

Advanced Nuclear Physics

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A Math Book

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Introduction

Nuclear physics

Nuclear physics is the field of physics that studies the building blocks and interactions of atomic nuclei.

The most commonly known applications of nuclear physics are nuclear power and nuclear weapons, but the research field is also the basis for a far wider range of applications, including in the medical sector (nuclear medicine, magnetic resonance imaging), in materials engineering (ion implantation) and in archaeology (radiocarbon dating).

The field of particle physics evolved out of nuclear physics and, for this reason, has been included under the same term in earlier times.

History

The discovery of the electron by J. J. Thomson was the first indication that the atom had internal structure. At the turn of the 20th century the accepted model of the atom was J. J. Thomson's "plum pudding" model in which the atom was a large positively charged ball with small negatively charged electrons embedded inside of it. By the turn of the century physicists had also discovered three types of radiation coming from atoms, which they named alpha, beta, and gamma radiation. Experiments in 1911 by Lise Meitner and Otto Hahn, and by James Chadwick in 1914 discovered that the beta decay spectrum was continuous rather than discrete. That is, electrons were ejected from the atom with a range of energies, rather than the discrete amounts of energies that were observed in gamma and alpha decays. This was a problem for nuclear physics at the time, because it indicated that energy was not conserved in these decays.

In 1905, Albert Einstein formulated the idea of mass–energy equivalence. While the work on radioactivity by Becquerel, Pierre and Marie Curie predates this, an explanation of the source of the energy of radioactivity would have to wait for the discovery that the nucleus itself was composed of smaller constituents, the nucleons.

Rutherford's team discovers the nucleus

In 1907 Ernest Rutherford published "Radiation of the α Particle from Radium in passing through Matter". Geiger expanded on this work in a communication to the Royal Society with experiments he and Rutherford had done passing α particles through air, aluminum foil and gold leaf. More work was published in 1909 by Geiger and Marsden and further greatly expanded work was published in 1910 by Geiger, In 1911-2 Rutherford went before the Royal Society to explain the experiments and propound the new theory of the atomic nucleus as we now understand it.

The key experiment behind this announcement happened in 1909 as Ernest Rutherford's team performed a remarkable experiment in which Hans Geiger and Ernest Marsden under his supervision fired alpha particles (helium nuclei) at a thin film of gold foil. The plum pudding model predicted that the alpha particles should come out of the foil with their trajectories being at most slightly bent. Rutherford had the idea to instruct his team to look for something that shocked him to actually observe: a few particles were scattered through large angles, even completely backwards, in some cases. The discovery, beginning with Rutherford's analysis of the data in 1911, eventually led to the Rutherford model of the atom, in which the atom has a very small, very dense nucleus containing most of its mass, and consisting of heavy positively charged particles with embedded electrons in order to balance out the charge (since the neutron was unknown). As an example, in this model (which is not the modern one) nitrogen-14 consisted of a nucleus with 14 protons and 7 electrons (21 total particles), and the nucleus was surrounded by 7 more orbiting electrons.

The Rutherford model worked quite well until studies of nuclear spin were carried out by Franco Rasetti at the California Institute of Technology in 1929. By 1925 it was known that protons and electrons had a spin of $1/2$, and in the Rutherford model of nitrogen-14, 20 of the total 21 nuclear particles should have paired up to cancel each other's spin, and the final odd particle should have left the nucleus with a net spin of $1/2$. Rasetti discovered, however, that nitrogen-14 has a spin of 1.

James Chadwick discovers the neutron

In 1932 Chadwick realized that radiation that had been observed by Walther Bothe, Herbert L. Becker, Irène and Frédéric Joliot-Curie was actually due to a neutral particle of about the same mass as the proton, that he called the neutron (following a suggestion about the need for such a particle, by Rutherford). In the same year Dmitri Ivanenko suggested that neutrons were in fact spin $1/2$ particles and that the nucleus contained neutrons to explain the mass not due to protons, and that there were no electrons in the nucleus-- only protons and neutrons. The neutron spin immediately solved the problem of the spin of nitrogen-14, as the one unpaired proton and one unpaired neutron in this model, each contribute a spin of $1/2$ in the same direction, for a final total spin of 1.

With the discovery of the neutron, scientists at last could calculate what fraction of binding energy each nucleus had, from comparing the nuclear mass with that of the protons and neutrons which composed it. Differences between nuclear masses calculated in this way, and when nuclear reactions were measured, were found to agree with Einstein's calculation of the equivalence of mass and energy to high accuracy (within 1% as of in 1934).

Yukawa's meson postulated to bind nuclei

In 1935 Hideki Yukawa proposed the first significant theory of the strong force to explain how the nucleus holds together. In the Yukawa interaction a virtual particle, later called a meson, mediated a force between all nucleons, including protons and neutrons. This force

explained why nuclei did not disintegrate under the influence of proton repulsion, and it also gave an explanation of why the attractive strong force had a more limited range than the electromagnetic repulsion between protons. Later, the discovery of the pi meson showed it to have the properties of Yukawa's particle.

With Yukawa's papers, the modern model of the atom was complete. The center of the atom contains a tight ball of neutrons and protons, which is held together by the strong nuclear force, unless it is too large. Unstable nuclei may undergo alpha decay, in which they emit an energetic helium nucleus, or beta decay, in which they eject an electron (or positron). After one of these decays the resultant nucleus may be left in an excited state, and in this case it decays to its ground state by emitting high energy photons (gamma decay).

The study of the strong and weak nuclear forces (the latter explained by Enrico Fermi via Fermi's interaction in 1934) led physicists to collide nuclei and electrons at ever higher energies. This research became the science of particle physics, the crown jewel of which is the standard model of particle physics which unifies the strong, weak, and electromagnetic forces.

Chapter-1

Modern nuclear physics

Liquid-drop model

Semi-empirical mass formula

In nuclear physics, the **semi-empirical mass formula (SEMF)**, sometimes also called **Weizsäcker's formula**, is a formula used to approximate the mass and various other properties of an atomic nucleus. As the name suggests, it is partially based on theory and partly on empirical measurements; the theory is based on the **liquid drop model**, and can account for most of the terms in the formula, and gives rough estimates for the values of the coefficients. It was first formulated in 1935 by German physicist Carl Friedrich von Weizsäcker, and although refinements have been made to the coefficients over the years, the form of the formula remains the same today.

This formula should not be confused with the mass formula of Weizsäcker's student Burkhard Heim.

The formula gives a good approximation for atomic masses and several other effects, but does not explain the appearance of magic numbers.

The liquid drop model and its analysis

The liquid drop model is a model in nuclear physics which treats the nucleus as a drop of incompressible nuclear fluid, first proposed by George Gamow and developed by Niels Bohr and John Archibald Wheeler. The fluid is made of nucleons (protons and neutrons), which are held together by the strong nuclear force.

This is a crude model that does not explain all the properties of nuclei, but does explain the spherical shape of most nuclei. It also helps to predict the binding energy of the nucleus.

Mathematical analysis of the theory delivers an equation which attempts to predict the binding energy of a nucleus in terms of the numbers of protons and neutrons it contains. This equation has five terms on its right hand side. These correspond to the cohesive binding of all the nucleons by the strong nuclear force, the electrostatic mutual repulsion of the protons, a surface energy term, an asymmetry term (derivable from the protons and neutrons occupying independent quantum momentum states) and a pairing term (partly derivable from the protons and neutrons occupying independent quantum spin states).

If we consider the sum of the following five types of energies, then the picture of a nucleus as a drop of incompressible liquid roughly accounts for the observed variation of binding energy of the nucleus:

Volume energy. When an assembly of nucleons of the same size is packed together into the smallest volume, each interior nucleon has a certain number of other nucleons in contact with it. So, this nuclear energy is proportional to the volume.

Surface energy. A nucleon at the surface of a nucleus interacts with fewer other nucleons than one in the interior of the nucleus and hence its binding energy is less. This surface energy term takes that into account and is therefore negative and is proportional to the surface area.

Coulomb Energy. The electric repulsion between each pair of protons in a nucleus contributes toward decreasing its binding energy.

Asymmetry energy (also called Pauli Energy). An energy associated with the Pauli exclusion principle. If it wasn't for the Coulomb energy, the most stable form of nuclear matter would have $N=Z$, since unequal values of N and Z imply filling higher energy levels for one type of particle, while leaving lower energy levels vacant for the other type.

Pairing energy. An energy which is a correction term that arises from the tendency of proton pairs and neutron pairs to occur. An even number of particles is more stable than an odd number.

The formula

In the following formulae, let A be the total number of nucleons, Z the number of protons, and N the number of neutrons.

The mass of an atomic nucleus is given by

where m_p and m_n are the rest mass of a proton and a neutron, respectively, and E_B is the binding energy of the nucleus. The semi-empirical mass formula states that the binding energy will take the following form:

Each of the terms in this formula has a theoretical basis, as will be explained below.

Terms

Volume term

The term $a_V A$ is known as the *volume term*. The volume of the nucleus is proportional to A , so this term is proportional to the volume, hence the name.

The basis for this term is the strong nuclear force. The strong force affects both protons and neutrons, and as expected, this term is independent of Z . Because the number of pairs that can be taken from A particles is , one might expect a term proportional to A^2 .

However, the strong force has a very limited range, and a given nucleon may only interact strongly with its nearest neighbors and next nearest neighbors. Therefore, the number of pairs of particles that actually interact is roughly proportional to A , giving the volume term its form.

The coefficient a_V is smaller than the binding energy of the nucleons to their neighbors E_b , which is of order of 40 MeV. This is because the larger the number of nucleons in the nucleus, the larger their kinetic energy is, due to Pauli's exclusion principle. If one treats the nucleus as a Fermi ball of A nucleons, with equal numbers of protons and neutrons, then the total kinetic energy is , with ϵ_F the Fermi energy which is estimated as 38 MeV. Thus the expected value of a_V in this model is , not far from the measured value.

Surface term

The term $a_S A^{2/3}$ is known as the *surface term*. This term, also based on the strong force, is a correction to the volume term.

The volume term suggests that each nucleon interacts with a constant number of nucleons, independent of A . While this is very nearly true for nucleons deep within the nucleus, those nucleons on the surface of the nucleus have fewer nearest neighbors, justifying this correction. This can also be thought of as a surface tension term, and indeed a similar mechanism creates surface tension in liquids.

If the volume of the nucleus is proportional to A , then the radius should be proportional to $A^{1/3}$ and the surface area to $A^{2/3}$. This explains why the surface term is proportional to $A^{2/3}$. It can also be deduced that a_S should have a similar order of magnitude as a_V .

Coulomb term

The term is known as the *Coulomb* or *electrostatic term*.

