The Manhattan Project

A very brief introduction to the physics of nuclear weapons

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This work is dedicated to Laurie.

Again.

Contents

Preface

No student of physics can resist learning about nuclear weapons. Whether you consider these devices a blessing which helped end the most brutal war in history and subsequently deterred further large-scale conflicts, or regard them as a curse which should never have been released upon the world, the power that they bestow on their holders and the influence they have in global affairs cannot be overstated. The science which underpins them is fascinating; learning anything about them gives one a sense of being close to their power and of being privy to otherwise forbidden knowledge.

Nuclear weapons are now nearly 75-year-old technology. First developed by the United States Army in World War II in an effort which came to be known as the Manhattan Project, they represented the fruition of discoveries that dated back to the beginnings of nuclear physics in the decade before World War I. Yet, the physics of nuclear weapons is not normally part of the syllabus of most college and university-level science courses; even most physics majors likely have only a vague notion of how they work. I have written this book for physics students who wish to apply some of the scientific concepts and mathematical techniques they have encountered to understanding something of 'first generation' fission weapons: what principles underlie them, how they are made, how they function, and what are some of their effects.

This book is not a conventional text. My purpose is not to develop concepts or derivations from first principles; there exist many very good and very comprehensive treatments of the history and physics of the Manhattan Project for readers who wish to explore the details (see the Bibliography). Rather, my intent is to whet your appetite to learn more about the Project from such sources by describing some of the relevant background discoveries, and by presenting some key equations and showing how they can be used to carry out approximate but informative calculations. It may come as a surprise to learn that much of the 'forbidden knowledge' surrounding nuclear weapons is quite accessible to a reader armed with an undergraduate-level understanding of physics.

I have written this book assuming a fairly substantial background on the part of its readers. Ideally, you will have had classes in modern physics and basic nuclear physics. You should know that nuclei are comprised of protons and neutrons, what is meant by 'atomic number' (Z) and 'mass number' (A), that chemical elements come in a variety of isotopic forms, what 'alpha decay' and 'beta decay' mean, what abbreviations like U-235, Pu-239, ${}^{235}_{92}\mathrm{U}$, and ${}^{239}_{94}\mathrm{Pu}$ mean, that energies in nuclear physics are measured in millions of electron-volts (MeVs), that nuclear physicists quantify the probability of a reaction by a 'cross-section' measured in 'barns', what nuclear fission involves, and the basic idea of how a reactor operates by maintaining a chain reaction of fissioning uranium-235 nuclei while simultaneously 'breeding' plutonium-239 via neutron-capture by U-238 nuclei. I also assume that you know something of the basic history and accomplishments of the Manhattan Project. Chapter 1 offers a brief qualitative refresher on some of the background physics, and an equally brief description of how the Project came to be organized. For a more thorough treatment, the companion volume to this book, *Atomic Bomb: The Story of the Manhattan Project*, is recommended reading. In essence, my goal here is to fill in some of the physics details that were skipped over in *Atomic Bomb*. Occasional exercises are scattered throughout the text so that you can try some calculations for yourself: you will get the most out of this book if you do them.

This book covers five main topics, one in each of chapters 2–6. Nuclear weapons derive their destructive power by initiating a fast-neutron fission chain reaction in any material which is known to suffer fission under neutron bombardment; for practical purposes, only uranium-235 (U-235) or plutonium-239 (Pu-239) or a combination of the two can be used to fuel a fission bomb. Chapter 2 quantifies the energy released in fission and the remarkable brevity of chain reactions, and explores why, out of over 2000 isotopes known to nuclear physicists, only U-235 and Pu-239 are practicable for use as fission-bomb materials. Particularly important in this latter context is an examination of how natural decay processes, specifically alpha-decay and spontaneous fission, limit the number of bomb-fuel candidates.

Chapter 3 addresses the intertwined issues of 'criticality' and 'efficiency'. Perhaps the single most important number one needs to know to develop a nuclear weapon is the so-called critical mass of fissile material necessary. Phrased loosely, the critical mass is the minimum mass of fissile material that can sustain a chain reaction, at least until it blows itself apart. If the critical mass should prove to be, say, 500 kg of a very rare or hard-to-synthesize isotope, it may not be practical to attempt to develop a nuclear weapon. The critical masses of U-235 and Pu-239 are on the order of tens of kilograms, but even these amounts are very hard to acquire from scratch. Related to this is the question of efficiency. A nuclear bomb blows itself apart over the course of mere microseconds, and it proves essentially impossible to fission all of the core material before this happens. Thus, even if a critical mass is within practical reach, one needs to have an idea of the expected efficiency to judge if making a nuclear bomb will be worth the effort—or not.

