MATTHEW MOYNIHAN
ALFRED B. BORTZ

Fusion's PROMISE

How Technological Breakthroughs in Nuclear Fusion Can Conquer Climate Change on Earth (And Carry Humans To Mars, Too)

Springer

Fusion's Promise

Matthew Moynihan • Alfred B. Bortz

Fusion's Promise

How Technological Breakthroughs in Nuclear Fusion Can Conquer Climate Change on Earth (And Carry Humans To Mars, Too)

Springer

Matthew Moynihan
Fairport, NY, USA

Alfred B. Bortz
Pittsburgh, PA, USA

ISBN 978-3-031-22905-3 ISBN 978-3-031-22906-0 (eBook)
https://doi.org/10.1007/978-3-031-22906-0

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

This book is dedicated to future generations, with the hope that they will live in a world where human ingenuity, including fusion power, has mitigated the impact of climate change. This book is also dedicated to fusioneers, past and present, who have struggled to pull this technology forward.

Foreword for "Fusion's Promise"

FUSION ENERGY INSIGHTS

Now is really an exciting time for fusion. We've seen huge changes in the last 5 years, perhaps the biggest of which is the increase in the amount of private investment going into the field. Additionally, there have been announcements of scientific progress in both the public and private sectors.

Last year scientists at the National Ignition Facility (NIF) achieved their main goal of ignition in their inertial fusion (laser fusion) experiment—where fusion becomes self-sustaining by generating sufficient heat to exceed the losses. Then the JET tokamak broke the record for fusion energy produced, sustaining an average of 11 MW over 5 s, which is a sufficiently long timescale to give confidence that this timescale can be extended on future tokamaks with superconducting magnets.

In private companies, Commonwealth Fusion Systems demonstrated key new magnet technology, First Light Fusion and HB11 announced their first achievements of fusion (notable in their original and untested approaches) and Tokamak Energy achieved plasma temperatures of 100 million degrees in their spherical tokamak—fusion temperatures and the highest achieved in any privately funded tokamak.

And then there's the money.

Over the past 5 years, we've seen a steep rise in the number of private companies and, alongside that, the private investment going into fusion. The survey by the Fusion Industry Association in Q2 of 2022 showed that over half of the 33 featured private fusion companies had been founded since 2018. They also found that private funding into fusion exceeds \$4.8 bn (including \$117 million in grants and other funding from governments), which is a 139% increase in funding since the survey was conducted just the previous year. One private company alone secured \$1.8 bn. The industry is changing from being dominated by government-funded research.

Ready When Society Needs It…

A key factor in this progress is the increased will to achieve fusion.

Fusion has a long history dating back to around the 1940s. It has taken a long time to develop, partly because it’s so challenging. We’re trying to replicate the conditions in the centres of stars to make a clean energy source here on Earth! It’s not trivial at all—it’s a huge engineering challenge even beyond the scientific challenge of getting the stellar conditions (That in itself is exciting and inspiring). But there also wasn’t the collective will.

We’ve known about the issues of climate change and energy security for some time, but until very recently people seemed content to continue to burn fossil fuels. Now we see more public demands for climate action, driving government pledges and increasing investment in clean technologies. There is a sense of urgency that motivates many fusion teams and, equally, investors.

Fusion will be a transformational energy technology. Not only would it produce clean, green, safe and abundant energy, it would enable developing countries to have an access to the energy they need to improve their lifestyles. It’s a versatile energy source—it could be used to generate electricity, but could also be used with modifications to provide industrial heat or desalination. That kind of versatility is what’s needed to fully decarbonise our society. Moreover, in a world with a surfeit of clean energy, we could imagine powering Direct Air Capture systems to remove carbon dioxide from the atmosphere to, hopefully, undo some of the climate harm we have already done.

The greater will to achieve fusion, coupled with scientific maturity of the field and new technologies and capabilities (such as high-temperature superconductors, improved lasers and digital technologies) is driving investment and progress.

Moving Forward

We now see an array of private companies with different concepts and different approaches, all trying to commercialise fusion energy faster.

These private companies are viewing the challenge from a different perspective than the government laboratories. They need to create a product for the market, not simply a fusion device that works. They have aggressive timetables and motivated employees. Government labs are increasingly taking notice and we are moving into a phase of partnership between the public and private fusion sectors, which will be essential to develop fusion energy into a commercial reality.

I’m excited to watch the evolution over the coming decades.

Different Approaches

The fusion landscape can seem a mind-boggling place now with so many different laboratories and companies with their own concepts and niches. If only there was a way to help us navigate….

This book is important because it looks at some of the different approaches to fusion. Historically, the tokamak approach and the laser fusion/Inertial Confinement approach have received the majority of government funding, but there are many other approaches. Some of these have been less thoroughly studied in the past and some are newer concepts that are opening up as new technologies emerge.