The basis for this term is the electrostatic repulsion between protons. To a very rough approximation, the nucleus can be considered a sphere of uniform charge density. The potential energy of such a charge distribution can be shown to be

where Q is the total charge and R is the radius of the sphere. Identifying Q with Ze , and noting as above that the radius is proportional to $A^{1/3}$, we get close to the form of the Coulomb term. However, because electrostatic repulsion will only exist for more than one proton, Z^2 becomes $Z(Z - 1)$. The value of a_C can be approximately calculated using the equation above.

where α is the fine structure constant and $r_0 A^{1/3}$ is the radius of a nucleus, giving r_0 to be approximately 1.25 femtometers. This gives a_C an approximate theoretical value of 0.691 MeV, not far from the measured value.

Asymmetry term

The term is known as the *asymmetry term*. The theoretical justification for this term is more complex. Note that as $A = N + Z$, the parenthesized expression can be rewritten as $(N - Z)$. The form $(A - 2Z)$ is used to keep the dependence on A explicit, as will be important for a number of uses of the formula.

The Pauli exclusion principle states that no two fermions can occupy exactly the same quantum state in an atom. At a given energy level, there are only finitely many quantum states available for particles. What this means in the nucleus is that as more particles are "added", these particles must occupy higher energy levels, increasing the total energy of the nucleus (and decreasing the binding energy). Note that this effect is not based on any of the fundamental forces (gravitational, electromagnetic, etc.), only the Pauli exclusion principle.

Protons and neutrons, being distinct types of particles, occupy different quantum states. One can think of two different "pools" of states, one for protons and one for neutrons. Now, for example, if there are significantly more neutrons than protons in a nucleus, some of the neutrons will be higher in energy than the available states in the proton pool. If we could move some particles from the neutron pool to the proton pool, in other words change some neutrons into protons, we would significantly decrease the energy. The imbalance between the number of protons and neutrons causes the energy to be higher than it needs to be, *for a given number of nucleons*. This is the basis for the asymmetry term.

The actual form of the asymmetry term can again be derived by modeling the nucleus as a Fermi ball of protons and neutrons. Its total kinetic energy is

where N_p, N_n are the numbers of protons and neutrons and ϵ_F are their Fermi energies. Since the latter are proportional to $N^{1/3}$ and $N^{1/3}$, respectively, one gets

for some constant C .

The leading expansion in the difference $N_n - N_p$ is then

At the zeroth order expansion the kinetic energy is just the Fermi energy multiplied by A . Thus we get

The first term contributes to the volume term in the semi-empirical mass formula, and the second term is minus the asymmetry term (remember the kinetic energy contributes to the total binding energy with a *negative* sign).

ϵ_F is 38 MeV, so calculating a_A from the equation above, we get only half the measured value. The discrepancy is explained by our model not being accurate: nucleons in fact interact with each other, and are not spread evenly across the nucleus. For example, in the shell model, a proton and a neutron with overlapping wavefunctions will have a greater strong interaction between them and stronger binding energy. This makes it energetically favourable (i.e. having lower energy) for protons and neutrons to have the same quantum numbers (other than isospin), and thus increase the energy cost of asymmetry between them.

One can also understand the asymmetry term intuitively, as follows. It should be dependent on the absolute difference $|N - Z|$, and the form $(A - 2Z)^2$ is simple and differentiable, which is important for certain applications of the formula. In addition, small differences between Z and N do not have a high energy cost. The A in the denominator reflects the fact that a given difference $|N - Z|$ is less significant for larger values of A .

Pairing term

The term $\delta(A, Z)$ is known as the *pairing term* (possibly also known as the pairwise interaction). This term captures the effect of spin-coupling. It is given by:

where

Due to Pauli exclusion principle the nucleus would have a lower energy if the number of protons with spin up will be equal to the number of protons with spin down. This is also true for neutrons. Only if both Z and N are even, both protons and neutrons can have equal numbers of spin up and spin down particles. This is a similar effect to the asymmetry term.

The factor $A^{-1/2}$ is not easily explained theoretically. The Fermi ball calculation we have used above, based on the liquid drop model but neglecting interactions, will give an A^{-1} dependence, as in the asymmetry term. This means that the actual effect for large nuclei will be larger than expected by that model. This should be explained by the interactions between nucleons; For example, in the shell model, two protons with the same quantum numbers (other than spin) will have completely overlapping wavefunctions and will thus have greater strong interaction between them and stronger binding energy. This makes it energetically favourable (i.e. having lower energy) for protons to pair in pairs of opposite spin. The same is true for neutrons.

Calculating the coefficients

The coefficients are calculated by fitting to experimentally measured masses of nuclei. Their values can vary depending on how they are fitted to the data. Several examples are as shown below, with units of megaelectronvolts (MeV):

	Least-squares fit	Wapstra	Rohlf
a_V	15.8	14.1	15.75
a_S	18.3	13	17.8
a_C	0.714	0.595	0.711
a_A	23.2	19	23.7
a_P	12	n/a	n/a
δ (even-even)	n/a	-33.5	+11.18
δ (odd-odd)	n/a	+33.5	-11.18
δ (even-odd)	n/a	0	0

- Wapstra: *Atomic Masses of Nuclides*, A. H. Wapstra, Springer, 1958
- Rohlf: *Modern Physics from α to Z0*, James William Rohlf, Wiley, 1994

The semi-empirical mass formula provides a good fit to heavier nuclei, and a poor fit to very light nuclei, especially ${}^4\text{He}$. This is because the formula does not consider the internal shell structure of the nucleus. For light nuclei, it is usually better to use a model that takes this structure into account.

Examples for consequences of the formula

By maximizing $B(A, Z)$ with respect to Z , we find the number of protons Z of the stable nucleus of atomic weight A . We get

This is roughly $A/2$ for light nuclei, but for heavy nuclei there is an even better agreement with nature.

By substituting the above value of Z back into B one obtains the binding energy as a function of the atomic weight, $B(A)$. Maximizing $B(A)/A$ with respect to A gives the nucleus which is most strongly bound, i.e. most stable. The value we get is $A=63$ (copper), close to the measured values of $A=62$ (nickel) and $A=58$ (iron).

Nuclear shell model

In nuclear physics, the **nuclear shell model** is a model of the atomic nucleus which uses the Pauli exclusion principle to describe the structure of the nucleus in terms of energy levels. The model was developed in 1949 following independent work by several physicists, most notably Eugene Paul Wigner, Maria Goeppert-Mayer and J. Hans D. Jensen, who shared the 1963 Nobel Prize in Physics for their contributions.

The shell model is partly analogous to the atomic shell model which describes the arrangement of electrons in an atom, in that a filled shell results in greater stability. When adding nucleons (protons or neutrons) to a nucleus, there are certain points where the binding energy of the next nucleon is significantly less than the last one. This observation, that there are certain magic numbers of nucleons: 2, 8, 20, 28, 50, 82, 126 which are more tightly bound than the next higher number, is the origin of the shell model.

Note that the shells exist for both protons and neutrons individually, so that we can speak of "magic nuclei" where one nucleon type is at a magic number, and "doubly magic nuclei", where both are. Due to some variations in orbital filling, the upper magic numbers are 126 and, speculatively, 184 for neutrons but only 114 for protons. This has a relevant role in the search of the so-called island of stability. Besides, there have been found some semimagic numbers, noticeably $Z=40$.

In order to get these numbers, the nuclear shell model starts from an average potential with a shape something between the square well and the harmonic oscillator. To this potential a relativistic spin orbit term is added. Even so, the total perturbation does not coincide with experiment, and an empirical spin orbit coupling, named the Nilsson Term, must be added with at least two or three different values of its coupling constant, depending on the nuclei being studied.

Nevertheless, the magic numbers of nucleons, as well as other properties, can be arrived at by approximating the model with a three-dimensional harmonic oscillator plus a spin-orbit interaction. A more realistic but also complicated potential is known as Woods Saxon potential.

Deformed harmonic oscillator approximated model

Consider a three-dimensional harmonic oscillator. This would give, for example, in the first two levels (" l " is angular momentum)

level n	l	m_l	m_s
0	0	0	1/2
			-1/2
1	1	1	1/2
			-1/2
	1	0	1/2
			-1/2
	1	-1	1/2
			-1/2

We can imagine ourselves building a nucleus by adding protons and neutrons. These will always fill the lowest available level. Thus the first two protons fill level zero, the next six protons fill level one, and so on. As with electrons in the periodic table, protons in the outermost shell will be relatively loosely bound to the nucleus if there are only few protons in that shell, because they are farthest from the center of the nucleus. Therefore nuclei which have a full outer proton shell will have a higher binding energy than other nuclei with a similar total number of protons. All this is true for neutrons as well.

This means that the magic numbers are expected to be those in which all occupied shells are full. We see that for the first two numbers we get 2 (level 0 full) and 8 (levels 0 and 1 full), in accord with experiment. However the full set of magic numbers does not turn out correctly. These can be computed as follows:

In a three-dimensional harmonic oscillator the total degeneracy at level n is . Due to the spin, the degeneracy is doubled and is $(n + 1)(n + 2)$.

Thus the magic numbers would be

for all integer k . This gives the following magic numbers: 2,8,20,40,70,112..., which agree with experiment only in the first three entries.

In particular, the first six shells are:

- level 0: 2 states ($l = 0$) = 2.
- level 1: 6 states ($l = 1$) = 6.
- level 2: 2 states ($l = 0$) + 10 states ($l = 2$) = 12.
- level 3: 6 states ($l = 1$) + 14 states ($l = 3$) = 20.
- level 4: 2 states ($l = 0$) + 10 states ($l = 2$) + 18 states ($l = 4$) = 30.
- level 5: 6 states ($l = 1$) + 14 states ($l = 3$) + 22 states ($l = 5$) = 42.

where for every l there are $2l+1$ different values of m_l and 2 values of m_s , giving a total of $4l+2$ states for every specific level.

