Bruce Cameron Reed

The Physics of the Manhattan Project

Third Edition

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This work is dedicated to my wife Laurie,
whose love knows no half-life.

Preface to the Third Edition

For readers familiar with earlier editions of this book, this revised edition of *The Physics of the Manhattan Project* incorporates a number of new sections, some significant revisions to existing sections, some new exercises, and clarifications and corrections of a number of minor points. These revisions reflect my own increased knowledge of the subject matter and a number of helpful suggestions contributed by readers who very kindly took time to contact me.

The new material in this edition comprises:

- Section 1.11 presents a model for numerically simulating the fission process on a desktop computer.
- An approximate treatment of criticality for cylindrical bomb cores and how their critical masses compare to spherical and cubical cores is developed in Sect. 2.7.
- Section 4.3 presents an analysis of how to estimate the probability of achieving a given fraction of the design yield of a fission weapon in view of the inevitable chance of its suffering a predetonation; this material follows from the discussion of predetonation in Sect. 4.2. As a result, what was Sect. 4.3 of the second edition has been moved back to become Sect. 4.4.

For both Sects. 2.7 and 4.3, corresponding spreadsheets are available at the companion Web site, www.manhattanphysics.com.

Notable revisions to existing material include:

- Section 2.2 now includes a brief discussion of an approximate analytic method for estimating the neutron-density exponential-growth parameter α in criticality calculations.
- The discussion of the effects of tamper on critical mass developed in Sect. 2.3 has been clarified.
- Section 2.4 now includes a discussion of an expression for the expected yield of a fission weapon developed in 1940 by Otto Frisch and Rudolf Peierls; their result is compared with the analysis developed herein.
- Results of a numerical simulation of an exploding and expanding bomb core and tamper presented in Section 2.5 have been improved by use of a program

utilizing finer time steps and direct computation of the exponential-growth parameter α at each time step.
- The derivation of the Bohr–Wheeler spontaneous-fission limit presented in Sect. 6.5 has been simplified while retaining the essential spirit and results of the analysis.
- The somewhat awkward numerical calculation of the spherical-core neutron escape probability developed in Sect. 6.6 has been replaced with a much more elegant analytic derivation due to Steve Croft.
- A Glossary of symbols has been added (Sect. 6.9).
- The "Further Reading" bibliography, now Sect. 6.10, has been updated.

For readers who are new to this work, the very fact that you are looking at it indicates that you appreciate that the discovery of nuclear energy and its liberation in the form of nuclear weapons was one of the pivotal events of the twentieth century. The strategic and military implications of this development drove much of cold-war geopolitics for the last half of that century, and remain with us today as reflected in issues such as weapons stockpiles and deployments, fissile-material security, test-ban treaties, and particularly the possibility that terrorists or unstable international players might be able to acquire enough fissile material to assemble a crude nuclear weapon. For better or worse, stabilizing or destabilizing, the legacies of the "U.S. Army Manhattan Engineer District," Los Alamos, Oak Ridge, Hanford, *Trinity*, *Little Boy*, *Fat Man*, Hiroshima and Nagasaki will continue to influence events for decades to come even as the number of deployed nuclear weapons in the world steadily declines.

To sensibly assess information and claims regarding these concerns, one needs some knowledge of the physics that backgrounds nuclear weapons. Should you be merely concerned or downright alarmed if you learn that a potential adversary country is "enriching uranium to 20 % U-235" or "developing fuel-rod reprocessing technology"? Why is there such a thing as a critical mass, and how can one estimate it? How does a nuclear reactor differ from a nuclear weapon? Why can't a nuclear weapon be made with a common metal such as aluminum or iron as its "active ingredient"? How did the properties of various uranium and plutonium isotopes lead to the development of the "gun-type" and "implosion-type" weapons used at Hiroshima and Nagasaki? How did the developers of those devices estimate their expected energy yields? How does one arrange to assemble a critical mass in such a way as to avoid blowing yourself up beforehand? This book is an effort to address such questions at about the level of a junior-year undergraduate physics student.