This is significant because different concepts and strategies might be appropriate in certain situations. In the future, we may well find a variety of fusion reactors employed in various applications, rather than one overall winner in the field. For instance, some power plants could be large gigawatt-scale suitable for powering entire cities, while others might be ~100-megawatt units. Some companies are working on generating electricity directly without producing heat first. So we could imagine that there could be different concepts finding different niches in the future energy market.

This book examines the various approaches and technologies of fusion. Alongside the science, the authors present some of the history of how the technology has evolved over time, as well as individual experiences of the scientists who have been working on these concepts. It gives a thorough overview of the fusion space, what is out there and how scientists are coming closer to harnessing the energy of the stars. It will be useful for anybody wishing to gain a more detailed knowledge of the breadth of fusion technology and insight into the benefits and difficulties of each, or those wishing to take inspiration from the people behind the work.

Now is a crucial time as we move towards the era of commercial fusion. We need dedication, investment, smart people, collaboration and public support. I hope that you enjoy reading this book and learning about this transformational energy technology and the people devoted to its success.

Melanie Windridge,
Founder and CEO of Fusion Energy Insights
London, UK
August 20, 2022

Preface: The Current State of Fusion

Summary This book takes on this burning question: Isn't nuclear fusion one of those technologies that always promises a future that can never be achieved? Our answer, of course, is no. We would never have decided to write this book if we thought otherwise. Commercialization of nuclear fusion, the energy source of stars like our sun, for electric power or propulsion would be one of the greatest technical accomplishments of human history, akin to landing humans on the surface of the Moon and returning them safely, or the first powered flight. Like those other technological breakthroughs, its achievement will require a steady progression of significant but obscure precursor events. Our task is to bring to light the science and technology of fusion and the work of innovative fusioneers who will bring about a future of nearly unlimited green energy as well as other applications of fusion technology.

Reframing the Argument

This is a book for open-minded skeptics. You probably have heard some version of the old saw, "Nuclear fusion is the energy source of the future, and it always will be." That skeptical view is amusing because it has a ring of truth. But we hope our readers are willing to consider that only the first clause of that sentence is true. Nuclear fusion is the energy source of the future—and that future is "green."

It is useful to compare the current state of nuclear technology to powered flight just before the Wright brothers' first success at Kitty Hawk NC in 1903. Achieving powered flight required a steady progression of significant but obscure precursor events. The Wrights often used an 1894 book that cataloged over 200 years of research, *Progress in Flying Machines* by Octave Chanute (reprinted in 1998 by Dover Publishing), as a reference as they refined their flyer (Fig. 1).

Before their achievement, most people were unaware of what the Wrights were doing, and many people viewed heavier-than-air flying machines as impossible. Likewise, today's public is generally unaware of significant progress toward viable nuclear fusion power plants. And if that milestone is achieved—as we argue here that it will—the accomplishment and its dramatic ripple effects will suddenly be seen as the inevitable progression of technology.

Fig. 1 The public believed that powered flight was impossible despite—or perhaps because of—several centuries of attempts. Real progress was not made until the 1890s when Octave Chanute published his 1894 book, *Progress in Flying Machines*, which cataloged over 200 years of research (reprinted in 1998 by Dover Publishing). It was a key reference for the Wright brothers, helping them avoid bad ideas and eventually leading to the first successful powered human flight at Kitty Hawk NC in 1903. Nuclear fusion is now at a similar point, scientifically understood but seemingly beyond humanity's ability to harness in useful technologies. Is a Kitty Hawk moment in fusion's future? We argue that the answer is yes. (Photo credit: Library of Congress https://www.loc.gov/pictures/item/00652085/)

That is the usual progression of public opinion: a technology never seems real until people can see it, touch it, and understand it. And that is the state of fusion technology today. While most of the public still believes practical fusion systems or devices will never be achieved, an intrepid band of scientists, engineers, and entrepreneurs are hard at work behind the scenes on projects designed to achieve fusion's promise and prove the doubters wrong. They and their work are the focus of this book.

Controlled nuclear energy dates back to the 1950s when engineers harnessed nuclear fission, the phenomenon that led to the atomic bomb, as a source of electrical power. At that time, it was natural to think that the next step would be controlling nuclear fusion, the energy source of hydrogen bombs, in a similar way.

True, engineers were aware of technological hurdles, but many were confident that those would be overcome in two decades, or perhaps three at most. One of us (Bortz) recalls those optimistic predictions. He was an adolescent in 1957 when electrical energy from the first commercial power plant in the United States in Shippingport, PA began flowing to his home in Pittsburgh.

By the mid-1970s, having completed a doctorate and postdoc in computational physics, he found a job as a nuclear engineer, working on computer modeling of advanced fission reactors for the Westinghouse Electric Corporation. Still excited about the prospects of fusion power, he eagerly took a temporary assignment with a group that was seeking a government contract where he could apply his skills to fusion power research and development.

The contract went to another company, and he soon left the nuclear industry. He still expected fusion power to be a major source of electrical energy before the end of the twentieth century, but he decided to take his career in a different direction. That ultimately led to writing about science and technology for young readers. Over the next four decades, his interest in fusion faded along with the industry's prospects, but did not entirely disappear.