Including a spin-orbit interaction

We next include a spin-orbit interaction. First we have to describe the system by the quantum numbers j , m_j and parity instead of l , m_l and m_s , as in the Hydrogen-like atom. Since every even level includes only even values of l , it includes only states of even (positive) parity; Similarly every odd level includes only states of odd (negative) parity. Thus we can ignore parity in counting states. The first six shells, described by the new quantum numbers, are

- level 0 ($n=0$): 2 states ($j = 1/2$). Even parity.
- level 1 ($n=1$): 4 states ($j = 3/2$) + 2 states ($j = 1/2$) = 6. Odd parity.
- level 2 ($n=2$): 6 states ($j = 5/2$) + 4 states ($j = 3/2$) + 2 states ($j = 1/2$) = 12. Even parity.
- level 3 ($n=3$): 8 states ($j = 7/2$) + 6 states ($j = 5/2$) + 4 states ($j = 3/2$) + 2 states ($j = 1/2$) = 20. Odd parity.
- level 4 ($n=4$): 10 states ($j = 9/2$) + 8 states ($j = 7/2$) + 6 states ($j = 5/2$) + 4 states ($j = 3/2$) + 2 states ($j = 1/2$) = 30. Even parity.
- level 5 ($n=5$): 12 states ($j = 11/2$) + 10 states ($j = 9/2$) + 8 states ($j = 7/2$) + 6 states ($j = 5/2$) + 4 states ($j = 3/2$) + 2 states ($j = 1/2$) = 42. Odd parity.

where for every j there are $2j+1$ different states from different values of m_j .

Due to the spin-orbit interaction the energies of states of the same level but with different j will no longer be identical. This is because in the original quantum numbers, when $\mathbf{s}$ is parallel to $\mathbf{l}$, the interaction energy is negative; and in this case $j = l + s = l + 1/2$. When $\mathbf{s}$ is anti-parallel to $\mathbf{l}$ (i.e. aligned oppositely), the interaction energy is positive, and in this case $j = l - s = l - 1/2$. Furthermore, the strength of the interaction is roughly proportional to l .

For example, consider the states at level 4:

- The 10 states with $j = 9/2$ come from $l = 4$ and s parallel to l . Thus they have a negative spin-orbit interaction energy.
- The 8 states with $j = 7/2$ came from $l = 4$ and s anti-parallel to l . Thus they have a positive spin-orbit interaction energy.
- The 6 states with $j = 5/2$ came from $l = 2$ and s parallel to l . Thus they have a negative spin-orbit interaction energy. However its magnitude is half compared to the states with $j = 9/2$.
- The 4 states with $j = 3/2$ came from $l = 2$ and s anti-parallel to l . Thus they have a positive spin-orbit interaction energy. However its magnitude is half compared to the states with $j = 7/2$.
- The 2 states with $j = 1/2$ came from $l = 0$ and thus have zero spin-orbit interaction energy.

Deforming the potential

The harmonic oscillator potential $V(r) = \mu\omega^2 r^2 / 2$ grows infinitely as the distance from the center r goes to infinity. A more realistic potential, such as Woods Saxon potential, would approach a constant at this limit. One main consequence is that the average radius of nucleons orbits would be larger in a realistic potential; This leads to a reduced term in the Laplacian in the Hamiltonian. Another main difference is that orbits with high average radii, such as those with high n or high l , will have a lower energy than in a harmonic oscillator potential. Both effects lead to a reduction in the energy levels of high l orbits.

Predicted magic numbers

Low-lying energy levels in a single-particle shell model with an oscillator potential (with a small negative term) without spin-orbit (left) and with spin-orbit (right) interaction. The number to the right of a level indicates its degeneracy, $(2j+1)$. The boxed integers indicate the magic numbers.

Together with the spin-orbit interaction, and for appropriate magnitudes of both effects, one is led to the following qualitative picture: At all levels, the highest j states have their energies shifted downwards, especially for high n (where the highest j is high). This is both due to the negative spin-orbit interaction energy and to the reduction in energy resulting from deforming the potential to a more realistic one. The second-to-highest j states, on the contrary, have their energy shifted up by the first effect and down by the second effect, leading to a small overall shift. The shifts in the energy of the highest j states can thus bring the energy of states of one level to be closer to the energy of states of a lower level. The "shells" of the shell model are then no longer identical to the levels denoted by n , and the magic numbers are changed.

We may then suppose that the highest j states for $n = 3$ have an intermediate energy between the average energies of $n = 2$ and $n = 3$, and suppose that the highest j states for

larger n (at least up to $n = 7$) have an energy closer to the average energy of $n-1$. Then we get the following shells (see the figure)

- 1st Shell: 2 states ($n = 0, j = 1/2$).
- 2nd Shell: 6 states ($n = 1, j = 1/2$ or $3/2$).
- 3rd shell: 12 states ($n = 2, j = 1/2, 3/2$ or $5/2$).
- 4th shell: 8 states ($n = 3, j = 7/2$).
- 5th shell: 22 states ($n = 3, j = 1/2, 3/2$ or $5/2$; $n = 4, j = 9/2$).
- 6th shell: 32 states ($n = 4, j = 1/2, 3/2, 5/2$ or $7/2$; $n = 5, j = 11/2$).
- 7th shell: 44 states ($n = 5, j = 1/2, 3/2, 5/2, 7/2$ or $9/2$; $n = 6, j = 13/2$).
- 8th shell: 58 states ($n = 6, j = 1/2, 3/2, 5/2, 7/2, 9/2$ or $11/2$; $n = 7, j = 15/2$).

and so on.

The magic numbers are then

- 2
- $8 = 2+6$
- $20 = 2+6+12$
- $28 = 2+6+12+8$
- $50 = 2+6+12+8+22$
- $82 = 2+6+12+8+22+32$
- $126 = 2+6+12+8+22+32+44$
- $184 = 2+6+12+8+22+32+44+58$

and so on. This gives all the observed magic numbers, and also predicts a new one (the so-called *island of stability*) at the value of 184 (for protons, the magic number 126 has not been observed yet, and more complicated theoretical considerations predict the magic number to be 114 instead).

Other properties of nuclei

This model also predicts or explains with some success other properties of nuclei, in particular spin and parity of nuclei ground states, and to some extent their excited states as well. Take $^{17}_8\text{O}^9$ as an example - its nucleus has eight protons filling the two first proton shells, eight neutrons filling the two first neutron shells, and one extra neutron. All protons in a complete proton shell have total angular momentum zero, since their angular momenta cancel each other; The same is true for neutrons. All protons in the same level (n) have the same parity (either +1 or -1), and since the parity of a pair of particles is the product of their parities, an even number of protons from the same level (n) will have +1 parity. Thus the total angular momentum of the eight protons and the first eight neutrons is zero, and their total parity is +1. This means that the spin (i.e. angular momentum) of the nucleus, as well as its parity, are fully determined by that of the ninth neutron. This one is in the first (i.e. lowest energy) state of the 3rd shell, and therefore have $n = 2$, giving it +1 parity, and $j = 5/2$. Thus the nucleus of $^{17}_8\text{O}^9$ is expected to have positive parity and spin 5/2, which indeed it has.

For nuclei farther from the magic numbers one must add the assumption that due to the relation between the strong nuclear force and angular momentum, protons or neutrons with the same n tend to form pairs of opposite angular momenta. Therefore a nucleus with an even number of protons and an even number of neutrons has 0 spin and positive parity. A nucleus with an even number of protons and an odd number of neutrons (or vice versa) has the parity of the last neutron (or proton), and the spin equal to the total angular momentum of this neutron (or proton). By "last" we mean the properties coming from the highest energy level.

In the case of a nucleus with an odd number of protons and an odd number of neutrons, one must consider the total angular momentum and parity of both the last neutron and the last proton. The nucleus parity will be a product of theirs, while the nucleus spin will be one of the possible results of the sum of their angular momenta (with other possible results being excited states of the nucleus).

The ordering of angular momentum levels within each shell is according to the principles described above - due to spin-orbit interaction, with high angular momentum states having their energies shifted downwards due to the deformation of the potential (i.e. moving from a harmonic oscillator potential to a more realistic one). For nucleon pairs, however, it is often energetically favorable to be at high angular momentum, even if its energy level for a single nucleon would be higher. This is due to the relation between angular momentum and the strong nuclear force.

Nuclear magnetic moment is partly predicted by this simple version of the shell model. The magnetic moment is calculated through j , l and s of the "last" nucleon, but nuclei are not in states of well defined l and s . Furthermore, for odd-odd nuclei, one has to consider the two "last" nucleons, as in deuterium. Therefore one gets several possible answers for the nuclear magnetic moment, one for each possible combined l and s state, and the real state of the nucleus is a superposition of them. Thus the real (measured) nuclear magnetic moment is somewhere in between the possible answers.

The electric dipole of a nucleus is always zero, because its ground state has a definite parity, so its matter density (Ψ^2 , where Ψ is the wavefunction) is always invariant under parity. This is usually the situations with the atomic electric dipole as well.

Higher electric and magnetic multipole moments cannot be predicted by this simple version of the shell model, for the reasons similar to those in the case of the deuterium.

A heavy nucleus can contain hundreds of nucleons which means that with some approximation it can be treated as a classical system, rather than a quantum-mechanical one. In the resulting liquid-drop model, the nucleus has an energy which arises partly from surface tension and partly from electrical repulsion of the protons. The liquid-drop model is able to reproduce many features of nuclei, including the general trend of binding energy with respect to mass number, as well as the phenomenon of nuclear fission.

Superimposed on this classical picture, however, are quantum-mechanical effects, which can be described using the nuclear shell model, developed in large part by Maria Goeppert-Mayer. Nuclei with certain numbers of neutrons and protons (the magic numbers 2, 8, 20, 50, 82, 126, ...) are particularly stable, because their shells are filled.

Other more complicated models for the nucleus have also been proposed, such as the interacting boson model, in which pairs of neutrons and protons interact as bosons, analogously to Cooper pairs of electrons.

Much of current research in nuclear physics relates to the study of nuclei under extreme conditions such as high spin and excitation energy. Nuclei may also have extreme shapes (similar to that of Rugby balls) or extreme neutron-to-proton ratios. Experimenters can create such nuclei using artificially induced fusion or nucleon transfer reactions, employing ion beams from an accelerator. Beams with even higher energies can be used to create nuclei at very high temperatures, and there are signs that these experiments have produced a phase transition from normal nuclear matter to a new state, the quark-gluon plasma, in which the quarks mingle with one another, rather than being segregated in triplets as they are in neutrons and protons.

Chapter-2

Radioactive decay & Exponential decay

Radioactive decay

Radioactive decay is the process in which an unstable atomic nucleus spontaneously loses energy by emitting ionizing particles and radiation. This decay, or loss of energy, results in an atom of one type, called the *parent nuclide* transforming to an atom of a different type, named the *daughter nuclide*. For example: a carbon-14 atom (the "parent") emits radiation and transforms to a nitrogen-14 atom (the "daughter"). This is a random process on the atomic level, in that it is impossible to predict when a given atom will decay, but given a large number of similar atoms the decay rate, on average, is predictable.

