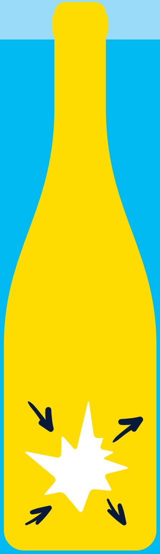
L. J. Reinders

Sun in a Bottle? ... Pie in the Sky!



The Wishful Thinking of Nuclear Fusion Energy

Springer

Sun in a Bottle?... Pie in the Sky!

L. J. Reinders

Sun in a Bottle?... Pie in the Sky!

The Wishful Thinking of Nuclear Fusion Energy

Springer

L. J. Reinders
Panningen, The Netherlands

ISBN 978-3-030-74733-6   ISBN 978-3-030-74734-3 (eBook)
https://doi.org/10.1007/978-3-030-74734-3

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2021
This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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

Preface

Nuclear fusion is the process that powers the stars, including our own Sun. As soon as these stellar processes started to be understood (in the early 1920s), people began dreaming about harnessing their power both for the benefit and for the destruction of mankind. The development of the hydrogen bomb made the latter part of this dream come true. We now possess bombs that can destroy the Earth and all that is on it in a matter of hours or less. The other part of the dream, which concerns an inexhaustible clean source of energy that will save mankind from the horrors of climate change and pollution, has not yet become a reality.

For the past seventy years nuclear scientists and engineers have been trying to create this source of energy on Earth. So far in vain. From the early 1950s, promises have been made that its unlimited benefits will be available in at most two decades. The general media upped these promises with blazing headlines of the perceived breakthroughs that were achieved, while presenting the same old stories over and over again without taking the trouble to ask any critical questions. Examples are: "China's quest for clean, limitless energy heats up", "Speeding the development of fusion power to create unlimited energy on Earth", "'Star in a jar' could lead to limitless fusion energy". No other scientific or other enterprise I am aware of has ever been in need of so many 'breakthroughs' without making any real progress. Why is it taking so long?

The scientists themselves are partly to blame for this with silly statements galore in the literature and other places, such as the following one from the

1980s: "If the Martians were attacking, if money were no object and the military wanted a working fusion reactor by the year 2000, there is no question we could have it. By the year 2000 we could build such a BIG turkey." Such completely empty statements, only invoking hullabaloo, lack everything one expects of thoughtful scientists and are very reminiscent of statements made by certain politicians in the (fortunately short-lived) Trumpian age we just managed to survive. Science should steer clear of such talk and base its statements solely on science and scientific results. And the fact is that there are no such results or hardly any. The emperor has no clothes and never had any, and nobody wants to see it!

This book has grown out of a more extensive, more technical and more comprehensive version of the history of nuclear fusion in the last seventy years, called *The Fairy Tale of Nuclear Fusion*,[1] also recently published by *Springer Nature*. The goal of the present version is to present a more accessible, 'chatty' version of the fusion enterprise, aimed at the general public, exemplified by an intelligent eighteen-year old with a high-school education, who wants to look behind the screaming headlines about fusion's 'unlimited, abundant energy.' It tries to explain what has been and is now going on in fusion research and where it is likely to lead. When climate change came along, fusion scientists saw new chances and jumped early on this bandwagon, propagating fusion as the path to carbon-free, unlimited, clean energy and as the solution to the climate-change problems we are currently faced with. This book will shatter this prospect. There is no possible scenario in which fusion will make a sizable contribution to the energy mix in this century, let alone before or around 2050 as required by the Paris Climate agreement. Fusion will not make any positive contribution to the mitigation of climate change, nor will fusion energy be as clean and limitless as claimed by its proponents. If it ever becomes a reality, at the earliest in the course of the next century, electricity production from nuclear fusion will most likely be so expensive and so complex that it will never become economically viable.

There are no references in this book. If you want to know more about a certain topic or find out where it came from, please consult the book mentioned above, which contains extensive references. In the back of this book I will only give a general list of books on nuclear fusion and some related topics.

Panningen, The Netherlands L. J. Reinders
March 2021

---

[1] L. J. Reinders, *The Fairy Tale of Nuclear Fusion* (Springer, 2021).

Contents

Acronyms and Abbreviations

AEC	Atomic Energy Commission
AERE	Atomic Energy Research Establishment
Alcator	Alto Campo Toro
APS	American Physical Society
ARIES	Advanced Reactor Innovation and Evaluation Study
ARPA-E	Advanced Research Projects Agency-Energy
ASDEX	Axially Symmetric Divertor Experiment
ASN	Autorité de Sûreté Nucléaire (French Nuclear Safety Authority)
BINP	Budker Institute of Nuclear Physics
CANDU	Canada Deuterium Uranium
CCFE	Culham Centre for Fusion Energy
CDA	Conceptional Design Activities (ITER)
CEA	Commissariat à l'énergie atomique et aux énergies alternatives
CFC	Carbon fibre composite
CFETR	China Fusion Engineering Test Reactor
CFS	Commonwealth Fusion Systems
CS	Central solenoid
DOE	Department of Energy (US)
DONES	DEMO Oriented Neutron Source
EAST	Experimental Advanced Superconducting Tokamak
ECRH	Electron Cyclotron Resonance Heating
EDA	Engineering Design Activities (ITER)
EFDA	European Fusion Development Agreement
ELM	Edge-localised mode
ETR	Engineering Test Reactor