Some scientists and engineers, whom we call fusioneers, continued to be optimistic about the field. For them, fusion power has remained a long-term target, and they have worked on a number of different technological approaches that continue to show promise. One of those fusioneers is author Moynihan, who did fusion-related doctoral work in mechanical engineering at the University of Rochester. He continues to be inspired by the possibility of making a significant contribution to a technology that produces abundant power without emitting greenhouse gases and with much less radioactive waste than fission.

Even while working on other projects in several cities, he has maintained his presence in the field by blogging, podcasting, interviewing, and organizing online meetings with other fusioneers. This book is an outgrowth of those activities. Moynihan wanted his ideas and enthusiasm to reach educated but non-expert readers, and he knew that he needed the help of a professional writer to shape his work for that readership. When he discovered that Bortz lived a few miles away, he reached out, and they arranged to meet.

Bortz was skeptical, asking, "Aren't fusioneers chasing steadily moving goalposts?" Moynihan said no, and eagerly began explaining why the technology is within reach. In fact, fusion is already finding commercial application in other economic sectors.

Moynihan's knowledge and enthusiasm were persuasive. Bortz, though remaining a skeptic, shared Moynihan's desire to find economically viable "green" alternatives to fossil fuels. If the goalposts had finally stopped moving, then fusion might well have a role in our energy future. He could see a book taking shape. You are reading the result.

A Rapidly Changing Field for a Rapidly Changing World

This book is, by necessity, a snapshot of a field in flux. Though scientists and engineers have studied nuclear fusion for more than seven decades and have consistently encountered obstacles to successful technological development, they have also found avenues that might lead to future success. As a result, both government agencies and private corporations and investors continue to commit financial support to large- and small-scale fusion projects. In fact, as we completed the writing of this book in early 2022, new achievements in fusion research and development led to a flurry of new government and private investment (See Epilogue for details).

As in any rapidly evolving field, practitioners are passionate about their own projects. Likewise, they may tend to disparage competing efforts. We as authors have chosen to take a broad view of fusion research and development. We have shared our ideas and benefited from the generous advice of many experts (see Acknowledgments). However, the descriptions and conclusions are our own.

Even though experts and their colleagues may disagree with some of our analyses, we hope they will appreciate the book for its goal of enabling the broader public to understand and appreciate their work. We want you, our readers, whose tax and investment dollars support those efforts, to have the knowledge you need to develop informed opinions about the investigations you are funding.

We begin with this point: We live in a world that is warming due to human production of greenhouse gases. Experts have calculated a carbon dioxide budget that will keep the average temperature within 2 °C of pre-industrial times—viewed as necessary to avoid catastrophic climate-related events. Many experts recommend a lower target of 1.5 °C.

Yet Earth's growing population and the need for economic development lead to a rapidly increasing demand for electrical energy. That creates an urgent need for "green" technologies. Technological breakthroughs in magnet and computer technology, which we describe in this book, have dramatically changed the trajectory of fusion power; and the urgent need to reduce greenhouse gas production has provided a strong incentive to fund necessary fusion R&D. Fusion's promise of a low-cost, low-pollution, and abundant energy source is, at last, on track to being realized. Fusioneers can now make a strong case that their field is on the verge of commercial viability and will make up a significant fraction of the green energy mix in the coming decades.

Why This Matters

(Both Authors)

Why is this subject so important? Although we are at different stages of life, each of us feels the urgency of reducing greenhouse gas emissions. Bortz looks at his grandchildren, who are young adults, and worries that his generation has created a climate crisis that will dominate the world they are about to inherit. No longer working as a scientist, he hopes that his active support of the bipartisan Citizens Climate Lobby and its policy proposals can make a difference. On the local level, he hopes his letters to the editor of his hometown newspaper raise his neighbors' awareness of the need to transform our energy usage. In his writing for young readers, he hopes to encourage his audience to avoid simplistic answers and ask critical questions (See for example *Meltdown! The Nuclear Disaster in Japan and Our Energy Future*, Lerner 2012. That book raises important questions about the future role of nuclear fission as an energy source but leaves them unanswered, recognizing that his readers will be the ones to decide among many alternatives in a rapidly changing world).

Moynihan, who is currently raising a toddler, will confront the problems of climate change more directly in his lifetime. That motivates his work as an engineer and advocate for nuclear fusion. The following paragraphs note his motivation for bringing the promise of nuclear fusion technology to the attention of our audience of educated non-specialists whose political and financial support will be essential to bringing that promise to fruition.

(Matthew Moynihan)

Besides the implications for climate change, achieving controlled nuclear fusion could be the greatest technological advancement of the twenty-first century and could significantly change the political and military calculus of nations around the world. Those governments would view it as a potential disaster if an adversary achieves fusion first. Controlled fusion could be exceedingly disruptive to the global economy, and governments need to be prepared to adapt.