This work has grown out of three courses that I have taught at Alma College, supplemented with information drawn from a number of my own and other published research articles. One of my courses is a conventional undergraduate sophomore-level "modern physics" class for physics majors which contains a unit on nuclear physics. Another is an algebra-level general-education class on the history of the making of nuclear weapons in World War II, and the third is a junior-level topics class for physics majors that uses the present volume as its text. What motivated me to prepare this book was that there seemed to be no one source available for a reader with a college-level background in physics and mathematics who desired to learn something of the technical aspects of the Manhattan Project in more detail than is typically presented in conventional texts or popular histories. As my own knowledge of these issues grew, I began assembling a collection of derivations and results to share with my students, and which evolved into the present volume. I hope that readers will discover, as I did, that studying the physics of nuclear weapons is not only fascinating in its own right but also an excellent vehicle for reinforcing understanding of many foundational areas of physics such as energy, electromagnetism, dynamics, statistical mechanics, modern physics, and, of course, nuclear physics.

This book is neither a conventional text nor a work of history. I assume that readers are already familiar with the basic history of some of the physics that led to the Manhattan Project and how the Project itself was organized (Fig. 1). Excellent background sources are Richard Rhodes' masterful *The Making of the Atomic Bomb* (1986) and F. G. Gosling's *The Manhattan Project: Making the Atomic Bomb* (1999); I also humbly recommend my own semi-popular *The History and Science of the Manhattan Project* (2014), which fills in much more of the background scientific discoveries and history of Project administration than are covered in the present book. While I include some background material here for sake of a reasonably self-contained treatment, I assume that within the area of nuclear physics readers will be familiar with concepts such as reactions, alpha and beta decay, Q-values, fission, isotopes, binding energy, the semi-empirical mass formula, cross sections, and the concept of the "Coulomb barrier." Familiarity with multivariable calculus and simple differential equations is also assumed. In reflection of my own interests (and understanding), the treatment here is restricted to World War II-era fission bombs. As I am neither a professional nuclear physicist nor a weapons designer, readers seeking information on postwar advances in bomb and reactor design and issues such as isotope separation techniques will have to look elsewhere; a good source is Garwin and Charpak (2001). Similarly, this book does not treat the *effects* of nuclear weapons, for which authoritative official analyses are available (Glasstone and Dolan 1977). For readers seeking more extensive references, an annotated bibliography appears in Sect. 6.10.

This book comprises 30 sections within five chapters. Chapter 1 examines some of the history of the discovery of the remarkable amounts of energy released in nuclear reactions, the discovery of the neutron, and characteristics of the fission process. Chapter 2 details how one can estimate both the critical mass of fissile material necessary for a fission weapon and the efficiency one might expect of a weapon that utilizes a given number of critical masses of such material. Aspects of producing fissile material by separating uranium isotopes and synthesizing plutonium are taken up in Chap. 3. Chapter 4 examines some complicating factors that weapons engineers need to be aware of. Some miscellaneous calculations comprise Chap. 5. Useful data are summarized in Sects. 6.1 and 6.2, and a number of background derivations are gathered in Sects. 6.3, 6.4, 6.5, 6.6, and 6.7. For readers wishing to try their own hand at calculations, Sect. 6.8 offers a number of exercises, with answers provided. A number of symbols are used in this text to designate