Euratom	European Atomic Energy Community
FRC	Field-reversed configuration
HELIAS	Helical-Axis Advanced Stellarator
HLW	High-level waste
HTS	High-temperature superconductor
IAEA	International Atomic Energy Agency
ICRH	Ion Cyclotron Resonance Heating
IDCD	Imposed-Dynamo Current Drive
IFMIF	International Fusion Materials Irradiation Facility
IFRC	International Fusion Research Council
ILW	Intermediate-level waste
INFUSE	Innovation Network for Fusion Energy
INTOR	International Tokamak Reactor
IPP	Max Planck Institute for Plasma Physics
ISS	International Space Station
ITER	International Thermonuclear Experimental Reactor
ITER-FEAT	ITER Fusion Energy Advanced Tokomak
JAERI	Japan Atomic Energy Research Institute
JET	Joint European Torus
KSTAR	Korea Superconducting Tokamak Advanced Research
LCE	Lithium carbonate equivalent
LCFS	Last closed flux surface
LCOE	Levelized cost of energy or levelized cost of electricity
LH	Lower Hybrid
LLW	Low-level waste
LTS	Low-temperature superconductor
MAST	Mega Ampere Spherical Tokamak
MFTF	Mirror Fusion Test Facility
MIT	Massachusetts Institute of Technology
NBI	Neutral-beam Injection
NSST	Next Step Spherical Torus
NSTX	National Spherical Torus Experiment
ORNL	Oak Ridge National Laboratory
PF coils	Poloidal field coils
PFC	Plasma facing component
PKA	Primary knock-on atom
PLT	Princeton Large Torus
PPPL	Princeton Plasma Physics Laboratory
PSFC	Plasma Science and Fusion Center (MIT)
RAFM	Reduced activation ferritic/martensitic
RFP	Reversed Field Pinch
SIFFER	SIno-French Fusion Energy Center
SOL	Scrape-Off Layer
SPI	Shattered pellet injection

SST	Steady-state Superconducting Tokamak
ST	Spherical tokamak
START	Small Tight Aspect Ratio Tokamak
STEP	Spherical Tokamak for Energy Production
TBM	Test Blanket Module
TBR	Tritium breeding ratio
TCV	Tokamak à Configuration Variable
TF coils	Toroidal field coils
TFR	Tokamak de Fontenay-aux-Roses
TFTR	Tokamak Fusion Test Reactor
VLLW	Very-low-level waste
WEST	Tungsten (Wolfram) Environment in Steady-state Tokamak
ZETA	Zero Energy Thermonuclear Assembly

Units and Related Quantities

dpa	displacements per atom
eV	electronvolt (1.6 x 10^{-19} joule)
GW	gigawatt (1 billion (10^9) watts)
keV	kiloelectronvolt
MA	megaamperes
MeV	mega-electronvolt (1 million electronvolt)
MW	megawatt (1 million watts; 10^6 joule/second)
MWe	megawatt electric
ppm	parts per million
T	tesla, unit of magnetic field strength equal to 10,000 gauss
TW	terawatt (1 trillion (10^{12}) watts)

1

What is Nuclear Fusion?

The energy that reaches us from the Sun is the product of a process called nuclear fusion, the fusion of nuclei of atoms, the basic constituents of matter. Although the particular process that takes place in the Sun cannot be reproduced on Earth, the idea of generating vast amounts of energy from combining light elements into heavier ones has been a dream of mankind ever since the processes in the Sun and other stars were unravelled early in the twentieth century. Per kilogram of matter consumed the release of energy is about ten million times greater than in a typical chemical process like the burning of fossil fuels (coal, oil or gas). As will be discussed in this book, for the last seventy years a lot of effort has been put into trying to control nuclear fusion on Earth, in order to harvest this energy and solve the energy problems of mankind once and for all.

Apart from nuclear *fusion*, there is also the more commonly known process of nuclear *fission*, which concerns the splitting of nuclei of heavy elements into lighter ones. The best-known example is uranium, whereby the nucleus of this element is split into two smaller, more stable nuclei, while releasing at the same time a certain amount of energy. Per kilogram of matter the release of energy is, however, less than 10% of the output of fusion. Present-day nuclear power stations use this fission process to generate energy, something people also want to do with nuclear fusion by fusing light elements into heavier ones. In this book we will see that this is not such an easy matter.

To explain how all this works we first must know a little about nuclear physics, starting with the observation that all matter is built up of chemical

L. J. Reinders, *Sun in a Bottle?... Pie in the Sky!*,
https://doi.org/10.1007/978-3-030-74734-3_1

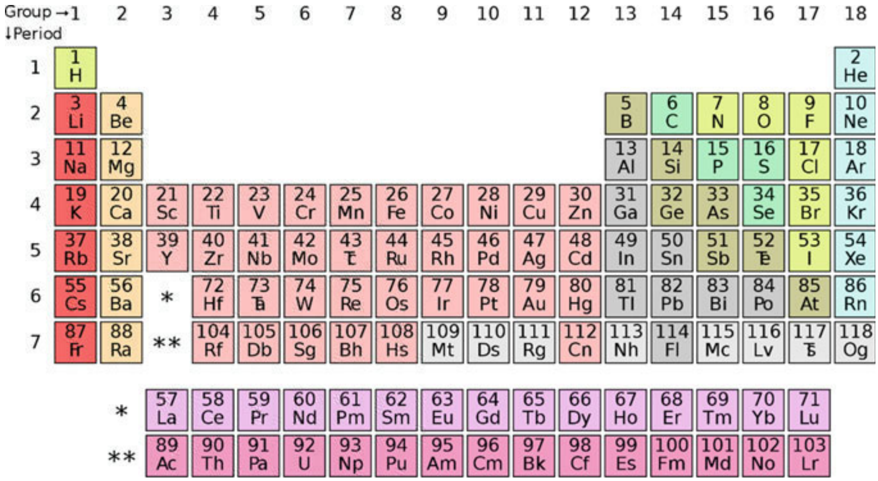


Fig. 1.1 Periodic table of elements in the modern standard form with 18 columns

elements, such as carbon, iron, hydrogen, oxygen, etc. These elements are arranged in the Periodic Table of Elements (Fig. 1.1). The basis for this table was laid down in the late nineteenth century by the Russian chemist Dmitri Mendeleev (1834–1907). The smallest unit of an element (that still possesses the chemical properties of that element) is called an atom. Every solid, liquid, or gas is composed of atoms, in most cases neutral, i.e., uncharged atoms. Such an atom has a nucleus at its centre, which is orbited by negatively charged electrons.