Nuclear weapons would not exist if we were not able to isolate naturally-occurring fissile isotopes or artificially synthesize non-naturally-occurring ones in sufficient quantity. Chapter 4 examines some of the physics behind isolating U-235 by two processes, one electromagnetic and the other based on results from kinetic theory, and of synthesizing Pu-239 by the process of neutron capture within a reactor. Estimates of the scales of time and number of processing steps involved in producing kilogram-level quantities of these substances explain why the industrial facilities of the Manhattan Project grew to such gargantuan proportions.

The end results of the Manhattan Project were two types of nuclear bombs. These were the so-called 'gun' design which employed uranium and was used in the *Little Boy* bomb detonated over Hiroshima, and the very complex 'implosion' design utilized in the *Fat Man* plutonium-based bomb, one of which was tested in New Mexico on July 16, 1945—the *Trinity* test—and another of which was soon thereafter used at Nagasaki. The uranium bomb contained about 65 kg of U-235, and the plutonium bomb contained about 6.4 kg of Pu-239; when making order-of-magnitude estimates I will often round these numbers to 60 kg and 10 kg. The need to develop the implosion design was a consequence of an initially only loosely-anticipated property of reactor-produced plutonium, its propensity to suffer *spontaneous fission*. Had this design not been developed, the plutonium bomb would have been extremely inefficient. Chapter 5 describes the designs of the two weapons, elaborates further upon some of the ramifications of the fissile-candidates issues raised in chapter 2, and describes the Hiroshima and Nagasaki bombing missions.

Chapter 6 addresses some of the effects of nuclear weapons. The energy released in fission reactions proves to be millions of times as much as that released by the same mass of a chemical explosive, and when a large amount of energy is released into the atmosphere over a short time, the result is a destructive high-pressure shock wave that propagates outward from the point of the explosion. In addition to this, nuclear explosions release fantastic amounts of light and heat radiation which can vaporize people and structures close to the explosion, cause blindness, and start fires even kilometers away. Another hazard is the immense flux of fission-generated neutrons which can cause cellular damage out to distances of hundreds of meters from the explosion. Finally, exposure to radioactivity, by either prompt mechanisms such as gamma-rays and neutrons or by longer-term ‘fallout’, can cause serious health effects up to the level of death. There is a multiplicity of very unpleasant ways to be harmed by a nuclear weapon.

Finally, chapter 7 presents a very brief summary of current worldwide nuclear weapons deployments, and the Bibliography lists a number of print and electronic sources for readers who wish to explore the Manhattan Project and nuclear weapons in more detail. The Glossary summarizes definitions of mathematical symbols used in the text.

A note on units

At the time of the Manhattan Project, customary United States units such as pounds, feet, and miles were still in widespread use in American scientific and engineering circles. Most original Project documentation uses such units, and I follow this pattern, giving SI equivalents for some of the more important quantities. Readers must be comfortable in translating between these different systems.

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When I began researching the Manhattan Project over 20 years ago, I never dreamed that it would become such a significant part of my professional career. Even after several dozen papers and articles, presentations at conferences, and this, my fourth book on the subject, the well seems inexhaustible. The most rewarding part of this journey has been interacting with other Manhattan aficionados I have met along the way. For conversations, correspondence, helpful suggestions, gentle corrections, comments on draft material, and continual encouragement, I am grateful to John Abelson, Joseph-James Ahern, Dana Aspinall, Jeremy Bernstein, Alan Carr, David Cassidy, Thomas Cochran, Pierce Corden, John Coster-Mullen, Steve Croft, Gene Deci, Eric Erpelding, Patricia Ezzell, Charles Ferguson, Edward Gerjuoy, Dennis Giangreco, Chris Gould, Robert Hayward, Dave Hafemeister, Siegfried Hecker, Dieter Hoffmann, Cindy Kelly, William Lanouette, Irving Lerch, Jeffrey Marque, Heather McLenahan, Albert Menard, Tony Murphy, Ed Neuenschwander, Stan Norris, Sean Prunty, Klaus Rohe, Frank Settle, Ruth Sime, Ray Smith, Roger Stuewer, Michael Traynor, Alex Wellerstein, John Yates, and Pete Zimmerman. Jeanine Burke and Nicki Dennis at IoP and Joel Claypool of Morgan & Claypool Publishers deserve thanks for suggesting this project and encouraging me to see it through.