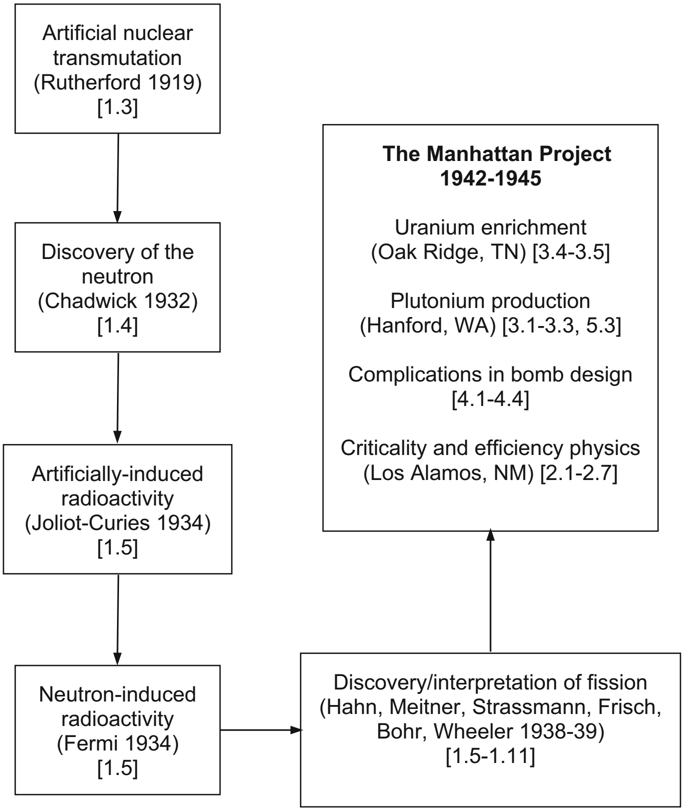

Fig. 1 Concept map of important discoveries in nuclear physics and the organization of the Manhattan Project. *Numbers in square brackets* indicate sections in this book where corresponding topics are discussed

different quantities in different places, and a handy Glossary of the most important ones appears in Sect. 6.9. A bibliography for further reading is offered in Sect. 6.10, and some useful constants and conversion factors appear in Sect. 6.11. The order of the main chapters, and particularly of individual sections within them, proceeds in such a way that understanding of later ones often depends on knowledge of earlier ones: Physics is a vertically integrated discipline.

It should be emphasized that there is no material in the present work that cannot be gleaned from publicly available texts, journals, and Web sites: I have no access to classified material.

I have developed spreadsheets for carrying out a number of the calculations described in this book, particularly those in Sects. 1.4, 1.7, 1.10, 1.11, 2.2, 2.3, 2.4, and 2.5, 4.1, 4.2, 4.3, and 4.4, and 5.3. These are freely available at a companion Web site, www.manhattanphysics.com. When spreadsheets are discussed in the text, they are referred to in **bold** type. Users are encouraged to download these, check calculations for themselves, and run their own computations for different choices of parameters. A number of the exercises in Sect. 6.8 are predicated on using these spreadsheets.

Over several years now I have benefitted from spoken and electronic conversations, correspondence, suggestions, willingness to read and comment on draft material, and general encouragement from John Abelson, Joseph-James Ahern, Dana Aspinall, Albert Bartlett, Jeremy Bernstein, Alan Carr, David Cassidy, John Coster-Mullen, Steve Croft, Gene Deci, Eric Erpelding, Patricia Ezzell, Ed Gerjuoy, Chris Gould, Robert Hayward, Dave Hafemeister, William Lanouette, Irving Lerch, Harry Lustig, Jeffrey Marque, Albert Menard, Tony Murphy, Robert S. Norris, Klaus Rohe, Frank Settle, Ruth Sime, D. Ray Smith, Roger Stuewer, Michael Traynor, Alex Wellerstein, Bill Wilcox, John Yates, and Pete Zimmerman. I am particularly grateful to Steve Croft and Klaus Rohe for a number of helpful comments and suggestions, and to John Coster-Mullen for permission to reproduce his beautiful cross-section diagrams of *Little Boy* and *Fat Man* that appear in Chaps. 2 and 4. If I have forgotten anybody, I apologize; know that you are in this list in spirit. Students in my advanced-level topics class—Charles Cook, Reid Cuddy, David Jack, and Adam Sypniewski—served as guinea pigs for much of the material in this book, and took justified pride in pointing out a number of confusing statements, Of course, I claim exclusive ownership of any errors that remain. Alma College interlibrary loan specialist Susan Cross has never failed to dig up any obscure document which I have requested; she is a true professional. I am also grateful to Alma for having awarded me a number of Faculty Small Grants over the years in support of projects and presentations involved in the development of this work, and for a sabbatical leave during which this book was revised. Angela Lahee and her colleagues at Springer deserve a big nod of thanks for believing in and committing to this project.

Most of all I thank Laurie, who continues to bear with my Manhattan Project obsession.