From my perspective as an American with a front-row seat in the field, I have been concerned that my country has been falling behind in this field. My view comes from conversations with government officials on the sidelines of conferences, on college campuses, and over the phone. The refrain has been universal. Although I have watched worldwide fusion research escalate in its scale and pace, those officials widely consider controlled fusion as impossible. Consequently, there is a lack of breadth or depth of knowledge within both the executive and legislative branches as well as within the federal bureaucracy.

This lack of expertise translates into low public enthusiasm for the subject—which translates into insufficient funding. For roughly a generation, from the middle 1980s through the 2010s, fusion was not a priority for the United States. This becomes especially apparent when you compare US funding for another national science priority—NASA (See Fig. 2). This has created a vicious cycle for nuclear fusion. With insufficient funding, the problem is harder to solve. By making it harder to solve, the problem looks more difficult than it would otherwise be.

Breaking this cycle has been the goal of fusioneers for the past 30 years. Fortunately, it finally feels as though this is starting to change (see Epilogue). By reading this book, you are getting involved at the beginning of this shift. It is going to be intriguing to see what happens next.

Why Cold Fusion Is No Longer Hot

Many readers of this book will recall the hullabaloo surrounding the March 1989 claim by Martin Fleischmann and Stanley Pons that they had achieved fusion in a tabletop apparatus, specifically an electrolysis cell with a palladium electrode filled with heavy water (see next paragraph for definition) [1]. The claim was soon dubbed "cold fusion" in the popular press because it did not require the high temperatures and pressures like those in the interior of a star believed necessary for fusion to

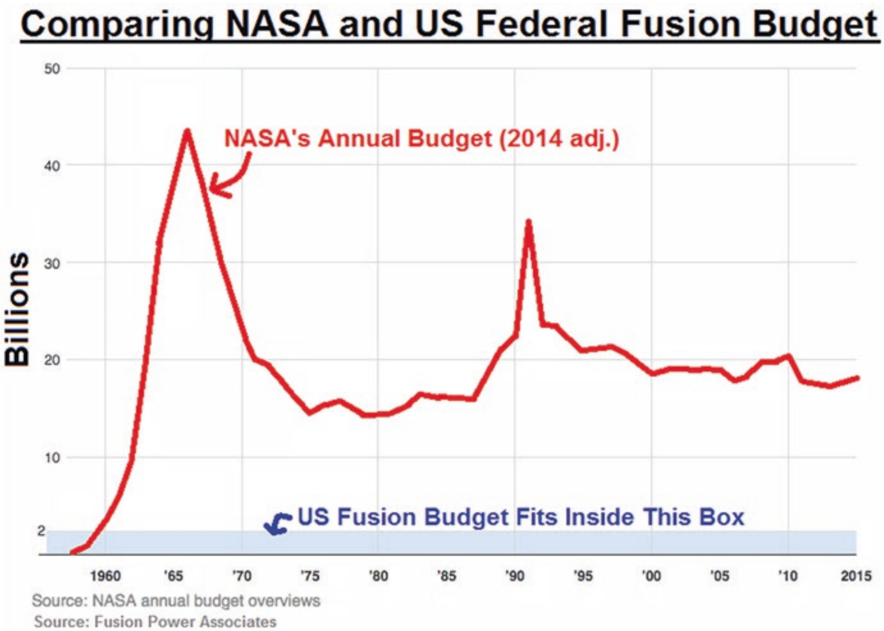

Fig. 2 US funding for fusion is dwarfed by the spending for NASA

occur. If their result could be commercialized, it would mark the beginning of an inexhaustible and virtually pollution-free source of energy from the Earth's most abundant natural resource, water.

Their evidence was excess heat and the production of neutrons and tritium, which would be the result of a fusion reaction of two deuterium nuclei. (Deuterium and tritium are heavy isotopes of hydrogen with one or two neutrons, respectively. Heavy water has two deuterium atoms instead of the most common hydrogen isotope with a single proton and no neutrons.) Unfortunately, no other experimenters could replicate their results, and instead uncovered flaws and experimental errors. Furthermore, no one developed a credible suggestion of a theoretical mechanism that could produce the claimed observations. By the end of the year, cold fusion had become a laughing stock, and Pons and Fleischmann's reputations were permanently tarnished.

Because of the enormous technological upside of such a discovery, a small but undaunted community of researchers remains on the case. They now describe their effort as a search for low-energy nuclear reactions (LENR), but so far it appears to be as fruitless as the Pons and Fleischmann work [2, 3]. For that reason, we have decided not to include it in this book.

A Partnership

We view this book as a partnership between you as readers and us as authors. Our goal is to pull together all the disparate threads, efforts, and projects that fusioneers have undertaken over the past 70 years to produce electrical energy from fusion. In that sense, we serve as historians.

However, we also recognize that the quest for fusion power is an intergenerational relay race. In one sense, the publication of this book marks the end of our leg of the relay. By reading it, you have agreed to accept the baton.