Hydrogen (H), the lightest element occupies first place in the table, helium (He) is in second place, and so it goes all the way up to the heaviest element oganesson with number 118. The number of the element in the Periodic Table is, quite reasonably, called the *atomic number*, denoted by the symbol Z, and is equal to the number of electrons orbiting the nucleus. Electrons are negatively charged, and the total charge of all electrons equals the positive charge of the nucleus, making the atom as a whole neutral in charge. The positive charge of the nucleus is carried by particles, called protons, and the number of protons in the nucleus is equal to the number of electrons. The mass of a proton is about two thousand times the mass of an electron, which explains why most of the mass of an element is concentrated in its nucleus. So, the lightest element hydrogen has a single electron, and its nucleus is a single proton, while uranium, for instance, with atomic number 92 has 92 electrons orbiting a nucleus with 92 protons.

Apart from the charge-carrying protons, nuclei also contain a number of neutral particles, called neutrons, which have approximately the same mass as protons. Protons and neutrons are jointly called nucleons, and the number of nucleons in an atomic nucleus is called the *mass number*, denoted by the symbol A. The nuclei of all elements are built from such positively charged protons, supplemented with a number of neutrons. Since protons are positively charged, they don't play well together, and neutrons are needed to shield the protons from each other; else the nucleus would be unstable due to the repulsion of the charges. Protons repel each other and for a nucleus with more than one proton to be stable, one or several neutrons are needed. This is the reason why in nature no elements exist whose nuclei just consist of protons, apart from the trivial case of hydrogen.

The first 94 elements in the Periodic Table occur naturally on Earth and the remaining 24 are synthetic elements produced in the laboratory in nuclear reactions. Oganesson, for instance, was created in 2002, but only recognized as an element in 2015. It is not much of an element though as it falls apart very quickly and only five (possibly six) atoms of oganesson have ever been detected. Of the 94 natural elements, 83 are so-called primordial elements, meaning that they already existed before the Earth was formed. Of these, 80 are stable elements (1 through 82, i.e., hydrogen through lead, exclusive of 43 and 61, technetium and promethium, respectively), with three radioactive primordial elements (bismuth, thorium, and uranium). Uranium, which is unstable with a half-life of 4.6 billion years, is the heaviest of the primordial elements.

The Periodic Table does not show the whole story though, and there is a complication that cannot be seen from the table. The table only tells you the number of protons in the nucleus (or the number of electrons orbiting the nucleus) but does not say anything about the number of neutrons. Most elements come in a number of variants, which all have the same chemical properties, so the same number of electrons and protons (else it would be another element) but a varying number of neutrons. Such versions of an element are called *isotopes*: variants of a particular element that have the same chemical properties as that element but differ in the composition of their nucleus. The word comes from the Greek words *isos topos*, meaning *same place*, i.e., the same place in the Periodic Table. So, an element can appear in the guise of several isotopes.

Some such isotopes are stable, meaning that they will not fall apart, i.e., transmute (decay) into other elements or isotopes. For instance, the element tin, number 50 in the Periodic Table and denoted by *Sn*, is an isotope champion and holds the record with ten stable isotopes. They all have the same atomic number but differ in the mass number. Other isotopes are unstable

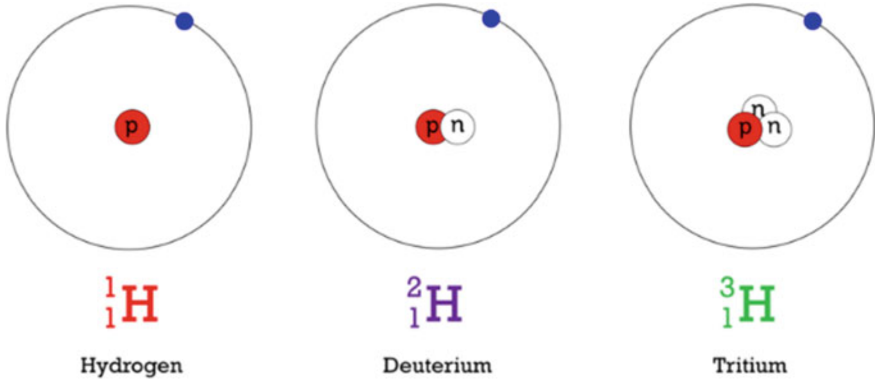


Fig. 1.2 Schematic representation of hydrogen and its isotopes

and will after some time decay, not necessarily into the element they were an isotope of in the first place. Such isotopes are said to be radioactive.

In Fig. 1.2 the three known isotopes of hydrogen are depicted. As can be seen in the figure the first isotope (deuterium) has one neutron in its nucleus apart from a proton, and the second isotope (tritium) has two neutrons. And, in general, the only difference between the isotopes of a certain element is the number of neutrons in their nuclei.