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Author biography

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Bruce Cameron Reed is the Charles A. Dana Professor of Physics at Alma College, Alma, Michigan. He holds a PhD in Physics from the University of Waterloo in Canada. In addition to a quantum mechanics text and three other books on the Manhattan Project (including the IOP Concise Physics volume *Atomic Bomb: The Story of the Manhattan Project*), he has published over 100 papers in peer-reviewed scientific journals on research in the fields of astronomy, data analysis, quantum physics, mathematics, nuclear physics, the history of physics, and the physics of nuclear weapons. In 2009 he was elected a Fellow of the American Physical Society 'For his contributions to the history of both the physics and the development of nuclear weapons in the Manhattan Project'. In 2016 he was elected a Fellow of the Institute of Physics. He lives in Michigan with his wife Laurie.

Chapter 1

The background

1.1 The physics

Neutron-induced fission of uranium was discovered in Berlin in late 1938 by Otto Hahn and Fritz Strassmann. Physicists soon realized that this phenomenon released a tremendous amount of energy, nearly 200 MeV per reaction. This is dramatically more than the few eVs typical of a chemical reaction. Such a great energy release immediately hinted at the possibility of developing a very powerful but compact bomb in which millions of pounds of conventional explosive could be replaced with a few pounds of a nuclear explosive.

The fact that the bombarding particles in fission are neutrons is a key point. Fission cannot be induced by attempting to strike one uranium nucleus with another uranium nucleus; the repulsive forces between the protons in the nuclei are so great that they will not be able to closely approach each other unless the incoming nucleus is given very great kinetic energy. But neutrons are electrically neutral and thus experience no such repulsion; there is nothing to stop them from coming into contact with a target nucleus and disrupting it. In the process of fission, the struck nucleus loses a small amount of mass, but this corresponds to a great amount of energy in accordance with Albert Einstein's famous equation $E = mc^2$. A few weeks after the discovery of fission, it was found that a by-product of each fission was the simultaneous liberation of two or three neutrons from the disrupted nucleus. These 'secondary' neutrons, if they can be prevented from escaping from the sample of uranium, can go on to induce fission in other nuclei and so initiate a *chain reaction* which, in theory, can continue until all of the uranium has been fissioned.

These discoveries raised a number of questions. Could any other elements undergo fission? Were both of the known isotopes of uranium (U-235 and U-238) fissile? Was some minimum amount of uranium necessary to create a chain reaction? Could the process be controlled by human intervention to create a power source, or would any attempt to initiate fission on a large scale result in a violent, uncontrolled explosion?

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By the time of the outbreak of World War II in September, 1939, it had been theoretically predicted that only the rare U-235 isotope would fission under neutron bombardment; in contrast, nuclei of the much more common U-238 isotope would likely capture incoming neutrons without fissioning. These predictions were confirmed experimentally in early 1940. Since most natural uranium is U-238 (>99%), this capture effect meant that it looked as if it would be impossible to achieve a chain reaction using natural-abundance uranium. To obtain a chain reaction, it would be necessary to isolate a sample of U-235 from its sister isotope, or at least process a sample of uranium in some way as to isolate a sub-sample with a dramatically increased percentage of U-235. Such processing is known as *enrichment*. Since isotopes of any element behave identically so far as their chemical properties are concerned, no chemical process can be employed to achieve enrichment; only a technique that depends on the slight mass difference between the two isotopes (~1%) could be a possibility.

By mid-1940, understanding of the differing responses of U-235 and U-238 nuclei to neutron bombardment led to the emergence of a new idea for obtaining a *controlled* (not explosive) chain reaction using natural uranium *without enrichment*. The key lies in how nuclei react to bombarding neutrons. When a nucleus is struck by a neutron, various reactions are possible. The nucleus might capture the neutron and then fission; it might capture the neutron and not fission but later decay to a more stable isotope of another element; or it might deflect the neutron into a new flight path. Each process has some probability of occurring, and these probabilities depend very sensitively on the *speed* of the incoming neutrons. Neutrons released in fissions are extremely energetic, emerging with average speeds of about 20 million meters per second; these are 'fast' neutrons. As remarked above, U-238 nuclei preferentially capture fast neutrons emitted in fissions of U-235 nuclei. However, when a nucleus of U-238 is struck by a *slow* neutron—one traveling on the order of a mere couple of thousand meters per second—it behaves very differently, with deflection of the neutron being about three times as likely as capture. But—and this is the crucial point—U-235 nuclei turn out to have an enormous probability for undergoing fission when struck by slow neutrons, over 200 times the capture probability for U-238. This factor is large enough to compensate for the small natural abundance of U-235 to the extent that a slowed neutron is about as likely to fission a nucleus of U-235 as it is to be captured by one of U-238 (figure 1.1); this is why it is possible to achieve a controlled 'slow-neutron' chain reaction. This is worth emphasizing: *if neutrons emitted in fissions can be slowed, then they have a good chance of going on to fission other U-235 nuclei before being lost to capture by U-238 nuclei*. In a nuclear reactor, the slowing is achieved by distributing lumps of uranium within a substance known as a 'moderator' which slows neutrons before they strike other uranium nuclei. Within an operating reactor, both fission of U-235 nuclei and neutron capture by U-238 nuclei proceed simultaneously.