In another sense, we are spectators watching the race together but with different roles. We are the public address announcers, introducing the fusioneers and their work, while you cheer them onward toward an indefinite finish line that may be just out of view.

We are particularly proud to describe the latest entries in the race, the risk-takers discussed in the sections on fusion startups. They and their companies are driven, creative, and determined to push this field forward. They are trying to do something new in the course of human history: to develop an entirely new energy technology and to build a market-based, commercially viable path to bring it to fruition.

References

1. *Fleischmann, Martin; Pons, Stanley (1989), "Electrochemically induced nuclear fusion of deuterium", Journal of Electroanalytical Chemistry,* ***261*** *(2A): 301–308, https://doi.org/10.1016/0022-0728(89)80006-3*
2. *Koziol, Michael (22 March 2021). "Whether Cold Fusion or Low-Energy Nuclear Reactions, U.S. Navy Researchers Reopen Case," IEEE Spectrum: Technology, Engineering, and Science News*. Retrieved 23 March 2021
3. Berlinguette, C.P., Chiang, YM., Munday, J.N. et al. Revisiting the cold case of cold fusion. Nature **570**, 45–51 (2019). https://doi.org/10.1038/s41586-019-1256-6

Acknowledgments

There are so many people who contributed indirectly or directly to the formation, content, and editing of this book over the many years that it was in development. Writing a book goes on far longer than anyone expects, because it takes place during the free moments you have while leading your normal life. This book took almost 5 years to pull together because we could only devote those free moments to developing it. Below are some of the people whom the authors wish to thank for helping to make *Fusion's Promise* a reality.

From Matthew Moynihan (Except Where Noted Otherwise)

I would like to thank Dr. Richard Hubbard, retired associate superintendent of the Naval Research Laboratory, for his mentorship on fusion and contributions to the Inertial Confinement Fusion chapter. Also thanks to Dr. Sam Cohen and Dr. Charles Swanson from Princeton University for their review and input on the plasma structures chapter. The book benefited greatly from Dr. Robert Terry's input on the pinch chapter and his encyclopedic knowledge of plasma instabilities. I am immensely grateful to Dr. Thomas Dolan from the University of Illinois for his review of the cusp material, general comments, and mentorship.

I would also like to thank Dr. Derek Sutherland who informed the content on the Dynomak. Dr. Ralph Moir who, although retired from Livermore, was immensely helpful in his critique and information on the Mirror chapter. He was also gracious enough to allow a visit to his home during the early stages of this book's development. Dr. Jay Kesner spent several hours walking me through the history of the US mirror program at his office in Boston. Also Dr. Francis Thio was willing to meet me in Virginia and go over the physics of the Plasma Liner Experiment.

I am grateful to the staff at Shine Medical Technologies for their general support of the book and willingness to approve the use of images from their work. Thanks also to Dr. Scott Hsu for feedback and insights provided over the years and Dr. Mike Campbell for his mentorship around the IFE chapter. Both authors would like to thank Dr. Melanie Windridge for her enthusiastic agreement to write the Foreword and her review of the Tokamak and Stellerator chapters.

I appreciate the support of Dr. Greg Brittles and the team at Tokamak Energy and their willingness to provide information about the ST-40 as an example system. Dr.

Bob Mummgraad graciously found time to review the Tokamak chapter despite his exceedingly busy schedule. Likewise, my thanks go to Commonwealth Fusion Systems for allowing a site visit when the company was just getting off the ground.

Thanks also to Dr. Stephen O Dean for his willingness to open up the Fusion Power Associates meetings to me. I am also grateful to Mr. Peter DeVieten, investor and former staffer at General Fusion, and to Dr. Simon Woodruff for general reviews of the book. Finally, I appreciate Mr. Tom Painter from the National High Magnetic Field Laboratory for sharing his insights and information about superconducting magnets.

Finally, both authors are grateful to all the people (including Dr. Drew Hazelton, Dina Zaid, Dr. Todd Rider, and many others) and organizations that approved the use of images in this text.

There were also many early, non-fusion, readers of the book who offered edits, suggestions, and insights. These readers included: Janet Norman, Ben Levitt, Albert Consentino, Igor Stevanovic, Eugene Francis, Sidney Fowler, Emma Palmer, Davin Young, and many others. I would like to thank Linda Giebel who was willing to do copyediting of an early version of the manuscript on short notice and meet to discuss the book at Panera Bread. Thanks also to Stephen Moretto and Sinclair Harris for opinions on the overall text of that manuscript.

Both authors are grateful to Fred Bortz's graduate school buddy and long-time friend Mike Walker, author of *Quantum Fuzz: The Strange True Makeup of Everything Around Us* (Prometheus Books, 2017), for commiserating about the process of finding the right publisher for a book on a highly technical topic for readers who may have limited technical backgrounds. If you enjoy *Fusion's Promise*, you may want to add *Quantum Fuzz* to your reading list.

We also like to thank Dr. Sam Harris, the editor at Nature-Springer, whose support of the project ensured its successful completion. Finally, the authors want to thank their wives for being supportive of the project. Without their support and patience, this book would have never been completed.

