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

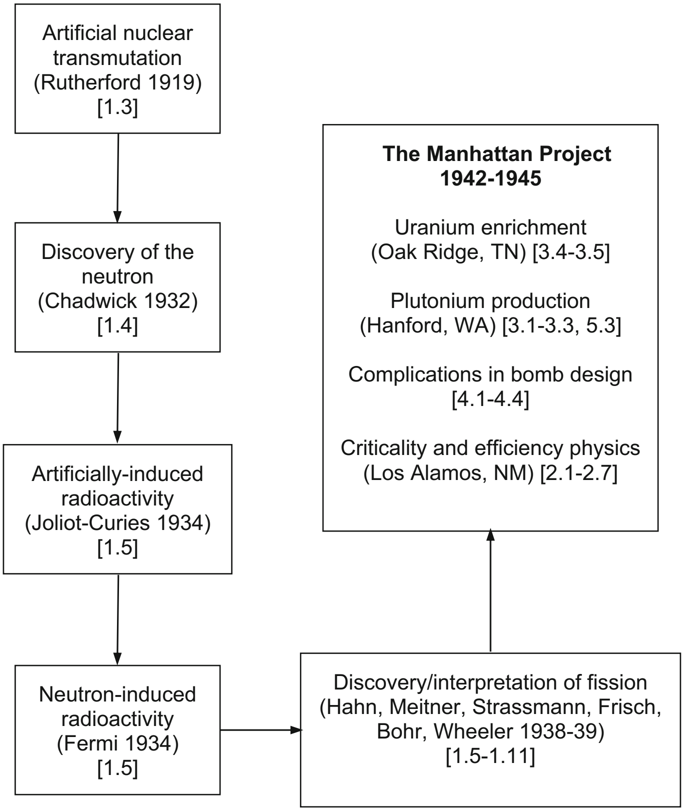

Fig. 1 Concept map of important discoveries in nuclear physics and the organization of the Manhattan Project. *Numbers in square brackets* indicate sections in this book where corresponding topics are discussed

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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