Of the isotopes of hydrogen shown in Fig. 1.2, ordinary hydrogen (^1H) and deuterium are stable while tritium is radioactive and decays into helium (^3He) plus an electron and a spooky particle, called a neutrino. Note the notation here with a left superscript denoting the mass number. To be complete a left subscript denoting the atomic number (place in the Periodic Table) should be added, as done in Fig. 1.2. This can be left out as the symbol for the element (H, He) already tells us what the atomic number is. The half-life of the decay of tritium is about 12 years, meaning that when you have a bunch of such tritium atoms and wait for 12 years half of them will have decayed. As we will see later, tritium is one of the main candidates for fusion fuel, together with deuterium. But it is not a very lucky choice, to put it mildly, as the radioactivity of tritium has extremely adverse, possibly even showstopping, consequences for fusion. Its radioactivity, although fairly mild, implies in the first place that all kind of precautions have to be taken, and secondly that it does not naturally occur on Earth and must be produced rather expensively in a special type of nuclear fission reactor.

Please note that the scale of the drawings in Fig. 1.2 does not reflect reality. Both the nuclei and the electrons occupy only a tiny part of the total atom, which mainly consists of ‘empty’ space filled with the electromagnetic fields generated by the charged nucleus and electrons. If the nuclei were as large

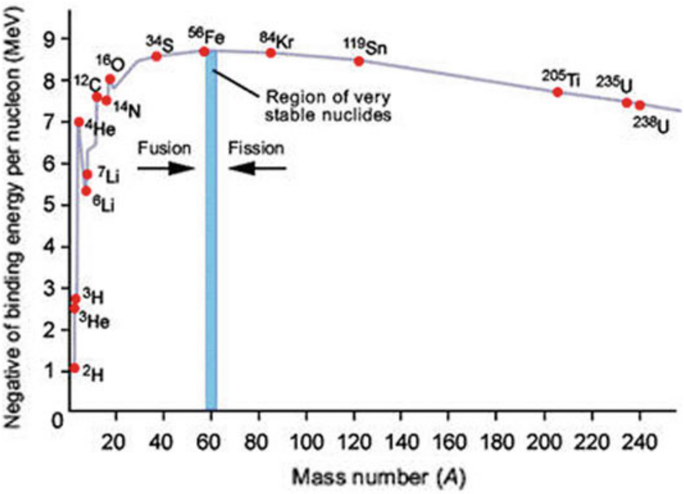


Fig. 1.3 Binding energy per nucleon plotted against the mass number

compared to the electron or the total atom as drawn in the figure, the electron orbit would not fit on the page.

How tightly bound are the nuclei of atoms and what is their mass? Nuclei consist of neutrons and protons, and one naively expects the mass of a nucleus to be equal to the sum of the masses of the protons and neutrons it consists of. That is indeed roughly the case, but not exactly, and this mass difference is precisely what the whole fuss is about. Many isotopes are lighter than expected from just adding up the masses of the nucleons in the nucleus or, saying it differently, a proton or neutron bound into a nucleus has slightly less mass than a free proton or neutron. This mass difference is called the *mass defect*. The energy equivalent to this mass defect, obtained from Einstein's famous formula $E=mc^2$, was released when the nucleus was formed from its constituent protons and neutrons.

The mass difference is therefore also the binding energy of the nucleus. In Fig. 1.3 the binding energy per nucleon, i.e., the total binding energy (or mass defect) divided by the number of nucleons in the nucleus, has been plotted against the mass number.

The figure shows that the binding energy per nucleon increases at first sharply with mass number and is largest for nuclei with mass number around 60, e.g., iron with atomic number 26 and mass number 56 (^{56}Fe), by far its most common isotope, is one of the most stable elements. Then the binding energy per nucleon slowly decreases down to mass number 240–250, the uranium isotopes. The consequence of this is that nuclei of elements heavier than iron can in principle yield energy by nuclear fission (in which

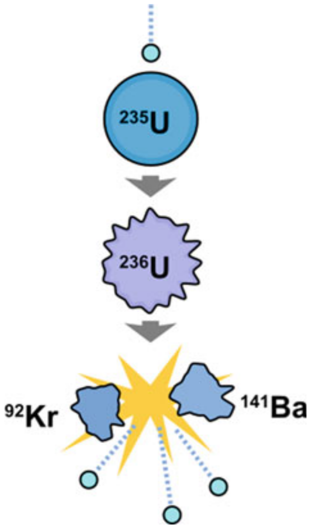


Fig. 1.4 Fission of a uranium-235 nucleus into barium and krypton

case they split into two more tightly bound nuclei), while elements lighter than iron can do this in principle by fusion (in which case they are fused into one more tightly bound nucleus). So, if a uranium-235 nucleus is split by bombarding it with neutrons, as happens in a nuclear fission reactor, many fission reactions are possible, but a typical one (with a neutron indicated by n) is:

$$n + ^{235}\text{U} \rightarrow ^{141}\text{Ba} + ^{92}\text{Kr} + 3n$$

or in a figure format as represented in Fig. 1.4.

In this process the uranium nucleus first absorbs the neutron, forming the unstable uranium-236, which then splits into a barium and a krypton nucleus (with atomic numbers 56 and 36, respectively, adding up to uranium's 92) with the simultaneous emission of three extra neutrons. These neutrons can split further uranium nuclei and set off a chain reaction. The barium and krypton nuclei are bound much more tightly than uranium, resulting in the release of about 200 MeV or 200 million eV of energy, mostly carried away as kinetic energy by these 'daughter' nuclei, while the three neutrons that are released in the process carry away about 1 to 2 MeV each (4.8 MeV in total). An electronvolt (eV) is the amount of energy gained by a single electron when moving across an electric potential difference of one volt; it is equal to 1.6×10^{-19} J. This energy unit is the standard unit for the microworld of atoms and molecules, and will be used throughout this book. For comparison, 1 J is roughly equal to the kinetic energy of a tennis ball hitting the floor after falling from a height of 2 m. So, if a single tennis ball falling from a height of 2 m were enough to dent a packet of butter, to achieve the same by splitting uranium nuclei you would need the staggering number of 30 billion of such events (each event being worth about 3×10^{-11} J).