Contents

About the Authors

Matthew Moynihan(Matt) has been keenly interested in nuclear fusion since he first took physics in high school. For the past 15 years, he has been working to build the broader fusion community and to explain the value of fusion as a green energy source to everyday citizens. He has been the host of a popular fusion podcast, written a fusion blog, and his work has appeared in *Forbes*, *CNBC*, *Bloomberg News*, *The Boston Globe*, and *IEEE Spectrum*. He holds a bachelor's degree in engineering from the University at Buffalo and a doctorate focused on fusion from the University of Rochester. Currently working as a consultant on fusion, he was previously a senior nuclear engineer for the US Navy, studying the safety of nuclear submarines and aircraft carriers. He lives in Fairport NY with his wife, Alison, and his son, Peter.

Alfred B. Bortz has lived in or near Pittsburgh, PA all his life, with the exception of a 4-year interlude early in his working career. He earned his Ph.D. in Physics from Carnegie Mellon University in 1971 and spent the next 25 years working in academic and industrial physics and engineering groups. Since then, he has forged a second career as Dr. Fred Bortz, an author of more than 30 science books for young readers. His most significant research publication, "A New Algorithm for Monte Carlo Simulation of Ising Spin Systems" (with M. H. Kalos and J. L. Lebowitz) published in the *Journal of Computational Physics* in 1975, is often described as seminal and is still frequently cited in research journals after nearly five decades. His best-known books for young readers are *Catastrophe! Great Engineering Failure—and Success* (a selector's choice on the 1996 National Science Teachers Association list of Outstanding Science Books for Children), *Meltdown! The Nuclear Disaster in Japan and Our Energy Future* (a 2012 Junior Library Guild Selection), and *Techno-Matter: The Materials Behind the Marvels*, which won the 2002 American Institute of Physics Science Writing Award for works intended for young readers. He and his wife, Susan, are the proud parents of a STEM educator and a librarian and grandparents of three young adults.

Plasma Science

1

Summary

This chapter covers the basic theory and modeling of the state of matter known as plasma, in which nuclear fusion can take place. It begins with an overview of the particles that make up atoms and nuclei and the forces that bind them together. It then describes how nuclei react and transform via fission and fusion to yield energy. Finally, it takes a deep dive into the ways that scientists create mathematical models that enable them to simulate and analyze the behavior of plasmas.

1.1 The Nature of Matter

The modern understanding of matter emerged in the first decade of the nineteenth century. John Dalton's landmark text *A New Theory of Chemical Philosophy*, published in 1808, described chemical elements (atoms) and compounds (molecules) and their properties. Throughout that century, chemists discovered numerous elements with a large range of atomic weights. As they began to see similarities and patterns in the properties of the elements, researchers sought a new way to organize them. Finally, in 1869, the Russian chemist Dmitri Ivanovich Mendeleev created the periodic table of elements that is familiar to all of us today. He ordered the 63 known elements by atomic weight and arranged them in rows and columns with several gaps, which were eventually filled by subsequent discoveries. Each row (today's columns) had atoms with similar chemical properties (Fig. 1.1).

At the time, atoms were regarded as the smallest particles of matter. In fact, the word atom came from the Greek *atomos*, meaning indivisible. Despite the atomic theory's many successes, important questions remained, including what makes atoms of one element different from another and why their properties are periodic.

M. Moynihan, A. B. Bortz, *Fusion's Promise*,
https://doi.org/10.1007/978-3-031-22906-0_1

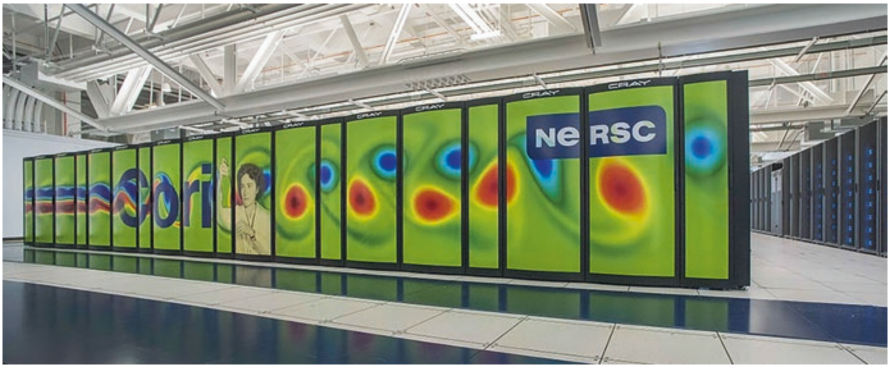

Fig. 1.1 Large fusion models drove the creation of large supercomputers, such as the Cori supercomputer at the National Energy Research Scientific Computing Center (NERSC). The computer is named after Gerty Cori, the third woman to win the Nobel Prize in medicine for discovering glycogen metabolism. The computer can execute 30 petaflops or 30 quadrillion calculations per second. Fusion researchers from around the United States apply for time on Cori and use it to run large plasma simulations

1.1.1 Subatomic Particles

Answering those questions required a dramatic change in thinking, which began to emerge as the nineteenth century was nearing an end. Atoms, it turned out, are not indivisible at all. Rather, they are comprised of smaller particles that we now call protons, neutrons, and electrons. (Protons and neutrons also have smaller components, known as quarks, but we will not need to go to that level of detail to explain the science and technology of nuclear fusion.)