The SI unit of radioactive decay is the becquerel (Bq). One Bq is defined as one transformation (or decay) per second. Since any reasonably-sized sample of radioactive material contains many atoms, a Bq is a tiny measure of activity; amounts on the order of TBq (terabecquerel) or GBq (gigabecquerel) are commonly used. Another unit of radioactivity is the curie, Ci, which was originally defined as the activity of one gram of pure radium, isotope Ra-226. At present it is equal, by definition, to the activity of any radionuclide decaying with a disintegration rate of 3.7×10^{10} Bq. The use of Ci is presently discouraged by the SI.

Explanation

The neutrons and protons that constitute nuclei, as well as other particles that may approach them, are governed by several interactions. The strong nuclear force, not observed at the familiar macroscopic scale, is the most powerful force over subatomic distances. The electrostatic force is almost always significant, and in the case of beta decay, the weak nuclear force is also involved.

The interplay of these forces produces a number of different phenomena in which energy may be released by rearrangement of particles. Some configurations of the particles in a nucleus have the property that, should they shift ever so slightly, the particles could rearrange into a lower-energy arrangement and release some energy. One might draw an analogy with a snowfield on a mountain: while friction between the ice crystals may be supporting the snow's weight, the system is inherently unstable with regard to a state of lower potential energy. A disturbance would thus facilitate the path to a state of greater entropy: the system will move towards the ground state, producing heat, and the total energy will be distributable over a larger number of quantum states. Thus, an avalanche results. The **total** energy does not change in this process, but because of the law of entropy, avalanches only happen in one direction and that is towards the "ground state" – the state with the largest number of ways in which the available energy could be distributed.

Such a collapse (a *decay event*) requires a specific activation energy. For a snow avalanche, this energy comes as a disturbance from outside the system, although such disturbances can be arbitrarily small. In the case of an excited atomic nucleus, the arbitrarily small disturbance comes from quantum vacuum fluctuations. A nucleus (or any excited system in quantum mechanics) is unstable, and can thus *spontaneously* stabilize to a less-excited system. The resulting transformation alters the structure of the nucleus and results in the emission of either a photon or a high-velocity particle which has mass (such as an electron, alpha particle, or other type).

Discovery

Radioactivity was first discovered in 1896 by the French scientist Henri Becquerel, while working on phosphorescent materials. These materials glow in the dark after exposure to light, and he thought that the glow produced in cathode ray tubes by X-rays might be

connected with phosphorescence. He wrapped a photographic plate in black paper and placed various phosphorescent minerals on it. All results were negative until he used uranium salts. The result with these compounds was a deep blackening of the plate. These radiations were called Becquerel Rays.

It soon became clear that the blackening of the plate had nothing to do with phosphorescence, because the plate blackened when the mineral was in the dark. Non-phosphorescent salts of uranium and metallic uranium also blackened the plate. Clearly there was a form of radiation that could pass through paper that was causing the plate to blacken.

At first it seemed that the new radiation was similar to the then recently discovered X-rays. Further research by Becquerel, Marie Curie, Pierre Curie, Ernest Rutherford and others discovered that radioactivity was significantly more complicated. Different types of decay can occur, but Rutherford was the first to realize that they all occur with the same mathematical approximately exponential formula (see below).

The early researchers also discovered that many other chemical elements besides uranium have radioactive isotopes. A systematic search for the total radioactivity in uranium ores also guided Marie Curie to isolate a new element polonium and to separate a new element radium from barium. The two elements' chemical similarity would otherwise have made them difficult to distinguish.

Dangers of radioactive substances

The dangers of radioactivity and of radiation were not immediately recognized. Acute effects of radiation were first observed in the use of X-rays when electric engineer Nikola Tesla intentionally subjected his fingers to X-rays in 1896. He published his observations concerning the burns that developed, though he attributed them to ozone rather than to X-rays. His injuries healed later.

The genetic effects of radiation, including the effects on cancer risk, were recognized much later. In 1927 Hermann Joseph Muller published research showing genetic effects, and in 1946 was awarded the Nobel prize for his findings.

Before the biological effects of radiation were known, many physicians and corporations had begun marketing radioactive substances as patent medicine and radioactive quackery. Examples were radium enema treatments, and radium-containing waters to be drunk as tonics. Marie Curie spoke out against this sort of treatment, warning that the effects of radiation on the human body were not well understood (Curie later died from aplastic anemia assumed due to her work with radium, but later examination of her bones showed that she had been a careful laboratory worker and had a low burden of radium. A more likely cause was her exposure to unshielded X-ray tubes while a volunteer medical worker in WWI). By the 1930s, after a number of cases of bone necrosis and death in enthusiasts, radium-containing medical products had nearly vanished from the market.

Types of decay

Alpha particles may be completely stopped by a sheet of paper, beta particles by aluminum shielding. Gamma rays can only be reduced by much more substantial barriers, such as a very thick layer of lead.

As for types of radioactive radiation, it was found that an electric or magnetic field could split such emissions into three types of beams. For lack of better terms, the rays were given the alphabetic names alpha, beta and gamma, still in use today. While alpha decay was seen only in heavier elements (atomic number 52 and greater), the other two types of decay were seen in all of the elements.

In analyzing the nature of the decay products, it was obvious from the direction of electromagnetic forces that alpha rays carried a positive charge, beta rays carried a negative charge, and gamma rays were neutral. From the magnitude of deflection, it was clear that alpha particles were much more massive than beta particles. Passing alpha particles through a very thin glass window and trapping them in a discharge tube allowed researchers to study the emission spectrum of the resulting gas, and ultimately prove that alpha particles are helium nuclei. Other experiments showed the similarity between beta radiation and cathode rays; they are both streams of electrons, and between gamma radiation and X-rays, which are both high energy electromagnetic radiation.

Although alpha, beta, and gamma are most common, other types of decay were eventually discovered. Shortly after discovery of the neutron in 1932, it was discovered by Enrico Fermi that certain rare decay reactions yield neutrons as a decay particle. Isolated proton emission was eventually observed in some elements. Shortly after the discovery of the positron in cosmic ray products, it was realized that the same process that operates in classical beta decay can also produce positrons (positron emission), analogously to negative electrons. Each of the two types of beta decay acts to move a nucleus toward a ratio of neutrons and protons which has the least energy for the combination. Finally, in a phenomenon called cluster decay, specific combinations of neutrons and protons other than alpha particles were spontaneously emitted from atoms on occasion.

Still other types of radioactive decay were found which emit previously seen particles, but by different mechanisms. An example is internal conversion, which results in electron and sometimes high energy photon emission, even though it involves neither beta nor gamma decay.

Decay modes in table form

Radionuclides can undergo a number of different reactions. These are summarized in the following table. A nucleus with mass number A and atomic number Z is represented as (A, Z) . The column "Daughter nucleus" indicates the difference between the new nucleus

and the original nucleus. Thus, $(A-1, Z)$ means that the mass number is one less than before, but the atomic number is the same as before.

Mode of decay	Participating particles	Daughter nucleus
Decays with emission of nucleons:		
Alpha decay	An alpha particle ($A=4, Z=2$) emitted from nucleus	$(A-4, Z-2)$
Proton emission	A proton ejected from nucleus	$(A-1, Z-1)$
Neutron emission	A neutron ejected from nucleus	$(A-1, Z)$
Double proton emission	Two protons ejected from nucleus simultaneously	$(A-2, Z-2)$
Spontaneous fission	Nucleus disintegrates into two or more smaller nuclei and other particles	-
Cluster decay	Nucleus emits a specific type of smaller nucleus (A_1, Z_1) smaller than, or larger than, an alpha particle	$(A-A_1, Z-Z_1) + (A_1, Z_1)$
Different modes of beta decay:		
Beta-Negative decay	A nucleus emits an electron and an antineutrino	$(A, Z+1)$
Positron emission, also Beta-Positive decay	A nucleus emits a positron and a neutrino	$(A, Z-1)$

Electron capture	A nucleus captures an orbiting electron and emits a neutrino — The daughter nucleus is left in an excited and unstable state	(A, Z–1)
Double beta decay	A nucleus emits two electrons and two antineutrinos	(A, Z+2)
Double electron capture	A nucleus absorbs two orbital electrons and emits two neutrinos — The daughter nucleus is left in an excited and unstable state	(A, Z–2)
Electron capture with positron emission	A nucleus absorbs one orbital electron, emits one positron and two neutrinos	(A, Z–2)
Double positron emission	A nucleus emits two positrons and two neutrinos	(A, Z–2)
Transitions between states of the same nucleus:		
Isomeric transition	Excited nucleus releases a high-energy photon (gamma ray)	(A, Z)
Internal conversion	Excited nucleus transfers energy to an orbital electron and it is ejected from the atom	(A, Z)

Radioactive decay results in a reduction of summed rest mass, once the released energy (the *disintegration energy*) has escaped. The energy carries mass with it (see mass in special relativity) according to the formula $E = mc^2$. The decay energy is initially released as kinetic energy of the emitted particles. Later these particles come to thermal equilibrium with their surroundings. The energy remains associated with a measure of mass of the decay system invariant mass, in as much as the kinetic energy of emitted particles, and, later, the thermal energy of the surrounding matter, contributes also to the total invariant mass of systems. Thus, the sum of rest masses of particles is not conserved in decay, but the *system* mass or system invariant mass (as also system total energy) is conserved.

Decay chains and multiple modes

The daughter nuclide of a decay event may also be unstable (radioactive). In this case, it will also decay, producing radiation. The resulting second daughter nuclide may also be radioactive. This can lead to a sequence of several decay events. Eventually a stable nuclide is produced. This is called a *decay chain*.

An example is the natural decay chain of uranium-238 which is as follows:

- decays, through alpha-emission, with a half-life of 4.5 billion years to thorium-234
- which decays, through beta-emission, with a half-life of 24 days to protactinium-234
- which decays, through beta-emission, with a half-life of 1.2 minutes to uranium-234
- which decays, through alpha-emission, with a half-life of 240 thousand years to thorium-230
- which decays, through alpha-emission, with a half-life of 77 thousand years to radium-226
- which decays, through alpha-emission, with a half-life of 1.6 thousand years to radon-222
- which decays, through alpha-emission, with a half-life of 3.8 days to polonium-218
- which decays, through alpha-emission, with a half-life of 3.1 minutes to lead-214
- which decays, through beta-emission, with a half-life of 27 minutes to bismuth-214
- which decays, through beta-emission, with a half-life of 20 minutes to polonium-214
- which decays, through alpha-emission, with a half-life of 160 microseconds to lead-210
- which decays, through beta-emission, with a half-life of 22 years to bismuth-210
- which decays, through beta-emission, with a half-life of 5 days to polonium-210
- which decays, through alpha-emission, with a half-life of 140 days to lead-206, which is a stable nuclide.