If U-235 has such an enormous fission probability for slow neutrons, why not build a bomb that incorporates a moderator to slow neutrons and thereby achieve lots of fissions, thus avoiding the difficulties of enriching uranium or breeding plutonium? This question gets to a vitally important point, one worth recalling even

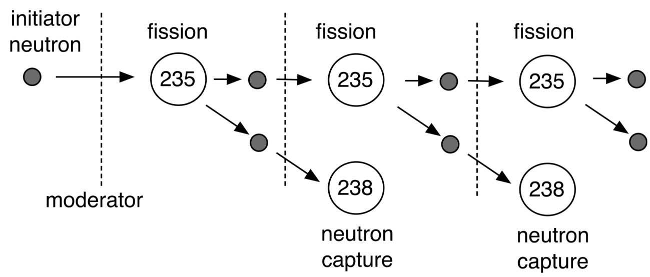

Figure 1.1. Schematic illustration of a chain reaction utilizing moderated neutrons. Each fission of a U-235 nucleus liberates two secondary neutrons, one of which goes on to fission another U-235 nucleus, while the other is captured by a nucleus of U-238. Reproduced from [1], figure 1.2.

if you are already very familiar with this material. Analysis of the efficiency of nuclear explosions reveals that the energy liberated is proportional to the square of a neutron's speed as it travels from where it is born in a fission to where it is likely to cause a subsequent fission: $E \sim v_{\text{neut}}^2$. (See chapter 3, specifically the discussion surrounding bomb efficiency, equation (3.24). In this equation, τ is the neutron travel time between fissions, which is inversely proportional to v_{neut}.) Fast neutrons travel at about 20 million meters per second, while slow neutrons travel at about 2000 meters per second, a speed ratio of 10 000. This means that the energy releases will compare as $E_{\text{fast}}/E_{\text{slow}} = (10\,000)^2 = 10^8$. In other words, the energy that would be released by a slow-neutron bomb would be only 10^{-8} of that which would be liberated by a fast-neutron bomb containing the same amount of fissile material. In comparison to a Nagasaki-type 20-kiloton TNT-equivalent fast-neutron bomb, a comparable slow-neutron weapon would release less energy than one pound of TNT! There is no point in making a slow-neutron bomb; in effect, you might as well attempt to drop a reactor on your target. Nuclear bombs utilize *fast-neutron* reactions in compact cores of highly-enriched fissile material to release large amounts of energy in brief, uncontrolled bursts, whereas reactors utilize controlled, *slow-neutron* reactions in a physically dispersed mass of non-enriched or low-enriched material to produce power and breed plutonium. So, do not be alarmed by stories where reactors threaten to behave like bombs: they operate far too slowly, and even if their neutron-absorbing 'control rods' are rendered inoperative, their fissile-material enrichment is too low to sustain an explosive chain reaction. As seen at Fukushima, an uncontrolled reactor will melt itself into a nasty mess of highly-radioactive fission products, but it will not cause a nuclear explosion.

In an interesting twist of nature, neutron capture by U-238 nuclei turned out to be advantageous for bomb-makers. On capturing a neutron, a nucleus of U-238 becomes one of U-239. Based on some experimentally-known patterns regarding the stability of nuclei, it was predicted in early 1940 that U-239 nuclei might decay within a short time to nuclei of atomic number 94, the element now named plutonium (Pu). It was further predicted that element 94 might be very similar in its fissionability properties to U-235. If this proved to be so, then a reactor could be used to 'breed' plutonium from neutron capture by U-238 nuclei while maintaining a self-sustaining, controlled, slow-neutron chain-reaction via fissions of U-235 nuclei.

The advantage of this would be that the plutonium so created could be separated from the uranium ‘fuel’ by chemical processes and used to construct a bomb, thus circumventing the need to develop enrichment technologies. These predictions were soon confirmed on a laboratory scale by creating a tiny sample of plutonium via neutron bombardment of uranium.