For fusion we have to be at the other end of Fig. 1.3, where the lightest elements at the very left of the figure are the most promising. In this respect it is especially important to observe that ^{4}He is particularly strongly bound, certainly compared to ^{2}H (or deuterium), so any fusion reaction that produces ^{4}He (for instance, by fusing two deuterium nuclei) will release a particularly large amount of energy.

Nuclear fission was discovered in 1938, about 20 years later than nuclear fusion, in Berlin by the German physicists Otto Hahn (1879–1968) and Fritz Strassman (1902–1980). Contrary to fusion, the discovery of nuclear fission immediately generated a lot of research, as it was soon realised that a self-sustaining nuclear chain reaction was possible, and a nuclear reactor could be built for harnessing the released energy. This was duly achieved in the first nuclear reactor, constructed in 1942 in Chicago as part of the Manhattan Project, America's effort to build an atomic bomb. Since then numerous nuclear fission reactors have been built and are still being built all over the world, providing a significant portion of mankind's energy needs. The price for this is, however, rather high, for many too high, in the form of waste products that due to their long-lasting radioactivity are difficult to dispose of, and in the form of accidents. Power from nuclear fission reactors rose rapidly in the second half of the twentieth century, stimulated in part by the oil crisis of the early 1970s and the supposedly scary thought of being dependent on the Arab countries for oil supply. Energy supply from nuclear fission reached a peak of a 17.6 percent share of globally generated electric power in 1996 and has declined ever since. As of August 2020, 440 reactors were operating in 30 countries. Its share of global electricity production has now declined to about 10%. The decline is reflected in the fact that more reactors are shut down than new constructions started (13 shutdowns versus just 5 construction starts in 2019).[1]

One of the reasons for this decline are accidents that have greatly diminished the appetite for fission reactors, especially in Western countries. The first large accident was the partial meltdown at the Three-Mile Island plant in Pennsylvania in 1979, followed in 1986 by the horrendous Chernobyl disaster. Especially the latter event sounded the death knell for power generation from nuclear fission. The last doubters were silenced by the Fukushima

---

[1] World Nuclear Association, 2020.

disaster in 2011, which like Chernobyl has left large areas of land contaminated with radioactive material. The Fukushima disaster led to panicky reactions of politicians all over the world, notably in Germany where plans were quickly drawn up to scrap all nuclear fission plants. It should be noted though that much of this panic was due to the way the disaster was reported in the press. Although nobody died in the nuclear accident with the Fukushima power plant, this aspect of the disaster got far more coverage in the press than the earthquake and subsequent tsunami which cost the lives of more than 20,000 people.

Although there is still quite a lot of activity in nuclear fission, as recalled above, its share of global electricity production will continue to fall. The public trust in nuclear fission as a power generation option has suffered a lethal blow and nobody seems to be able to turn the tide. This is unfortunate as many have argued that decarbonization of electricity generation will be a tough job, if not impossible, without nuclear fission plants. Whatever the rather fanatic anti-nuclear lobbyists are saying about nuclear fission power, it remains a fact that in the past (1980s–1990s) several countries, including France, Belgium, Switzerland and Sweden, managed to radically cut their greenhouse gas emissions by installing nuclear power. These countries now enjoy comparatively low carbon dioxide emissions, while the countries that have been installing renewable energy (solar and wind) in the last twenty years have hardly been able to cut their emissions and are still at a much higher level.

The bad reputation of fission power also has consequences for nuclear fusion, which likes to present itself as the safe nuclear option. That may well be the case, but it is a hazardous strategy as everything nuclear is viewed with suspicion by the public. Germany is a case in point, where the Green Party also opposes nuclear fusion as an energy option.

A further reason for the decline is the recent glut of cheap (shale) oil and gas coupled to a rapid increase in wind and solar energy, forcing nuclear fission power plants out of business, a trend that can only be reversed by slapping a substantial carbon tax on fossil fuels. A deeper reason for the decline is also that the technology of commercial nuclear fission reactors has stagnated. Nearly every nuclear fission power plant built in the last half century has been a light-water reactor, a design that in rare instances can indeed allow a meltdown and was aggressively marketed by the United States, which has now all but quit the field. Meltdown-proof, cheaper and more efficient designs, like very high-temperature reactors and other Generation IV nuclear reactors, have remained on the drawing boards for years, but are now being developed, mainly in China and Russia.

The reason why fission was developed in just a few years much earlier and much more extensively than fusion is in the first place that the technical realization of fusion is vastly more difficult than fission. The fundamental reason for this difficulty lies in the fact that fission can be achieved by firing neutral particles (neutrons) at nuclei, as shown in Fig. 1.4, while in the case of fusion, positively charged nuclei must be persuaded to fuse, which as we will see is a formidable task. Secondly, as regards fission, it was very soon realised that a bomb could be built on the basis of nuclear fission. For the latter the Manhattan Project was started up in the US in the early 1940s during World War II and fusion was put on a backburner for the duration of the war as the required temperatures, tens of millions of degrees, could only be achieved by a fission explosion. The technique of using a nuclear fission bomb as a 'matchstick' was eventually deployed in building the hydrogen or thermonuclear bomb. Thermonuclear bombs are still of this type. A pure fusion bomb (without the help of a fission bomb) has not yet seen the light, and hopefully never will. On the other hand, the fact that it hasn't, in spite of a colossal research effort, both by Western powers and by the Soviet Union, does not bode well either for fusion as an energy source. For if an uncontrolled release of fusion energy can apparently not be achieved without help from fission, how then can we have faith in controlled fusion ever being possible? Remember that in fission research it was the other way round. Scientists succeeded in keeping fission under control before a start was made with constructing an atomic bomb.