Suggestions for corrections and additional material will be gratefully received. I can be reached at: Department of Physics, Alma College, Alma, MI 48801, USA.

April 10, 2014 Cameron Reed

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Contents

About the Author

Cameron Reed is the Charles A. Dana Professor of Physics at Alma College in Alma, MI, where he teaches courses ranging from first-year algebra-based mechanics to senior-level quantum mechanics. He earned a Ph.D. in Physics at the University of Waterloo (Canada). His semi-popular level text *The History and Science of the Manhattan Project* can be considered a companion volume to the present book. He has also authored a quantum mechanics textbook in addition to over 100 peer-reviewed papers in the areas of astronomy, data analysis, quantum mechanics, nuclear physics, the history of physics, and pedagogical aspects of physics and astronomy. In 2009 he was elected to Fellowship in the American Physical Society (APS) for his work on the history of the Manhattan Project. From 2009 to 2013 he edited the APS's *Physics and Society* newsletter, and is presently serving as Secretary-Treasurer of the Society's Forum on the History of Physics. He lives in Michigan with his wife Laurie and a variable number of cats.

Chapter 1
Energy Release in Nuclear Reactions, Neutrons, Fission, and Characteristics of Fission

While this book is not intended to be a history of nuclear physics, it will be helpful to set the stage by briefly reviewing some relevant discoveries. To this end, we first explore the discovery of the enormous energy release characteristic of nuclear reactions, research that goes back to Ernest Rutherford and his collaborators at the opening of the twentieth century; this is covered in Sect. 1.2. Rutherford also achieved, in 1919, the first artificial transmutation of an element (as opposed to this happening naturally, such as in an alpha-decay), an issue we examine in Sect. 1.3. Nuclear reactors and weapons cannot function without neutrons, so we devote Sect. 1.4 to a fairly detailed examination of James Chadwick's 1932 discovery of this fundamental constituent of nature. The neutron had almost been discovered by Irène and Frédéric Joliot-Curie, who misinterpreted their own experiments. They did, however, achieve the first instance of artificially inducing radioactive decay, a situation we examine in Sect. 1.5, which also contains a brief summary of events leading to the discovery of fission. In Sects. 1.6, 1.7, 1.8, 1.9, 1.10, and 1.11 we examine the process of fission, the release of energy and neutrons during fission, and explore why only certain isotopes of particular heavy elements are suitable for use in fission weapons. Before doing any of these things, however, it is important to understand how physicists notate and calculate the energy liberated in nuclear reactions. This is the topic of Sect. 1.1.

1.1 Notational Conventions for Mass Excess and *Q*-Values

On many occasions we will need to compute the energy liberated or consumed in a nuclear reaction. Such energies are known as *Q*-values; this section develops convenient notational and computational conventions for dealing with such calculations.

Any reaction will involve *input* and *output* reactants. The total energy of any particular reactant is the sum of its kinetic energy and its relativistic mass-energy, mc^2. Since total mass-energy must be conserved, we can write

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$$\sum KE_{input} + \sum m_{input}c^2 = \sum KE_{output} + \sum m_{output}c^2, \tag{1.1}$$

where the sums are over the reactants; the masses are the *rest masses* of the reactants. The Q-value of a reaction is defined as the difference between the output and input kinetic energies:

$$Q = \sum KE_{output} - \sum KE_{input} = \left(\sum m_{input} - \sum m_{output}\right) c^2. \tag{1.2}$$

If $Q > 0$, then the reaction liberates energy, whereas if $Q < 0$ the reaction demands a *threshold* energy to cause it to happen.