Some radionuclides may have several different paths of decay. For example, approximately 36% of bismuth-212 decays, through alpha-emission, to thallium-208 while approximately 64% of bismuth-212 decays, through beta-emission, to polonium-212. Both the thallium-208 and the polonium-212 are radioactive daughter products of bismuth-212, and both decay directly to stable lead-208.

Occurrence and applications

According to the Big Bang theory, stable isotopes of the lightest five elements (H, He, and traces of Li, Be, and B) were produced very shortly after the emergence of the

universe, in a process called Big Bang nucleosynthesis. These lightest stable nuclides (including deuterium) survive to today, but any radioactive isotopes of the light elements produced in the Big Bang (such as tritium) have long since decayed. Isotopes of elements heavier than boron were not produced at all in the Big Bang, and these first five elements do not have any long-lived radioisotopes. Thus, all radioactive nuclei are therefore relatively young with respect to the birth of the universe, having formed later in various other types of nucleosynthesis in stars (particularly supernovae), and also during ongoing interactions between stable isotopes and energetic particles. For example, carbon-14, a radioactive nuclide with a half-life of only 5730 years, is constantly produced in Earth's upper atmosphere due to interactions between cosmic rays and nitrogen.

Radioactive decay has been put to use in the technique of radioisotopic labeling, which is used to track the passage of a chemical substance through a complex system (such as a living organism). A sample of the substance is synthesized with a high concentration of unstable atoms. The presence of the substance in one or another part of the system is determined by detecting the locations of decay events.

On the premise that radioactive decay is truly random (rather than merely chaotic), it has been used in hardware random-number generators. Because the process is not thought to vary significantly in mechanism over time, it is also a valuable tool in estimating the absolute ages of certain materials. For geological materials, the radioisotopes and some of their decay products become trapped when a rock solidifies, and can then later be used (subject to many well-known qualifications) to estimate the date of the solidification. These include checking the results of several simultaneous processes and their products against each other, within the same sample. In a similar fashion, and also subject to qualification, the rate of formation of carbon-14 in various eras, the date of formation of organic matter within a certain period related to the isotope's half-life may be estimated, because the carbon-14 becomes trapped when the organic matter grows and incorporates the new carbon-14 from the air. Thereafter, the amount of carbon-14 in organic matter decreases according to decay processes which may also be independently cross-checked by other means (such as checking the carbon-14 in individual tree rings, for example).

Radioactive decay rates

The **decay rate**, or **activity**, of a radioactive substance are characterized by:

Constant quantities:

- half life — symbol $t_{1/2}$ — the time taken for the activity of a given amount of a radioactive substance to decay to half of its initial value.
- mean lifetime — symbol τ — the average lifetime of a radioactive particle.
- decay constant — symbol λ — the inverse of the mean lifetime.

Although these are constants, they are associated with statistically random behavior of populations of atoms. In consequence predictions using these constants are less accurate for small number of atoms.

Time-variable quantities:

- **Total activity** — symbol A — number of decays an object undergoes per second.
- **Number of particles** — symbol N — the total number of particles in the sample.
- **Specific activity** — symbol S_A — number of decays per second per amount of substance. (The "amount of substance" can be the unit of either mass or volume.)

These are related as follows:

where a_0 is the initial amount of active substance — substance that has the same percentage of unstable particles as when the substance was formed.

Activity measurements

The units in which activities are measured are: becquerel (symbol Bq) = number of disintegrations per second; curie (Ci) = 3.7×10^{10} disintegrations per second. Low activities are also measured in **disintegrations per minute** (dpm).

Decay timing

As discussed above, the decay of an unstable nucleus is entirely random and it is impossible to predict when a particular atom will decay. However, it is equally likely to decay at any time. Therefore, given a sample of a particular radioisotope, the number of decay events— dN expected to occur in a small interval of time dt is proportional to the number of atoms present. If N is the number of atoms, then the probability of decay ($-dN/N$) is proportional to dt :

Particular radionuclides decay at different rates, each having its own decay constant (λ). The negative sign indicates that N decreases with each decay event. The solution to this first-order differential equation is the following function:

Where N_0 is the value of N at time zero ($t = 0$). The second equation recognizes that the differential decay constant λ has units of 1/time, and can thus also be represented as $1/\tau$, where τ is a characteristic time for the process. This characteristic time is called the time constant of the process. In radioactive decay, this process time constant is also the mean lifetime for decaying atoms. Each atom "lives" for a finite amount of time before it decays, and it may be shown that this mean lifetime is the arithmetic mean of all the atoms' lifetimes, and that it is τ , which again is related to the decay constant as follows:

The previous exponential function generally represents the result of exponential decay. It is only an approximate solution, for two reasons. Firstly, the exponential function is continuous, but the physical quantity N can only take non-negative integer values. Secondly, because it describes a random process, it is only statistically true. However, in most common cases, N is an extremely large number (comparable to Avogadro's number) and the function is a good approximation.

Half life

A more commonly used parameter is the half-life. Given a sample of a particular radionuclide, the half-life is the time taken for half the radionuclide's atoms to decay. The half life is related to the decay constant as follows:

This relationship between the half-life and the decay constant shows that highly radioactive substances are quickly spent, while those that radiate weakly endure longer. Half-lives of known radionuclides vary widely, from more than 10^{19} years (such as for very nearly stable nuclides, e.g. ^{209}Bi), to 10^{-23} seconds for highly unstable ones.

The factor of $\ln 2$ in the above relations results from the fact that concept of "half life" is merely a way of selecting a different base other than the natural base e for the life time expression. The time constant τ is the "1/e" life (time till only $1/e = \text{about } 36.8\%$ remains) rather than the "1/2" life of a radionuclide where 50% remains (thus, τ is longer than $t_{1/2}$). Thus, the following equation can easily be shown to be valid.

Since radioactive decay is exponential with a constant probability, each process could as easily be described with a different constant time period which (for example) gave its "1/3 life" (how long until only 1/3rd is left) or "1/10 life" (a time period till only 10% is left) and so on. Thus the choice of τ and $t_{1/2}$ for marker-times, are only for convenience, and from convention. They reflect a fundamental principle only in so much as they show that the *same proportion* of a given radioactive substance will decay, during any time-period that one chooses.

Exponential decay

A quantity undergoing exponential decay. Larger decay constants make the quantity vanish much more rapidly. This plot shows decay for decay constants of 25, 5, 1, 1/5, and 1/25 for x from 0 to 4.

A quantity is said to be subject to **exponential decay** if it decreases at a rate proportional to its value. Symbolically, this can be expressed as the following differential equation, where N is the quantity and λ is a positive number called the decay constant.

The solution to this equation (see below for derivation) is:

Here $N(t)$ is the quantity at time t , and $N_0 = N(0)$ is the initial quantity, i.e. the quantity at time $t = 0$.

Measuring rates of decay

Mean lifetime

If the decaying quantity is the same as the number of discrete elements of a set, it is possible to compute the average length of time for which an element remains in the set. This is called the *mean lifetime* (or simply the *lifetime*) and it can be shown that it relates to the decay rate,

The mean lifetime (also called the exponential time constant) is thus seen to be a simple "scaling time":

Thus, it is the time needed for the assembly to be reduced by a factor of e .

A very similar equation will be seen below, which arises when the base of the exponential is chosen to be 2, rather than e . In that case the scaling time is the "half-life".

Half-life

Half-life

A more intuitive characteristic of exponential decay for many people is the time required for the decaying quantity to fall to one half of its initial value. This time is called the *half-life*, and often denoted by the symbol $t_{1/2}$. The half-life can be written in terms of the decay constant, or the mean lifetime, as:

When this expression is inserted for τ in the exponential equation above, and $\ln 2$ is absorbed into the base, this equation becomes:

Thus, the amount of material left is $2^{-1} = 1/2$ raised to the (whole or fractional) number of half-lives that have passed. Thus, after 3 half-lives there will be $1/2^3 = 1/8$ of the original material left.

Therefore, the mean lifetime τ is equal to the half-life divided by the natural log of 2, or:

E.g. Polonium-210 has a half-life of 138 days, and a mean lifetime of 200 days.

Solution of the differential equation

The equation that describes exponential decay is

or, by rearranging,

Integrating, we have

where C is the constant of integration, and hence

where the final substitution, $N_0 = e^C$, is obtained by evaluating the equation at $t = 0$, as N_0 is defined as being the quantity at $t = 0$.

This is the form of the equation that is most commonly used to describe exponential decay. Any one of decay constant, mean lifetime or half-life is sufficient to characterise the decay. The notation λ for the decay constant is a remnant of the usual notation for an eigenvalue. In this case, λ is the eigenvalue of the opposite of the differentiation operator with $N(t)$ as the corresponding eigenfunction. The units of the decay constant are s^{-1} .

Derivation of the mean lifetime

Given an assembly of elements, the number of which decreases ultimately to zero, the **mean lifetime**, τ , (also called simply the **lifetime**) is the expected value of the amount of time before an object is removed from the assembly. Specifically, if the *individual lifetime* of an element of the assembly is the time elapsed between some reference time and the removal of that element from the assembly, the mean lifetime is the arithmetic mean of the individual lifetimes.

Starting from the population formula

,

we firstly let c be the normalizing factor to convert to a probability space:

or, on rearranging,

We see that exponential decay is a scalar multiple of the exponential distribution (i.e. the individual lifetime of a each object is exponentially distributed), which has a well-known expected value. We can compute it here using integration by parts.

Decay by two or more processes

A quantity may decay via two or more different processes simultaneously. In general, these processes (often called "decay modes", "decay channels", "decay routes" etc.) have different probabilities of occurring, and thus occur at different rates with different half-lives, in parallel. The total decay rate of the quantity N is given by the *sum* of the decay routes; thus, in the case of two processes:

The solution to this equation is given in the previous section, where the sum of is treated as a new total decay constant .

Since , a combined can be given in terms of s:

In words: the mean life for combined decay channels is the harmonic mean of the mean lives associated with the individual processes divided by the total number of processes.

Since half-lives differ from mean life by a constant factor, the same equation holds in terms of the two corresponding half-lives:

where $T_{1/2}$ is the combined or total half-life for the process, t_1 is the half-life of the first process, and t_2 is the half life of the second process.

In terms of separate decay constants, the total half-life $T_{1/2}$ can be shown to be

For a decay by three simultaneous exponential processes the total half-life can be computed, as above, as the harmonic mean of separate mean lives:

Applications and examples

Exponential decay occurs in a wide variety of situations. Most of these fall into the domain of the natural sciences. Any application of mathematics to the social sciences or humanities is risky and uncertain, because of the extraordinary complexity of human behavior. However, a few roughly exponential phenomena have been identified there as well.

Many decay processes that are often treated as exponential, are really only exponential so long as the sample is large and the law of large numbers holds. For small samples, a more general analysis is necessary, accounting for a Poisson process.