Fusion is conceptually a rather simple process, much simpler than fission and, more importantly, it is a great deal cleaner. The nuclei involved are much simpler, just a handful of nucleons compared to hundreds in the case of fission. Little radioactivity is released in the fusion process itself, and the radioactive waste it produces in a reactor is manageable, although a future nuclear fusion reactor is not as clean in this respect as many have wanted us to believe in the past. The radioactive waste problem in power generation from nuclear fusion is far from negligible, since, as we will see, the vast number of highly energetic neutrons released in the fusion processes will make much of the material of the reactor radioactive. In view of the general public's sensitivity to radioactivity it is paramount to be clear and transparent about this from the very beginning. A comparison with nuclear fission, which is indeed worse as regards long-lived radioactive waste, is not relevant in this respect, for something that is better than the perceived absolute evil is of course not necessarily good. Fusion may be well advised to avoid the comparison with fission as much as possible.

This brings us to the most important, and in the end perhaps decisive advantage of power generation from fusion over both fission and fossil fuels, namely that the primary fuel, the hydrogen isotope deuterium, can be obtained cheaply from water. This is one of the reasons that fusion is sometimes called "the ultimate energy source". In the water of the Earth's oceans one atom in every 6420 hydrogen atoms is deuterium, accounting for approximately 0.0156% (or 0.0312% on a mass basis, as a deuterium atom is twice the mass of ordinary hydrogen) of all naturally occurring hydrogen in the oceans. No mines are needed, no miners can get trapped, no transport of fuel to be burned in power stations, and a virtually inexhaustible supply. That is indeed true for deuterium, but in the currently preferred version of nuclear fusion, as we will see, tritium is also required, and this is in very short supply and moreover dangerously radioactive, making this claim of being the "ultimate energy source" a rather weak one.

As mentioned, fusion is technically much more demanding than fission, the root of the problem being that it cannot be induced by uncharged particles. The nuclei that must be brought together in a fusion process are all positively charged and, therefore, repel each other and want to be as far apart as possible. The larger the nuclei, the larger the charge and, since the repulsive force, called the Coulomb force, is proportional to the product of the charges of the nuclei, even for nuclei of moderately large atoms this repulsive force becomes prohibitive. This implies that, in order to have any chance of success, fusion fuels must be chosen from the lightest elements–hydrogen, helium, lithium, beryllium and boron. In spite of this small number of candidate elements, it still leaves us with more than 100 possible fusion reactions, of which those involving elements with only one charged particle in the nucleus (i.e., hydrogen and its family members) are the most promising.

Early progress in fusion devices for generating energy was also hampered by the fact that all fusion research, like fission research, not only for weapons development, but also for power generation, was kept secret until the late 1950s. The US, for instance, harboured fears that fusion reactors could be used as a neutron source to make bomb fuel. And indeed, a stimulus to most fusion research in the early days was the production of bomb-grade material for thermonuclear weapons and the fear of being left behind in their construction.

The nuclear powers at the time, the US, Britain and the Soviet Union, all started their own fusion research programmes after World War II and jealously guarded them from the outside world. They all employed essentially the same methods and techniques and encountered the same problems, yet none managed to construct a working fusion reactor. The fact that secrecy was lifted had undoubtedly to do with this lack of success. If any of the parties involved in fusion research in the early 1950s had made promising progress towards a working reactor, the secrecy would surely have become tighter still. This latter point is also borne out by the declassification guide jointly worked out by the British and Americans in 1957, which stated that "all information except that bearing on devices exhibiting a net power gain was to be opened." So, had there been any success with a working reactor, the information would have remained classified.

Since then it has gone up and down with fusion without any great success, although proponents would like us to believe otherwise. The Indian nuclear physicist Homi J. Bhabha (1909–1966), who chaired the 1955 First International Conference on the Peaceful Uses of Atomic Energy in Geneva, predicted at that conference that "a method will be found for liberating fusion energy in a controlled manner within the next two decades", i.e., by 1975. It has since become one of the clichés of nuclear fusion research that a commercial nuclear fusion reactor is ever only a few decades away. As the saying goes "nuclear fusion power is the energy of the future, and always will be". A former leader of the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory recently stated, blaming insufficient funding, as is common practice among failing scientists and indeed people in most human endeavours, that "the goal of commercial fusion energy recedes 1 year per year", so as the Red Queen tells Alice in Lewis Carroll's "Through the Looking Glass," for fusion, too, 'it takes all the running you can do to stay in the same place'.

There is no other endeavour or project undertaken by mankind on which energy and money have been spent for close to a hundred years without any tangible results, and only a dim prospect of success in another fifty years or so. The reason must be that there is a lot at stake, or perceived to be: the promise of nuclear fusion power being an abundant, inexhaustible source of energy with little or no side-effects, at any rate manageable side-effects, and "too cheap to meter". Although the latter argument no longer seems to hold, the rest is already too good to be true, and if true, not something you would like to miss out on. No wonder that large teams of scientists in many countries are still working hard to try to solve the colossal scientific and technical problems involved in nuclear fusion. It would be a major achievement if in 25–40 years from now a working reactor for demonstration purposes were to become available, meaning a reactor which demonstrates that it is possible to build reactors that consume less energy than is needed to run them. This book intends to show that the chances for this to happen are very slim indeed.

2

Stellar Processes and Quantum Mechanics

As already mentioned, nuclear fusion is the source of energy in the Sun and in this chapter we will say a little more about this, starting with a 1920 article in the journal *Science* by the English astronomer, physicist and mathematician Arthur Eddington (1882–1944). He proposed that large amounts of energy released by fusing small nuclei might provide the energy source that powers the stars, although he had no idea yet how this would work. This is all the more remarkable as he was not even sure about the actual structure of atoms and the relationship between the various elements in the Periodic Table. His proposal predated the advent of quantum mechanics and a possible mechanism for such fusion was unknown. The only forces known to Eddington were electromagnetism and gravity. Gravitational contraction, i.e., the contraction of an astronomical object due to the influence of its own mass, drawing matter inwards towards the centre of gravity, was known to be responsible for star formation, and it had been estimated that if this were the source of the Sun's radiation it could only shine for about 20 million years. The Sun's surface would need to drop by about 35 m per year to provide enough energy from such gravitational contraction. So, there was a problem there, as around the same time geologists had shown that the Earth was at least two billion years old. In actual fact both the Sun and the Earth are as old as 4.6 billion years.