The first indication that atoms have component parts came in 1897 at the famous Cavendish Laboratory of the University of Cambridge in England, then headed by noted physicist Joseph John (J. J.) Thomson. Thomson and his students, including a young New Zealander by the name of Ernest Rutherford, were studying the phenomenon of cathode rays, which were emitted from heated metal filaments. They discovered that the rays were made up of tiny particles all carrying the same small amount of negative electric charge and having a mass much less than a thousandth of that of a hydrogen atom. They were the same no matter what metal the filament was made from. Thomson called them corpuscles.

That research led him to conclude that the corpuscles, which we now call electrons, came from inside atoms. Because they were so light, he theorized that an atom was like a “plum pudding” with tiny electrons distributed throughout a positively charged bulk that carried the rest of the atom’s mass. That idea, though useful, turned out to be spectacularly wrong, and it was Rutherford’s work that overturned it.

After completing his fellowship with Thomson, Rutherford accepted a position at McGill University in Montreal, where he did groundbreaking research in radioactivity. In 1907, he returned to England as chair of physics at Victoria University of

Manchester (now the University of Manchester). There, in 1909, with students Hans Geiger and Ernest Marsden, Rutherford's research revealed that atoms were not at all like plum pudding. Most of their mass was contained in a tiny nucleus that was less than ten thousandth the size of the atom itself and carried a positive electric charge. That positive charge was equal to the negative charge of all the atom's electrons, which Rutherford viewed as orbiting the nucleus bound by electrostatic attraction, analogous to planets orbiting the Sun bound by gravity.

In 1919, Rutherford succeeded Thomson as the head of the Cavendish Laboratory. By then, scientists had come to understand that the periodic table should be ordered not by atomic weight but by nuclear charge, which they called the atomic number. The atomic weight (more correctly the atomic mass) generally increased as the atomic number did but was not proportional to it. As the atomic number increased one unit at a time through the periodic table, the atomic mass generally increased faster.

It became apparent that an atomic nucleus contained the atomic number of positively charged particles, which Rutherford named protons, plus something else. That "something else" had to be very important because it held the protons together much more strongly than the electric repulsion between them pushed them apart. Rutherford proposed that the extra mass came from neutrally charged particles that he called neutrons. In 1931, James Chadwick, a colleague of Rutherford at the Cavendish, did an experiment that demonstrated the existence of neutrons, which had just slightly more mass than protons.

At that point, the basic components of the atomic structure were known. Atoms are comprised of very light negatively charged electrons surrounding and bound electrically to a very dense nucleus of protons and neutrons.

1.1.2 Isotopes and Binding Energy

This knowledge led to a new understanding of atomic mass. Just as the atomic number corresponds to the number of protons in the nucleus, the atomic mass number is the number of nucleons, i.e., the number of protons plus the number of neutrons. That explains the phenomenon of isotopes, in which atoms having the same chemistry (because of their electrons) can have different masses. The number of protons is the same in the nucleus of two different isotopes of an element, but the number of neutrons is different.

From this discussion, you might think that the mass of a nucleus could be calculated by this simple formula: the number of protons times the mass of a proton plus the number of neutrons times the mass of a neutron. Yet in every case (except for the hydrogen nucleus, which is a single proton), that simple formula leads to an overestimate by an amount known as the mass defect. The difference is due to perhaps the most famous formula in physics, $E = mc^2$. Einstein's theory of relativity describes the equivalence of mass and energy. In order to break a nucleus into its component nucleons, you need to add energy, which means that the total mass of the products will be greater than the original mass.

Another way to describe this is by saying that a nucleus is held together by a negative binding energy. In this book, we will be describing nuclear reactions that release vast amounts of energy because the products have less mass (or more binding energy) than the reactants.

That may lead you to question what you learned in chemistry class, namely the "law" of conservation of mass. You are surely familiar with chemical reactions, such as combustion, that release energy. You probably learned that the mass of the combustion products is equal to the mass of the reacting atoms and molecules. In fact, that is not true. The energy released in combustion does indeed correspond to a very slight decrease in mass. But the amount of lost mass is so small that it is not measurable by typical chemistry lab instruments. The actual law is the conservation of mass plus energy, which your chemistry teachers almost certainly knew, but they also recognized that it was beyond the scope of the course.