If the masses in (1.2) are in kg and c is in m/s, Q will emerge in Joules. However, rest masses are usually tabulated in atomic mass units (abbreviation: amu or just u). If f is the number of kg in one amu, then we can put

$$Q = \left(\sum m_{input}^{(amu)} - \sum m_{output}^{(amu)}\right) f c^2. \tag{1.3}$$

Q-values are conventionally quoted in MeV. If g is the number of MeV in 1 J, then Q in MeV for masses given in amu will be given by

$$Q = \left(\sum m_{input}^{(amu)} - \sum m_{output}^{(amu)}\right) \left(g f c^2\right). \tag{1.4}$$

Define $\varepsilon = gfc^2$. With 1 MeV $= 1.602176462 \times 10^{-13}$ J, then $g = 6.24150974 \times 10^{12}$ MeV/J. Putting in the numbers gives

$$\begin{aligned} \varepsilon &= gfc^2 \\ &= \left(6.24150974 \times 10^{12} \frac{\text{MeV}}{\text{J}}\right) \times \left(1.66053873 \times 10^{-27} \frac{\text{kg}}{\text{amu}}\right) \\ &\quad \times \left(2.99792458 \times 10^8 \tfrac{\text{m}}{\text{s}}\right)^2 = 931.494 \frac{\text{MeV}}{\text{amu}}. \end{aligned} \tag{1.5}$$

More precisely, this number is 931.494013. Thus, we can write (1.4) as

$$Q = \left(\sum m_{input}^{(amu)} - \sum m_{output}^{(amu)}\right) \varepsilon, \tag{1.6}$$

where $\varepsilon = 931.494$ MeV/amu. Equation (1.6) will give Q-values in MeV when the rest masses are in amu.

Now consider an individual reactant of mass number (=nucleon number) A. The *mass excess* μ of this species is defined as the number of amu that has to be added to A amu (as an integer) to give the actual mass (in amu) of the species:

$$m^{(amu)} = A + \mu. \tag{1.7}$$

Substituting this into (1.6) gives

$$Q = \left(\sum\left[A_{input} + \mu_{input}\right] - \sum\left[A_{output} + \mu_{output}\right]\right)\varepsilon. \tag{1.8}$$

Nucleon number is always conserved, $\Sigma A_{input} = \Sigma A_{output}$, which reduces (1.8) to

$$Q = \left(\sum \mu_{input} - \sum \mu_{output}\right)\varepsilon. \tag{1.9}$$

The product $\mu\varepsilon$ for any reactant is conventionally designated as Δ:

$$Q = \left(\sum \Delta_{input} - \sum \Delta_{output}\right). \tag{1.10}$$

Δ-values for various nuclides are tabulated in a number of texts and references, usually in units of MeV. The most extensive such listing is published as the *Nuclear Wallet Cards* and is available from the Brookhaven National Laboratory at www.nndc.bnl.gov; a list of selected values appears in Sect. 6.1. The advantage of quoting mass excesses as Δ-values is that the Q-value of any reaction can be quickly computed via (1.10) without having to worry about factors of c^2 or 931.494. Many examples of Δ-value calculations appear in the following sections.

For a nuclide of given Δ-value, its mass in atomic mass units is given by

$$m^{(amu)} = A + \frac{\Delta}{\varepsilon}. \tag{1.11}$$

1.2 Rutherford and the Energy Release in Radium Decay

The energy released in nuclear reactions is on the order of a million times or more than that typical of chemical reactions. This vast energy was first quantified by Rutherford and Soddy (1903) in a paper titled "Radioactive Change." In that paper they wrote: "It may therefore be stated that the total energy of radiation during the disintegration of 1 g of radium cannot be less than 10^8 g-cal and may be between 10^9 and 10^{10} g-cal.... The union of hydrogen and oxygen liberates approximately 4×10^3 g-cal per gram of water produced, and this reaction sets free more energy for a given weight than any other chemical change known. The energy of radioactive change must therefore be at least 20,000 times, and may be a million times, as great as the energy of any molecular change."

Let us have a look at the situation using modern numbers. ^{226}Ra has an approximately 1,600-year half-life for alpha decay:

$$^{226}_{88}\mathrm{Ra} \;\rightarrow\; ^{222}_{86}\mathrm{Rn} \;+\; ^{4}_{2}\mathrm{He}. \tag{1.12}$$

The Δ-values are, in MeV,

$$\begin{cases} \Delta\left(^{226}_{88}\mathrm{Ra}\right) = 23.669 \\ \Delta\left(^{222}_{86}\mathrm{Rn}\right) = 16.374 \\ \Delta\left(^{4}_{2}\mathrm{He}\right) \;\; = 2.425. \end{cases} \tag{1.13}$$

These give $Q = 4.87$ MeV in contrast to the *few eV* typically released in chemical reactions.