In his paper Eddington says: "*A star is drawing on some vast reservoir of energy by means unknown to us. This reservoir can scarcely be other than the sub-atomic energy which, it is known, exists abundantly in all matter; we sometimes*

L. J. Reinders, *Sun in a Bottle?... Pie in the Sky!*,
https://doi.org/10.1007/978-3-030-74734-3_2

dream that man will one day learn how to release it and use it for his service. The store is well-nigh inexhaustible, if only it could be tapped. There is sufficient in the sunto maintain its output of heat for 15 billion years." Now a century after Eddington wrote these words, we are still dreaming of tapping this source of energy, and it looks as if we are indeed getting a little closer, but the day of actually realizing this dream may still be far in the future or, more likely, remain elusive forever.

Although no real explanation of these stellar processes was possible before the advent of quantum mechanics, Eddington goes on to say that he believes "*that some portion of this sub-atomic energy is actually being set free in the stars.*" He based his belief on experiments carried out by the English chemist and physicist Francis William Aston (1877–1945), which in Eddington's mind had conclusively shown that "*all elements are constituted out of hydrogen atoms bound together with negative electrons.*" The structure of an atomic nucleus was not yet known at the time. It was thought to consist of an assembly of protons and electrons, the only elementary particles then known.

In his paper Eddington went on to state that, more importantly, Aston's precise measurements had also shown that "*the mass of a heliumatom is less than the sum of the masses of the 4 hydrogen atoms which enter in it*. (...) *There is a loss of mass in the synthesis amounting to about 1 part in 120. (...) Now mass cannot be annihilated, and the deficit can only represent the mass of the electrical energy set free in the transmutation.*" In the previous chapter we called this deficit the mass defect.

The equivalence of mass and energy, embodied in the formula $E = mc^2$, was proposed by Einstein in 1905. Because of the factor c^2 in this formula, with c the speed of light in vacuum being equal to about 300,000 km/s, even a minuscule amount of mass is equivalent to an awesome amount of energy. Where the chemical reaction of burning 100 grammes of coal would release 1 million joules of energy, the mass of these 100 grammes would according to Einstein's formula actually be equivalent to 10 million billion joules of energy, if only we knew how to get that energy out.

Einstein's formula was of course well-known to Eddington and he used it to calculate the amount of energy released when helium is made out of hydrogen. He concludes: "*If 5% of a star's mass consists initially of hydrogen atoms,*[1] *which are gradually being combined to form more complex elements, the total heat liberated will more than suffice for our demands, and we need look no further for the source of a star's energy.*" And "*If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring*

---

[1] We now know that it is actually around 75%.

a little nearer to fulfilment our dream of controlling this latent power for the well-being of the human race – or for its suicide." The final part of his paper, which as we now know contained much truth, is a rather lengthy apology on his part for having in the eyes of many gone over to speculation.

How does this energy production in stars come about? A star starts off as an interstellar cloud of gas, mainly consisting of hydrogen, which begins to collapse under the influence of gravity as soon as it is massive enough for the gravitational forces to be stronger than the internal pressure in the gas. The star becomes ever denser and hotter until at some point the temperature becomes so high that hydrogen nuclei start to fuse into helium, according to the process to be described in greater detail in the next chapter, and energy is radiated off into space to warm planets like the Earth. In the star it increases the temperature still further and forces the gas to expand, countering the inward gravitational contraction. This results in an equilibrium whereby the star is held together by its own gravity and the internal gas pressure prevents it from collapsing further. This process continues until all the hydrogen has been burned away, after which a further contraction follows and other fusion processes take over, but it is in the first place the gravitational attraction that gets the process going.

This is also the way it works in the Sun. Being more than 300,000 times more massive than the Earth, the Sun can generate sufficiently large gravitational forces. It will be clear that gravity on Earth is (fortunately) much too weak to bring about such a contraction. If we want to establish fusion, the gas has to be compressed in another way. That this might be extremely difficult can be surmised from the fact that there are two forces competing here, the inward compression (in stars by gravity) and the outward pressure by the gas heating up. When a star that is powered by burning hydrogen into helium, like the Sun, has exhausted all its hydrogen, its core will become denser and hotter while its outer layers expand, eventually transforming the Sun into what is called a red giant. It will become so large that it engulfs the current orbits of Mercury and Venus, rendering Earth uninhabitable. But this will not happen for another five billion years or so. After this, it will shed its outer layers and become a dense type of star known as a white dwarf. It will be very dense with a volume comparable to Earth and no longer produce energy by fusion, but still glow and give off heat from its stored thermal energy from previous fusion reactions.

A star contains a hot burning core in which the fusion processes take place; the burning does not occur throughout the star. Eddington calculated that the temperature at the Sun's core would have to be about 40 million degrees, which is two to three times as hot as the currently accepted value of about 15 million degrees.

But there was another rather pressing problem. How could four protons (nuclei of hydrogen), all positively charged, come together to form the nucleus of a helium atom? The protons would repel each other and there was no way in Eddington's time to see how this repulsive Coulomb force could be overcome. Moreover, according to the classical laws of physics, the temperatures existing in the Sun were far too low for such fusion processes to take place. To find an explanation for this puzzle, quantum mechanics was needed, a new theory that was developed in the 1920s, mainly in Germany, in which utterly impossible things are allowed to happen.