Natural sciences

- In a sample of a radionuclide that undergoes radioactive decay to a different state, the number of atoms in the original state follows exponential decay as long as the remaining number of atoms is large. The decay product is termed a radiogenic nuclide.
- If an object at one temperature is exposed to a medium of another temperature, the temperature difference between the object and the medium follows exponential decay (in the limit of slow processes; equivalent to "good" heat conduction inside the object, so that its temperature remains relatively uniform through its volume). See also Newton's law of cooling.
- The rates of certain types of chemical reactions depend on the concentration of one or another reactant. Reactions whose rate depends only on the concentration of one reactant (known as first-order reactions) consequently follow exponential decay. For instance, many enzyme-catalyzed reactions behave this way.
- Atmospheric pressure decreases approximately exponentially with increasing height above sea level, at a rate of about 12% per 1000m.

- The electric charge (or, equivalently, the potential) stored on a capacitor (capacitance C) decays exponentially, if the capacitor experiences a constant external load (resistance R). The exponential time-constant τ for the process is RC , and the half-life is therefore $RC \ln 2$. (Furthermore, the particular case of a capacitor discharging through several parallel resistors makes an interesting example of multiple decay processes, with each resistor representing a separate process. In fact, the expression for the equivalent resistance of two resistors in parallel mirrors the equation for the half-life with two decay processes.)
- Some vibrations may decay exponentially; this characteristic is often used in creating ADSR envelopes in synthesizers.
- In pharmacology and toxicology, it is found that many administered substances are distributed and metabolized (see *clearance*) according to exponential decay patterns. The biological half-lives "alpha half-life" and "beta half-life" of a substance measure how quickly a substance is distributed and eliminated.
- The intensity of electromagnetic radiation such as light or X-rays or gamma rays in an absorbent medium, follows an exponential decrease with distance into the absorbing medium.
- The decline in resistance of a Negative Temperature Coefficient Thermistor as temperature is increased.

Social sciences

- The field of glottochronology attempts to determine the time elapsed since the divergence of two languages from a common root, using the assumption that linguistic changes are introduced at a steady rate; given this assumption, we expect the similarity between them (the number of properties of the language that are still identical) to decrease exponentially.
- In history of science, some believe that the body of knowledge of any particular science is gradually disproved according to an exponential decay pattern (see half-life of knowledge).

Computer science

- BGP, the core routing protocol on the Internet, has to maintain a routing table in order to remember the paths a packet can be deviated to. When one of these paths repeatedly changes its state from *available* to *not available* (and *vice-versa*), the BGP router controlling that path has to repeatedly add and remove the path record from its routing table (*flaps* the path), thus spending local resources such as CPU and RAM and, even more, broadcasting useless information to peer routers. To prevent this undesired behavior, an algorithm named *route flapping damping* assigns each route a weight that gets bigger each time the route changes its state

and decays exponentially with time. When the weight reaches a certain limit, no more flapping is done, thus suppressing the route.

Spontaneous changes from one nuclide to another: nuclear decay

There are 80 elements which have at least one stable isotope (defined as isotopes never observed to decay), and in total there are about 256 such stable isotopes. However, there are thousands more well-characterized isotopes which are unstable. These radioisotopes may be unstable and decay in all timescales ranging from fractions of a second to weeks, years, or many billions of years.

For example, if a nucleus has too few or too many neutrons it may be unstable, and will decay after some period of time. For example, in a process called beta decay a nitrogen-16 atom (7 protons, 9 neutrons) is converted to an oxygen-16 atom (8 protons, 8 neutrons) within a few seconds of being created. In this decay a neutron in the nitrogen nucleus is turned into a proton and an electron and antineutrino, by the weak nuclear force. The element is transmuted to another element in the process, because while it previously had seven protons (which makes it nitrogen) it now has eight (which makes it oxygen).

In alpha decay the radioactive element decays by emitting a helium nucleus (2 protons and 2 neutrons), giving another element, plus helium-4. In many cases this process continues through several steps of this kind, including other types of decays, until a stable element is formed.

In gamma decay, a nucleus decays from an excited state into a lower state by emitting a gamma ray. The element is not changed in the process.

Other more exotic decays are possible (see the main article). For example, in internal conversion decay, the energy from an excited nucleus may be used to eject one of the inner orbital electrons from the atom, in a process which produces high speed electrons, but is not beta decay, and (unlike beta decay) does not transmute one element to another.

Chapter-3

Nuclear fusion

Nuclear fusion

Fusion of deuterium with tritium creating helium-4, freeing a neutron, and releasing 17.59 MeV of energy, as an appropriate amount of mass converting to the kinetic energy of the products, in agreement with $E = \Delta m c^2$.

In nuclear physics and nuclear chemistry, **nuclear fusion** is the process by which multiple like-charged atomic nuclei join together to form a heavier nucleus. It is accompanied by the release or absorption of energy, which allows matter to enter a plasma state.

The fusion of two nuclei with lower mass than iron (which, along with nickel, has the largest binding energy per nucleon) generally releases energy while the fusion of nuclei heavier than iron absorbs energy; vice-versa for the reverse process, nuclear fission. In the simplest case of hydrogen fusion, two protons have to be brought close enough for their mutual electric repulsion to be overcome by the nuclear force and the subsequent release of energy.

Nuclear fusion occurs naturally in stars. Artificial fusion in human enterprises has also been achieved, although has not yet been completely controlled. Building upon the nuclear transmutation experiments of Ernest Rutherford done a few years earlier, fusion of light nuclei (hydrogen isotopes) was first observed by Mark Oliphant in 1932; the steps of the main cycle of nuclear fusion in stars were subsequently worked out by Hans Bethe throughout the remainder of that decade. Research into fusion for military purposes began in the early 1940s as part of the Manhattan Project, but was not successful until 1952. Research into controlled fusion for civilian purposes began in the 1950s, and continues to this day.

Overview

Fusion reactions power the stars and produce all but the lightest elements in a process called nucleosynthesis. Although the fusion of lighter elements in stars releases energy, production of the heavier elements absorbs energy.

When the fusion reaction is a sustained uncontrolled chain, it can result in a thermonuclear explosion, such as that generated by a hydrogen bomb. Reactions which are not self-sustaining can still release considerable energy, as well as large numbers of neutrons.

Research into controlled fusion, with the aim of producing fusion power for the production of electricity, has been conducted for over 50 years. It has been accompanied by extreme scientific and technological difficulties, but has resulted in progress. At present, break-even (self-sustaining) controlled fusion reactions have not been demonstrated in the few tokamak-type reactors around the world. Workable designs for a reactor which will theoretically deliver ten times more fusion energy than the amount needed to heat up plasma to required temperatures (see ITER) is scheduled to be operational in 2018.

It takes considerable energy to force nuclei to fuse, even those of the lightest element, hydrogen. This is because all nuclei have a positive charge (due to their protons), and as like charges repel, nuclei strongly resist being put too close together. Accelerated to high speeds (that is, heated to thermonuclear temperatures), they can overcome this electromagnetic repulsion and get close enough for the attractive nuclear force to be sufficiently strong to achieve fusion. The fusion of lighter nuclei, which creates a heavier nucleus and a free neutron, generally releases more energy than it takes to force the nuclei together; this is an exothermic process that can produce self-sustaining reactions.

The energy released in most nuclear reactions is much larger than that in chemical reactions, because the binding energy that holds a nucleus together is far greater than the energy that holds electrons to a nucleus. For example, the ionization energy gained by adding an electron to a hydrogen nucleus is 13.6 electron volts—less than one-millionth of the 17 MeV released in the D-T (deuterium-tritium) reaction shown in the diagram to the right. Fusion reactions have an energy density many times greater than nuclear fission; i.e., the reactions produce far greater energies per unit of mass even though

individual fission reactions are generally much more energetic than *individual* fusion ones, which are themselves millions of times more energetic than chemical reactions. Only direct conversion of mass into energy, such as that caused by the collision of matter and antimatter, is more energetic per unit of mass than nuclear fusion.

Requirements

A substantial energy barrier of electrostatic forces must be overcome before fusion can occur. At large distances two naked nuclei repel one another because of the repulsive electrostatic force between their positively charged protons. If two nuclei can be brought close enough together, however, the electrostatic repulsion can be overcome by the attractive nuclear force which is stronger at close distances.

When a nucleon such as a proton or neutron is added to a nucleus, the nuclear force attracts it to other nucleons, but primarily to its immediate neighbours due to the short range of the force. The nucleons in the interior of a nucleus have more neighboring nucleons than those on the surface. Since smaller nuclei have a larger surface area-to-volume ratio, the binding energy per nucleon due to the strong force generally increases with the size of the nucleus but approaches a limiting value corresponding to that of a nucleus with a diameter of about four nucleons.

The electrostatic force, on the other hand, is an inverse-square force, so a proton added to a nucleus will feel an electrostatic repulsion from *all* the other protons in the nucleus. The electrostatic energy per nucleon due to the electrostatic force thus increases without limit as nuclei get larger.

At short distances the attractive nuclear force is stronger than the repulsive electrostatic force. As such, the main technical difficulty for fusion is getting the nuclei close enough to fuse. Distances not to scale.

The net result of these opposing forces is that the binding energy per nucleon generally increases with increasing size, up to the elements iron and nickel, and then decreases for heavier nuclei. Eventually, the binding energy becomes negative and very heavy nuclei (all with more than 208 nucleons, corresponding to a diameter of about 6 nucleons) are not stable. The four most tightly bound nuclei, in decreasing order of binding energy, are ^{62}Ni , ^{58}Fe , ^{56}Fe , and ^{60}Ni . Even though the nickel isotope, ^{62}Ni , is more stable, the iron isotope ^{56}Fe is an order of magnitude more common. This is due to a greater disintegration rate for ^{62}Ni in the interior of stars driven by photon absorption.

A notable exception to this general trend is the helium-4 nucleus, whose binding energy is higher than that of lithium, the next heaviest element. The Pauli exclusion principle provides an explanation for this exceptional behavior—it says that because protons and neutrons are fermions, they cannot exist in exactly the same state. Each proton or neutron energy state in a nucleus can accommodate both a spin up particle and a spin down particle. Helium-4 has an anomalously large binding energy because its nucleus consists

of two protons and two neutrons; so all four of its nucleons can be in the ground state. Any additional nucleons would have to go into higher energy states.

The situation is similar if two nuclei are brought together. As they approach each other, all the protons in one nucleus repel all the protons in the other. Not until the two nuclei actually come in contact can the strong nuclear force take over. Consequently, even when the final energy state is lower, there is a large energy barrier that must first be overcome. It is called the Coulomb barrier.

