. D. SMYTH

July 1, 1945

Minor changes have been made for this edition. These changes consist of the following variations from the report as issued August 12, 1945: (1) Minor clarifications and corrections in wording; (2) Inclusion of a paragraph on radioactive effects issued by the War Department to accompany the original release of this report; (3) Addition of a few sentences on the success of the health precautions; (4) Addition of a few names; (5) Addition of Appendix 6, giving the War Department release on the New Mexico test of July 16, 1945; (6) Inclusion of the photographic section; (7) Inclusion of an index.

H. D. S.

September 1, 1945

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ATOMIC ENERGY
FOR MILITARY PURPOSES

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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

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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 avail-

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able. (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-Müller 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 wave-length. Such a "particle" or quantum of gamma

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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 small heavy 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

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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.

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

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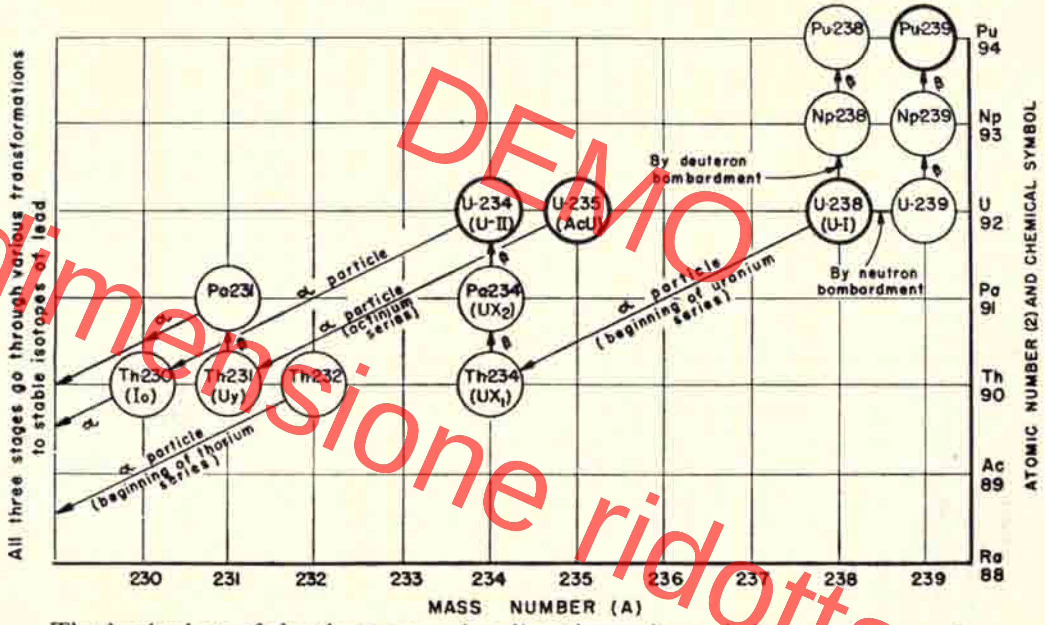
All three stages go through various transformations to stable isotopes of lead
Pu238
Pu239
Np238
Np239
U-234 (U-II)
U-235 (AcU)
U-238 (U-I)
U-239
Pa231
Pa234 (UX2)
Th230 (Io)
Th231 (Uy)
Th232
Th234 (UX1)
β
α
α particle
α particle (actinium series)
α particle (beginning of thorium series)
α particle (beginning of uranium series)
By deuteron bombardment
By neutron bombardment
Pu 94
Np 93
U 92
Pa 91
Th 90
Ac 89
Ra 88
ATOMIC NUMBER (Z) AND CHEMICAL SYMBOL
230
231
232
233
234
235
236
237
238
239
MASS NUMBER (A)

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

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. Chadwick in England per-

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formed 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,

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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,

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