It was the Russian physicist George Gamow (1904–1968) who, in 1928, while on leave in Göttingen from the Leningrad Physico-Technical Institute, added a vital ingredient to the solution of the puzzle by introducing the mathematical basis for what is known as *quantum tunnelling*. He saw that all the quantum physicists in Göttingen were beavering away at trying to understand the quantum mechanics of atoms and molecules, and instead of joining this crowded fray, he decided to have a look at what quantum theory could do for the atomic nucleus. In the library he had come across an article describing an experiment on the scattering of α-particles (an alternative name for nuclei of helium atoms) on uranium. From the scattering pattern it was clear that the α-particles were unable to penetrate the uranium nucleus. In itself not a strange result when one realizes the strong repulsive Coulomb forces between the positively charged α-particles and the positively charged uranium nucleus.

But, so Gamow asked himself, if that is the case how then is it possible that uranium, being a radioactive element, does itself actually emit α-particles which have about half the energy of the α-particles used to bombard the uranium nuclei? Apparently, a barrier prohibits the α-particles of the radioactive decay from getting out of the uranium nucleus for a rather long time. So how then can they get out? Gamow immediately realized what the answer should be. In quantum mechanics, unlike classical Newtonian mechanics, there are no impenetrable barriers, and there is a non-zero probability for a particle, that also can be described by a wave, to tunnel through a barrier (Fig. 2.1). The figure shows the potential barrier encountered by the particle, similar to a golf ball that has to get into a hole on the top of a little hill. The golf ball must scale the hillside before it can drop into the hole. Not so for a quantum mechanical particle, which can be described by an oscillating wave and has a non-zero probability to tunnel through the barrier and get into the hole, even if it does not have the energy to climb to the top. When encountering the barrier, the wave doesn't end abruptly. Instead, it continues

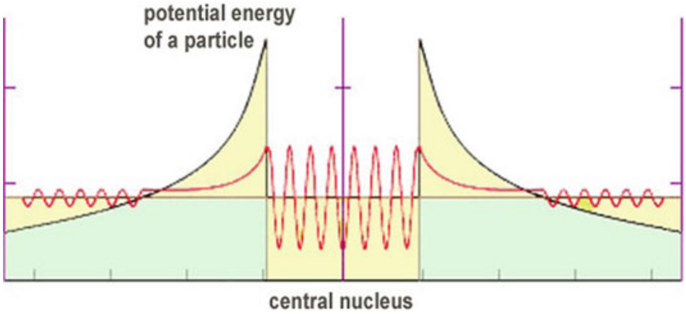


Fig. 2.1 A schematic picture of quantum tunnelling

inside and on the other side of the barrier, albeit with a smaller amplitude. Tunnelling gives a nonzero probability of finding a particle on the other side of a barrier. So, it doesn't behave like a golf ball at all!

A year later Robert d'Escourt Atkinson (1898–1982) and Fritz Houtermans (1903–1966) applied Gamow's tunnelling to provide the first calculation of the rate of nuclear fusion in stars. Their paper can be seen as the start of thermonuclear fusion energy research. The word 'thermonuclear' indicates the extremely high temperatures required in such nuclear processes. They give the particles a large enough thermal energy to overcome the Coulomb repulsion. Atkinson and Houtermans showed that, because of Gamow's tunnelling, fusion can occur at lower energies than previously believed (Eddington's 40 million degrees in the Sun's core) and that, in the fusing of light nuclei, energy could be created in accordance with Einstein's formula of mass-energy equivalence.

The energy released in the fusion of light elements is due to the interplay of two opposing forces. Protons are positively charged and repel each other due to the Coulomb force, but when they come very close together, due to their high thermal energy, quantum tunnelling allows the attractive nuclear force to overcome the repulsion of the Coulomb force and attract the nuclei further towards each other. This nuclear force is short-range, i.e., it is only felt when the nuclei are very close to each other (less than 10^{-15} m, a distance comparable to their size). Light nuclei are sufficiently small and have few protons. This allows them to come close enough to feel the attractive nuclear force. But to make this happen, extremely high temperatures and pressures are needed.

3

Nuclear Fusion of Light Elements

At the centre of the Sun, where the fusion takes place that eventually provides us on Earth with energy and light, the temperature is around fifteen million degrees. At this temperature, the electrons of the hydrogen atoms that make up about 75% of the Sun's mass have been stripped away. The resulting positively charged nuclei (protons) and unbound negative electrons move around with extremely high velocities in a very dense gaseous state (ten times the density of lead). This dense gaseous state is called a plasma and will be discussed in greater detail in the next chapter. The energy in the Sun is created by fusing protons in the plasma into helium. The process, called the "proton-proton" chain, involves three steps and was identified in 1939 by the German-American physicist Hans Bethe (1906–2005).

The first step involves the exceedingly rare process of the fusion of two protons. On average it takes a billion years for a proton to fuse with another proton and the proton-proton fusion processes taking place in 1 m^3 volume of the Sun produce just 30 W of heat, less than the heat on average given off by a human body. If the fusion rate were much higher, the Sun would burn up rather quickly and it would soon be over for us here on Earth, so we would not be able to arrogantly comment on the inefficiency of the Sun's fusion process. Fortunately, there is a huge amount of hydrogen present in the Sun, and at the Sun's temperature, this means that hydrogen-hydrogen fusion can take place frequently enough to keep the Sun burning for our benefit for a very long time. In spite of the rarity of the process, the Sun fuses in its core a staggering 600 billion kilograms of hydrogen every second giving 596 billion

L. J. Reinders, *Sun in a Bottle?... Pie in the Sky!*,
https://doi.org/10.1007/978-3-030-74734-3_3