1.2 The Manhattan Project

The idea that nuclear fission could lead to bombs of immense power occurred very quickly to several researchers in the physics community. In America, three émigré Hungarian physicists, Leo Szilard, Eugene Wigner, and Edward Teller, prevailed upon their friend and colleague Albert Einstein (also then living in America) to sign a letter to President Franklin Roosevelt which described the possibility of fission bombs; their rationale in recruiting Einstein was that he was likely the only physicist famous enough to be known to the President. The letter reached Roosevelt in October, 1939, and prompted the formation of an ‘Advisory Committee on Uranium’ to fund and coordinate research on the physics of uranium fission, on how reactors might be constructed, and on developing technologies for separating U-235 from U-238. The Advisory Committee initially reported to the National Bureau of Standards, but in June, 1940, it came under the administration of the National Defense Research Committee (NDRC), an agency Roosevelt established to organize research which might have military applications. The NDRC was directed by Vannevar Bush, a Massachusetts Institute of Technology electrical engineer. In June 1941, the NDRC was absorbed into a successor agency, the Office of Scientific Research and Development (OSRD), also directed by Bush. By the time of the Japanese attack at Pearl Harbor, the NDRC/OSRD had funded contracts totaling some $300 000 for research on fission and isotope separation.

When the NDRC inherited the uranium issue, Bush appointed University of Chicago physics Nobel laureate Arthur Compton to chair a separate committee, the ‘National Academy of Sciences Committee on Atomic Fission’. From the spring through the late fall of 1941, Compton’s committee prepared three reports on the feasibility of reactors and bombs; their final report, which Bush took to Roosevelt just before Pearl Harbor, laid out the prospects for fission bombs in considerable detail. This last Compton report was heavily influenced by a report prepared by a parallel group in Britain. In March, 1940, Otto Frisch and Rudolf Peierls, respectively Austrian and German émigré physicists then working at Birmingham University, prepared a memorandum in which they estimated the critical mass of U-235 to be about a pound. This was an underestimate, but their document reached the government’s Scientific Survey of Air Warfare, whose chairman, Sir Henry Tizard, asked physicist George P Thomson to investigate the issue. (Thomson was the son of J J Thomson, discoverer of the electron.) This resulted in the formation of the so-called MAUD committee, which in July, 1941, produced an extensive report on the feasibility of fission bombs and isotope-separation methods. This report reached American officials that October, at which time Bush briefed Roosevelt on its conclusions. About a month later, Bush used the third Compton report to bolster the case for proceeding with an all-out project to construct fission weapons.

In summary, by late 1941, physicists in both America and Britain had converged on the conclusion that there looked to be two possible means of creating nuclear explosives. These were: (i) isolate tens of kilograms of U-235 by some isotope enrichment method and use it to create a fast-neutron chain-reaction bomb, and/or (ii) develop reactors and use them to breed plutonium (specifically, Pu-239) via U-238 slow-neutron capture, extract the plutonium, and use it to build a bomb. U-235 was predicted to be almost certain to make an excellent nuclear explosive, but the kilograms would have to be extracted one atom at a time from a mass of uranium ore. On the up-side, various isotope enrichment methods looked promising, even if they would be difficult to put into practice on large scales. Regarding plutonium, nobody had ever built an operating reactor; also, an unknown element might well prove to have some property that obviated its value as an explosive. Bush made the only recommendation he could in the circumstances of wartime: both methods should be pursued. However, it was clear that such a dual effort would require building enormous factories to enrich uranium, and a vast research and development effort to build reactors. The only organization which possessed the budget and resources necessary to carry out such an operation with the requisite secrecy was the Corps of Engineers of the United States Army, and Bush began lobbying Roosevelt to turn the project over to the Corps. The President approved the transfer in March, 1942, and the Army formally established the 'Manhattan Engineer District' (MED) on August 13, 1942. The name came from the fact that the MED's first commander, Colonel James Marshall, established his headquarters in Manhattan. In September, 1942, the MED was placed under the command of Brigadier General Leslie Groves (figure 1.2), then in charge of all domestic military construction; his most recent large project had been the building of the Pentagon. Groves wasted no time in getting to work on his new responsibility, acquiring sites at which to locate factories to isolate U-235 (Oak Ridge, Tennessee), reactors to synthesize plutonium (Hanford, Washington), and set up a highly-secret bomb design laboratory (Los Alamos, New Mexico); see figure 1.3. And with this, it is time for us to explore some of the physics of Manhattan.

Figure 1.2. General Leslie Richard Groves (1896–1970) http://commons.wikimedia.org/wiki/File:Leslie_Groves.jpg.

Figure 1.3. Locations of major Manhattan Project sites. From [2].

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