The Coulomb barrier is smallest for isotopes of hydrogen—they contain only a single positive charge in the nucleus. A bi-proton is not stable, so neutrons must also be involved, ideally in such a way that a helium nucleus, with its extremely tight binding, is one of the products.

Using deuterium-tritium fuel, the resulting energy barrier is about 0.01 MeV. In comparison, the energy needed to remove an electron from hydrogen is 13.6 eV, about 750 times less energy. The (intermediate) result of the fusion is an unstable ${}^5\text{He}$ nucleus, which immediately ejects a neutron with 14.1 MeV. The recoil energy of the remaining ${}^4\text{He}$ nucleus is 3.5 MeV, so the total energy liberated is 17.6 MeV. This is many times more than what was needed to overcome the energy barrier.

If the energy to initiate the reaction comes from accelerating one of the nuclei, the process is called *beam-target* fusion; if both nuclei are accelerated, it is *beam-beam* fusion. If the nuclei are part of a plasma near thermal equilibrium, one speaks of *thermonuclear* fusion. Temperature is a measure of the average kinetic energy of particles, so by heating the nuclei they will gain energy and eventually have enough to overcome this 0.01 MeV. Converting the units between electronvolts and kelvins shows that the barrier would be overcome at a temperature in excess of 120 million kelvins, obviously a very high temperature.

There are two effects that lower the actual temperature needed. One is the fact that temperature is the *average* kinetic energy, implying that some nuclei at this temperature would actually have much higher energy than 0.01 MeV, while others would be much lower. It is the nuclei in the high-energy tail of the velocity distribution that account for most of the fusion reactions. The other effect is quantum tunneling. The nuclei do not actually have to have enough energy to overcome the Coulomb barrier completely. If they have nearly enough energy, they can tunnel through the remaining barrier. For this reason fuel at lower temperatures will still undergo fusion events, at a lower rate.

The fusion reaction rate increases rapidly with temperature until it maximizes and then gradually drops off. The DT rate peaks at a lower temperature (about 70 keV, or 800 million kelvins) and at a higher value than other reactions commonly considered for fusion energy.

The reaction **cross section** σ is a measure of the probability of a fusion reaction as a function of the relative velocity of the two reactant nuclei. If the reactants have a distribution of velocities, e.g. a thermal distribution with thermonuclear fusion, then it is useful to perform an average over the distributions of the product of cross section and velocity. The reaction rate (fusions per volume per time) is $\langle \sigma v \rangle$ times the product of the reactant number densities:

If a species of nuclei is reacting with itself, such as the DD reaction, then the product $n_1 n_2$ must be replaced by $(1/2)n^2$.

increases from virtually zero at room temperatures up to meaningful magnitudes at temperatures of 10 – 100 keV. At these temperatures, well above typical ionization energies (13.6 eV in the hydrogen case), the fusion reactants exist in a plasma state.

The significance of σ as a function of temperature in a device with a particular energy confinement time is found by considering the Lawson criterion.

Gravitational confinement

One force capable of confining the fuel well enough to satisfy the Lawson criterion is gravity. The mass needed, however, is so great that gravitational confinement is only found in stars (the smallest of which are brown dwarfs). Even if the more reactive fuel deuterium were used, a mass greater than that of the planet Jupiter would be needed. In stars heavy enough, after the supply of hydrogen is exhausted in their cores, their cores (or a shell around the core) start fusing helium to carbon. In the most massive stars (at least 8-11 solar masses), the process is continued until some of their energy is produced by fusing lighter elements to iron. As iron has one of the highest binding energies, reactions producing heavier elements are generally endothermic. Therefore significant amounts of heavier elements are not formed during stable periods of massive star evolution, but are formed in supernova explosions and some lighter stars. Some of these heavier elements can in turn produce energy in nuclear fission.

Magnetic confinement

Magnetic confinement fusion

Magnetic confinement fusion is an approach to generating fusion energy that uses magnetic fields to confine the fusion fuel in the form of a plasma. Magnetic confinement is one of two major branches of fusion energy research, the other being inertial confinement fusion. The magnetic approach is more highly developed and is usually considered more promising for energy production. A 500-MW heat generating fusion plant using tokamak magnetic confinement geometry is currently being built in France (see ITER).

Fusion reactions combine light atomic nuclei such as hydrogen to form heavier ones such as helium. In order to overcome the electrostatic repulsion between them, the nuclei must have a temperature of several tens of millions of degrees, under which conditions they no longer form neutral atoms but exist in the plasma state. In addition, sufficient density and energy confinement are required, as specified by the Lawson criterion.

Magnetic confinement fusion attempts to create the conditions needed for fusion energy production by using the electrical conductivity of the plasma to contain it with magnetic fields. The basic concept can be thought of in a fluid picture as a balance between magnetic pressure and plasma pressure, or in terms of individual particles spiraling along magnetic field lines.

The pressure achievable is usually on the order of one bar with a confinement time up to a few seconds. In contrast, inertial confinement has a much higher pressure but a much lower confinement time. Most magnetic confinement schemes also have the advantage of being more or less steady state, as opposed to the inherently pulsed operation of inertial confinement.

The simplest magnetic configuration is a solenoid, a long cylinder wound with magnetic coils producing a field with the lines of force running parallel to the axis of the cylinder. Such a field would hinder ions and electrons from being lost radially, but not from being lost from the ends of the solenoid.

There are two approaches to solving this problem. One is to try to stop up the ends with a magnetic mirror, the other is to eliminate the ends altogether by bending the field lines around to close on themselves. A simple toroidal field, however, provides poor confinement because the radial gradient of the field strength results in a drift in the direction of the axis.

Magnetic mirrors

A major area of research in the early years of fusion energy research was the magnetic mirror. Most early mirror devices attempted to confine plasma near the focus of a non-planar magnetic field, or to be more precise, two such mirrors located close to each other and oriented at right angles. In order to escape the confinement area, nuclei had to enter a small annular area near each magnet. It was known that nuclei would escape through this area, but by adding and heating fuel continually it was felt this could be overcome. As development of mirror systems progressed, additional sets of magnets were added to either side, meaning that the nuclei had to escape through two such areas before leaving the reaction area entirely. A highly developed form, the MFTF, used two mirrors at either end of a solenoid to increase the internal volume of the reaction area.

Toroidal machines

An early attempt to build a magnetic confinement system was the stellarator, introduced by Lyman Spitzer in 1951. Essentially the stellarator consists of a torus that has been cut in half and then attached back together with straight "crossover" sections to form a figure-8. This has the effect of propagating the nuclei from the inside to outside as it orbits the device, thereby canceling out the drift across the axis, at least if the nuclei orbit fast enough. Newer versions of the stellarator design have replaced the "mechanical" drift cancellation with additional magnets that "wind" the field lines into a helix to cause the same effect.

In 1968 Russian research on the toroidal tokamak was first presented in public, with results that far outstripped existing efforts from any competing design, magnetic or not. Since then the majority of effort in magnetic confinement has been based on the tokamak principle. In the tokamak a current is periodically driven through the plasma itself, creating a field "around" the torus that combines with the toroidal field to produce a winding field in some ways similar to that in a modern stellarator, at least in that nuclei move from the inside to the outside of the device as they flow around it.

In 1991, START was built at Culham, UK, as the first purpose built spherical tokamak. This was essentially a spheromak with an inserted central rod. START produced impressive results, with β values at approximately 40% - three times that produced by standard tokamaks at the time. The concept has been scaled up to higher plasma currents and larger sizes, with the experiments NSTX (US), MAST (UK) and Globus-M (Russia) currently running. Spherical tokamaks are not limited by the same instabilities as tokamaks and as such the area is receiving considerable experimental attention.

Some more novel configurations produced in toroidal machines are the reversed field pinch and the Levitated Dipole Experiment.

Compact toroids

Compact toroids, e.g. the spheromak and the Field-Reversed Configuration, attempt to combine the good confinement of closed magnetic surfaces configurations with the simplicity of machines without a central core. An early experiment of this type was Trisops.

Magnetic fusion energy

All of these devices have faced considerable problems being scaled up and in their approach toward the Lawson criterion. One researcher has described the magnetic confinement problem in simple terms, likening it to squeezing a balloon – the air will always attempt to "pop out" somewhere else. Turbulence in the plasma has proven to be a major problem, causing the plasma to escape the confinement area, and potentially touch the walls of the container. If this happens, a process known as "sputtering", high-mass particles from the container (often steel and other metals) are mixed into the fusion fuel, lowering its temperature.

Progress has been remarkable – both in the significant progress toward a "burning" plasma and in the advance of scientific understanding. In 1997, scientists at the Joint European Torus (JET) facilities in the UK produced 16 megawatts of fusion power in the laboratory and have studied the behavior of fusion products (alpha particles) in weakly burning plasmas. Underlying this progress are strides in fundamental understanding, which have led to the ability to control aspects of plasma behavior. For example, scientists can now exercise a measure of control over plasma turbulence and resultant energy leakage, long considered an unavoidable and intractable feature of plasmas; the plasma pressure above which the plasma disassembles can now be made large enough to sustain a fusion reaction rate acceptable for a power plant. Electromagnetic waves can be injected and steered to manipulate the paths of plasma particles and then to produce the large electrical currents necessary to produce the magnetic fields to confine the plasma. These and other control capabilities have flowed from advances in basic understanding of plasma science in such areas as plasma turbulence, plasma macroscopic stability, and plasma wave propagation. Much of this progress has been achieved with a particular emphasis on the tokamak.

Inertial confinement

Inertial confinement fusion



Inertial confinement fusion using lasers rapidly progressed in the late 1970s and early 1980s from being able to deliver only a few joules of laser energy (per pulse) to being able to deliver tens of kilojoules to a target. At this point, incredibly large scientific devices were needed for experimentation. Here, a view of the 10 beam LLNL Nova laser, shown shortly after the laser's completion in 1984. Around the time of the construction of its predecessor, the Shiva laser, laser fusion had entered the realm of "big science".

Inertial confinement fusion (ICF) is a process where nuclear fusion reactions are initiated by heating and compressing a fuel target, typically in the form of a pellet that most often contains a mixture of deuterium and tritium.