The notation used here to designate nuclides, $^{A}_{Z}\mathrm{X}$, is standard in the field of nuclear physics. *X* denotes the symbol for the element, *Z* its atomic number (=number of protons) and *A* its nucleon number (=number of neutrons plus number of protons, also known as the atomic weight and as the mass number). The number of neutrons *N* is given by $N = A–Z$.

Rutherford and Soddy expressed their results in gram-calories, which means the number of calories liberated per gram of material. Since 1 eV $= 1.602 \times 10^{-19}$ J, then 4.87 MeV $= 7.80 \times 10^{-13}$ J. One calorie is equivalent to 4.186 J, so the *Q*-value of this reaction is 1.864×10^{-13} cal. One mole of ^{226}Ra has a mass of 226 g, so a single radium atom has a mass of 3.75×10^{-22} g. Hence the energy release per gram is about 4.97×10^{8} cal, in line with their estimate of 10^{8}–10^{10}. The modern figure for the heat of formation of water is 3,790 cal/g; gram-for-gram, therefore, radium decay releases about 131,000 times as much energy as the formation of water from hydrogen and oxygen. In computing the figure of ~5×10^{8} cal we are assuming that the entire gram of radium is decaying; in reality, this would take an infinite amount of time and cannot be altered by any human intervention. But the important fact is that individual alpha decays release *millions* of electron-Volts of energy, a fantastic number compared to any chemical reaction.

Another notational convention can be introduced at this point. In this book, reactions will usually be written out in detail as above, but some sources express them in a more compact notation. As an example, in the next section we will encounter a reaction where alpha-particles (helium nuclei) bombard nitrogen nuclei to produce protons and oxygen:

$$^{4}_{2}\mathrm{He} \;+\; ^{14}_{7}\mathrm{N} \;\rightarrow\; ^{1}_{1}\mathrm{H} \;+\; ^{17}_{8}\mathrm{O}. \tag{1.14}$$

This can be written more compactly as

$$^{14}_{7}\mathrm{N}\left(^{4}_{2}\mathrm{He}, ^{1}_{1}\mathrm{H}\right)\,^{17}_{8}\mathrm{O}. \tag{1.15}$$

An even more abbreviated notation is $^{14}\mathrm{N}(\alpha, p)^{17}\mathrm{O}$. In this notation, convention is to have the target nucleus as the first term, the bombarding particle as the first term within the brackets, the lighter product nucleus as the second term within the brackets, and finally the heavier product nucleus outside the right bracket.

1.3 Rutherford's First Artificial Nuclear Transmutation

The discovery that nitrogen could be transformed into oxygen by alpha-particle bombardment marked the first time that a nuclear transmutation was deliberately achieved (Rutherford 1919). This work had its beginnings in experiments conducted by Ernest Marsden in 1915.

In Marsden and Rutherford's experiment, alpha particles emitted by radium bombard nitrogen, producing hydrogen and oxygen via the reaction:

$$ {}^{4}_{2}\mathrm{He} \ + \ {}^{14}_{7}\mathrm{N} \ \rightarrow \ {}^{1}_{1}\mathrm{H} \ + \ {}^{17}_{8}\mathrm{O}. \tag{1.16} $$

The hydrogen nuclei (protons) were detected via the scintillations they produced upon striking a fluorescent screen. The Δ-values for this reaction are:

$$ \begin{cases} \Delta\left({}^{4}_{2}\mathrm{He}\right) = 2.425 \\ \Delta\left({}^{14}_{7}\mathrm{N}\right) = 2.863 \\ \Delta\left({}^{1}_{1}\mathrm{H}\right) = 7.289 \\ \Delta\left({}^{17}_{8}\mathrm{O}\right) = -0.809. \end{cases} \tag{1.17} $$

The Q-value of this reaction is –1.19 MeV. That Q is negative means that this process has a *threshold* of 1.19 MeV, that is, the bombarding alpha must possess at least this much kinetic energy to cause the reaction to happen. This energy is available from the spontaneous decay of radium which gives rise to the alphas; refer to the preceding section where it was shown that decay of ^{226}Ra liberates some 4.87 MeV of energy, more than enough to power the nitrogen-bombardment reaction.