1.2 Nuclear Reactions and Transformations

Nuclear reactions take two forms: fission, in which large nuclei break apart and release energy, and fusion, in which small nuclei combine to release energy. Figure 1.2 shows how these processes relate to binding energy. The vertical axis is

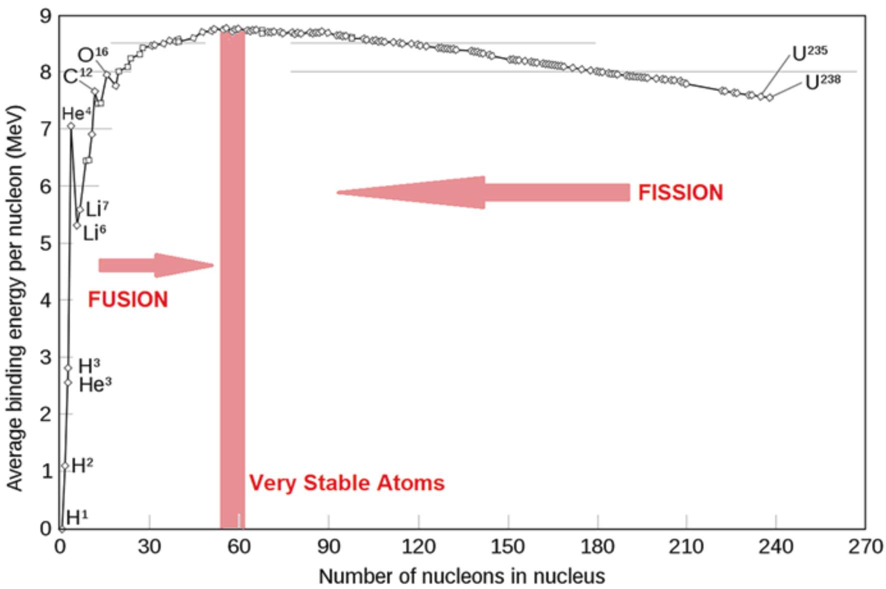

Fig. 1.2 The binding energy per nucleon of each isotope. The isotope with the highest energy per nucleon is Nickel-62, with Iron-58 and Iron-56 very close behind, which makes them the hardest nuclei to change. (Image based on https://en.wikipedia.org/wiki/Helium-4#/media/File:Binding_energy_curve-common_isotopes.svg*)

(negative) binding energy per nucleon, while the horizontal axis is the number of nucleons.

The shape of the curve results from the nature of the "strong" nuclear force that binds nucleons together in a nucleus. (There is a second nuclear force, called the weak nuclear force, which comes into play in the process of transforming one form of nucleon into the other.) It peaks at Nickel-62, a nucleus with 28 protons and 34 neutrons, with Iron-58 and Iron-56 (26 protons, 32 or 30 neutrons) very close behind. (Iron-56 has the largest mass defect per nucleon.) Natural processes favor the lowest energy state, i.e., more negative energy and thus higher on the graph. So fusion processes take place on the left side of the graph, while the fission process occurs on the right.

The strong force between two nucleons differs from the more familiar (attractive) gravitational and (attractive or repulsive depending on relative charge) electromagnetic forces in a significant way. Those forces are inverse-square forces, meaning that their strength is inversely proportional to the square of the separation of the interacting particles. The strong nuclear force is attractive and more powerful than electrostatic repulsion at distances comparable to the size of the nucleus but, unlike the electrostatic force, drops off more sharply than the inverse square of the distance between them as their separation increases. It also becomes less attractive and eventually repulsive at separations smaller than the nuclear size, as if the nucleons have a hard core.

Besides showing the comparison between those two forces between nucleons, Fig. 1.3 can also help us understand why neutrons are necessary for a nucleus larger than hydrogen to be stable. Imagine that two protons approach each other within the

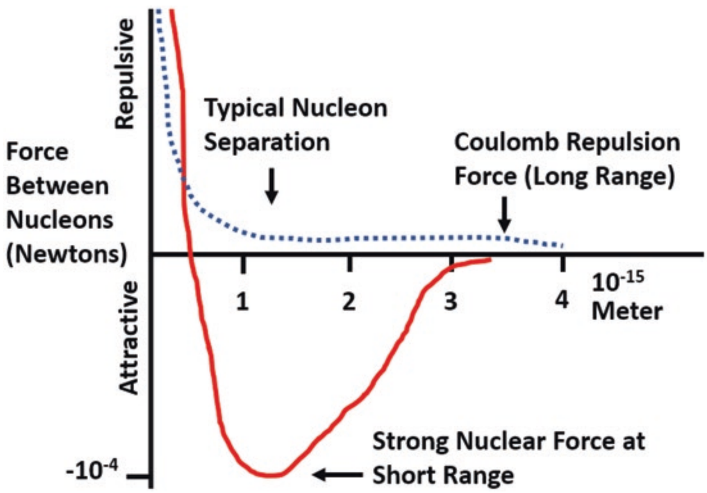

Fig. 1.3 Comparison of the strong nuclear force between two nucleons and the electrostatic repulsion (Coulomb's inverse-square law) between two protons. Neutrons experience no electrostatic forces