In reality, for reactions with $Q < 0$ the threshold energy is actually greater than $|Q|$ because both energy and momentum have to be conserved; for the above reaction the threshold energy is about 1.53 MeV if the incoming alpha strikes the nitrogen nucleus head-on. The conditions of energy and momentum conservation relevant to such head-on "two body" reactions of the general form $\mathrm{A} + \mathrm{B} \rightarrow \mathrm{C} + \mathrm{D}$ are detailed in Sect. 6.3. A companion spreadsheet, **TwoBody.xls**, allows a user to input nucleon numbers and Δ-values for all four nuclides, along with an input kinetic energy for reactant A; nucleus B is presumed to be stationary when struck by A. The spreadsheet then computes and displays the Q-value for the reaction, the threshold energy (if appropriate), and the post-reaction kinetic energies and momenta for the products C and D. Of course, most reactions will *not* be head-on, but the point here is to get some sense of the numbers and to be able to make a judgment as to whether or not a transformation might in principle be possible. Many nuclear physics textbooks examine the physics of non head-on collisions, an important aspect of analyzing scattering experiments.

Independent of the Q-value being positive or negative, a related issue in these transmutation reactions that needs to be kept in mind is that of whether or not the incoming particle has enough kinetic energy to overcome the Coulomb repulsion of the target nucleus and so get close enough to it to allow nuclear forces to come into play; this is examined in Exercise 1.12 in Sect. 6.8.

The physics of two-body collisions is put to considerable use in the following section.

1.4 Discovery of the Neutron

Much of the material in this section is adopted from Reed (2007).

James Chadwick's discovery of the neutron in early 1932 was a critical turning point in the history of nuclear physics. Within 2 years, Enrico Fermi would generate artificially-induced radioactivity by neutron bombardment, and less than 5 years after that Otto Hahn and Fritz Strassmann would discover neutron-induced uranium fission. The latter would lead directly to the *Little Boy* uranium-fission bomb, while Fermi's work would lead to reactors to produce plutonium for the *Trinity* and *Fat Man* bombs.

Chadwick's discovery was reported in two papers. The first, titled "Possible Existence of a Neutron," is a brief report dated February 17, 1932, and published in the February 27 edition of *Nature* (Chadwick 1932a). A more extensive follow-up paper dated May 10, 1932, was published on June 1 in the *Proceedings of the Royal Society of London* (Chadwick 1932b). As we work through Chadwick's analysis, these will be referred to as Papers 1 and 2, respectively. The *Nature* paper is reproduced in Andrew Brown's excellent biography of Chadwick (Brown 1997). A complete description of the experimental background of the discovery of the neutron would be quite extensive, so only a brief summary of the essentials is given here. A more thorough discussion appears in Chap. 6 of Brown; see also Chap. 6 of Rhodes (1986).

The experiments which lead to the discovery of the neutron were first reported in 1930 by Walther Bothe and his student Herbert Becker, working in Germany. Their research involved studying gamma radiation which is produced when light elements such as magnesium and aluminum are bombarded by energetic alpha-particles emitted in the natural decay of elements such as radium or polonium. In such reactions, the alpha particles often interact with a target nucleus to yield a proton (hydrogen nucleus) and a gamma-ray, both of which can be detected by Geiger counters. A good example of such a reaction is the one used by Chadwick's mentor, Ernest Rutherford, to produce the first artificially-induced nuclear transmutation that was discussed in the preceding section:

$$ {}_{2}^{4}\mathrm{He} + {}_{7}^{14}\mathrm{N} \rightarrow {}_{1}^{1}\mathrm{H} + {}_{8}^{17}\mathrm{O} + \gamma. \tag{1.18} $$

The mystery began when Bothe and Becker found that boron, lithium, and particularly beryllium gave experimental evidence of gamma emission under alpha bombardment *but with no accompanying protons being emitted*. The key