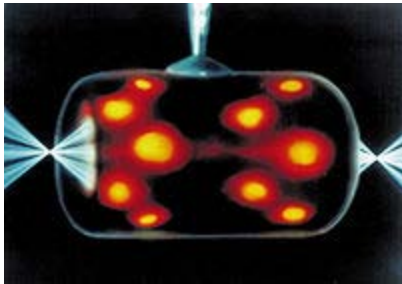
To compress and heat the fuel, energy is delivered to the outer layer of the target using high-energy beams of laser light, electrons or ions, although for a variety of reasons, almost all ICF devices to date have used lasers. The heated outer layer explodes outward, producing a reaction force against the remainder of the target, accelerating it inwards, and sending shock waves into the center. A sufficiently powerful set of shock waves can compress and heat the fuel at the center so much that fusion reactions occur. The energy released by these reactions will then heat the surrounding fuel, which may also begin to undergo fusion. The aim of ICF is to produce a condition known as "ignition", where this heating process causes a chain reaction that burns a significant portion of the fuel. Typical fuel pellets are about the size of a pinhead and contain around 10 milligrams of fuel: in practice, only a small proportion of this fuel will undergo fusion, but if all this fuel were consumed it would release the energy equivalent to burning a barrel of oil.

ICF is one of two major branches of fusion energy research, the other being magnetic confinement fusion. To date most of the work in ICF has been carried out in the United States, and generally has seen less development effort than magnetic approaches. When it was first proposed, ICF appeared to be a practical approach to fusion power production, but experiments during the 1970s and '80s demonstrated that the efficiency of these devices was much lower than expected. For much of the 1980s and '90s ICF experiments focused primarily on nuclear weapons research. More recent advances suggest that major gains in performance are possible, once again making ICF attractive for commercial power generation. A number of new experiments are underway or being planned to test this new "fast ignition" approach.

Description

Basic fusion

Nuclear fusion



Indirect drive laser ICF uses a "hohlraum" which is irradiated with laser beam cones from either side on its inner surface to bathe a fusion microcapsule inside with smooth high intensity X-rays. The highest energy X-rays can be seen leaking through the hohlraum, represented here in orange/red.

Fusion reactions combine lighter atoms, such as hydrogen, together to form larger ones. Generally the reactions take place at such high temperatures that the atoms have been ionized, their electrons stripped off by the heat; thus, fusion is typically described in terms of "nuclei" instead of "atoms".

Nuclei are positively charged, and thus repel each other due to the electrostatic force. Counteracting this is the strong force which pulls nucleons together, but only at very short ranges. Thus a fluid of nuclei will generally not undergo fusion. The nuclei must be forced together before the strong force can pull them together into stable collections. Fusion reactions on a scale useful for energy production require a very large amount of energy to initiate in order to overcome the so-called *Coulomb barrier* or *fusion barrier energy*. Generally less energy will be needed to cause lighter nuclei to fuse, as they have less charge and thus a lower barrier energy, and when they do fuse, more energy will be released. As the mass of the nuclei increase, there is a point where the reaction no longer gives off net energy — the energy needed to overcome the energy barrier is greater than the energy released in the resulting fusion reaction. This happens at Fe^{56} .

The key to practical fusion power is to select a fuel that requires the minimum amount of energy to start, that is, the lowest barrier energy. The best fuel from this standpoint is a one to one mix of deuterium and tritium; both are heavy isotopes of hydrogen. The D-T (deuterium & tritium) mix has a low barrier because of its high ratio of neutrons to protons. The presence of neutral neutrons in the nuclei helps pull them together via the strong force; while the presence of positively charged protons pushes the nuclei apart via Coulombic forces (the electromagnetic force). Tritium has one of the highest ratios of neutrons to protons of any stable or moderately unstable nuclide—two neutrons and one proton. Adding protons or removing neutrons increases the energy barrier.

In order to create the required conditions, the fuel must be heated to tens of millions of degrees, and/or compressed to immense pressures. The temperature and pressure required for any particular fuel to fuse is known as the Lawson criterion. These conditions have been known since the 1950s when the first H-bombs were built.

ICF mechanism of action

In a "hydrogen bomb" the fusion fuel is compressed and heated with a separate fission bomb. A variety of mechanisms transfers the energy of the "trigger"'s explosion into the fusion fuel. The use of a nuclear bomb to ignite a fusion reaction makes the concept less than useful as a power source. Not only would the triggers be prohibitively expensive to produce, but there is a minimum size that such a bomb can be built, defined roughly by the critical mass of the plutonium fuel used. Generally it seems difficult to build nuclear devices smaller than about 1 kiloton in size, which would make it a difficult engineering problem to extract power from the resulting explosions. Also the smaller a thermonuclear bomb is, the "dirtier" it is, that is to say, the percentage of energy produced in the explosion by fusion is decreased while the percent produced by fission reactions tends toward unity (100%). This did not stop efforts to design such a system however, leading to the PACER concept.

If some source of compression could be found, other than a nuclear bomb, then the size of the reaction could be scaled down. This idea has been of intense interest to both the bomb-making and fusion energy communities. It was not until the 1970s that a potential solution appeared in the form of very large, very high power, high energy lasers, which were then being built for weapons and other research. The D-T mix in such a system is known as a *target*, containing much less fuel than in a bomb design (often only micro or milligrams), and leading to a much smaller explosive force.

Generally ICF systems use a single laser, the *driver*, whose beam is split up into a number of beams which are subsequently individually amplified by a trillion times or more. These are sent into the reaction chamber (called a target chamber) by a number of mirrors, positioned in order to illuminate the target evenly over its whole surface. The heat applied by the driver causes the outer layer of the target to explode, just as the outer layers of an H-bomb's fuel cylinder do when illuminated by the X-rays of the nuclear device.

The material exploding off the surface causes the remaining material on the inside to be driven inwards with great force, eventually collapsing into a tiny near-spherical ball. In modern ICF devices the density of the resulting fuel mixture is as much as one-hundred times the density of lead, around 1000 g/cm^3 . This density is not high enough to create any useful rate of fusion on its own. However, during the collapse of the fuel, shock waves also form and travel into the center of the fuel at high speed. When they meet their counterparts moving in from the other sides of the fuel in the center, the density of that spot is raised much further.

Given the correct conditions, the fusion rate in the region highly compressed by the shock wave can give off significant amounts of highly energetic alpha particles. Due to the high density of the surrounding fuel, they move only a short distance before being "thermalized", losing their energy to the fuel as heat. This additional energy will cause additional fusion reactions in the heated fuel, giving off more high-energy particles. This process spreads outward from the center, leading to a kind of self sustaining burn known as *ignition*.

Schematic of the stages of inertial confinement fusion using lasers. The blue arrows represent radiation; orange is blowoff; purple is inwardly transported thermal energy.

2. Fuel is compressed by the rocket-like blowoff of the hot surface material.
3. During the final part of the capsule implosion, the fuel core reaches 20 times the density of lead and ignites at $100,000,000^\circ\text{C}$.
4. Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

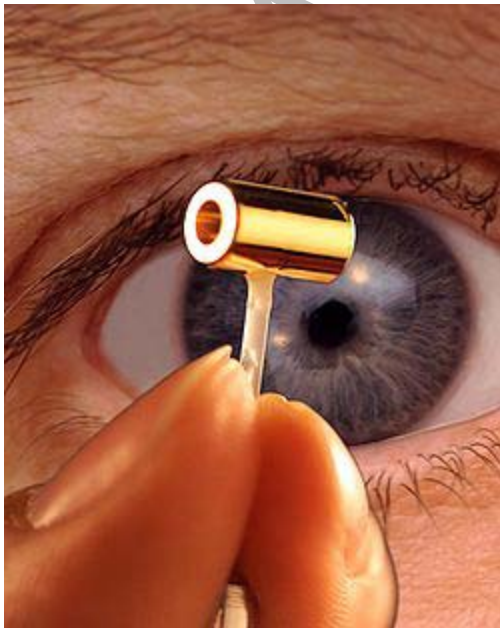
Issues with the successful achievement of ICF

The primary problems with increasing ICF performance since the early experiments in the 1970s have been of energy delivery to the target, controlling symmetry of the imploding fuel, preventing premature heating of the fuel (before maximum density is

achieved), preventing premature mixing of hot and cool fuel by hydrodynamic instabilities and the formation of a 'tight' shockwave convergence at the compressed fuel center.

In order to focus the shock wave on the center of the target, the target must be made with extremely high precision and sphericity with aberrations of no more than a few micrometres over its surface (inner and outer). Likewise the aiming of the laser beams must be extremely precise and the beams must arrive at the same time at all points on the target. Beam timing is a relatively simple issue though and is solved by using delay lines in the beams' optical path to achieve picosecond levels of timing accuracy. The other major problem plaguing the achievement of high symmetry and high temperatures/densities of the imploding target are so called "beam-beam" imbalance and beam anisotropy. These problems are, respectively, where the energy delivered by one beam may be higher or lower than other beams impinging on the target and of "hot spots" within a beam diameter hitting a target which induces uneven compression on the target surface, thereby forming Rayleigh–Taylor instabilities in the fuel, prematurely mixing it and reducing heating efficacy at the time of maximum compression.

All of these problems have been substantially mitigated to varying degrees in the past two decades of research by using various beam smoothing techniques and beam energy diagnostics to balance beam to beam energy though RT instability remains a major issue. Target design has also improved tremendously over the years. Modern cryogenic hydrogen ice targets tend to freeze a thin layer of deuterium just on the inside of a plastic sphere while irradiating it with a low power IR laser to smooth its inner surface while monitoring it with a microscope equipped camera, thereby allowing the layer to be closely monitored ensuring its "smoothness". Cryogenic targets filled with a deuterium tritium (D-T) mixture are "self-smoothing" due to the small amount of heat created by the decay of the radioactive tritium isotope. This is often referred to as "beta-layering".



Mockup of a gold plated NIF hohlraum.



An inertial confinement fusion fuel microcapsule (sometimes called a "microballon") of the size to be used on the NIF which can be filled with either deuterium and tritium gas or DT ice. The capsule can be either inserted in a hohlraum (as above) and imploded in the **indirect drive** mode or irradiated directly with laser energy in the **direct drive** configuration. Microcapsules used on previous laser systems were significantly smaller owing to the less powerful irradiation earlier lasers were capable of delivering to the target.

Certain targets are surrounded by a small metal cylinder which is irradiated by the laser beams instead of the target itself, an approach known as "*indirect drive*". In this approach the lasers are focused on the inner side of the cylinder, heating it to a superhot plasma which radiates mostly in X-rays. The X-rays from this plasma are then absorbed by the target surface, imploding it in the same way as if it had been hit with the lasers directly. The absorption of thermal x-rays by the target is more efficient than the direct absorption of laser light, however these *hohlraums* or "burning chambers" also take up considerable energy to heat on their own thus significantly reducing the overall efficiency of laser-to-target energy transfer. They are thus a debated feature even today; the equally numerous "*direct-drive*" design does not use them. Most often, indirect drive hohlraum targets are used to simulate thermonuclear weapons tests due to the fact that the fusion fuel in them is also imploded mainly by X-ray radiation.

A variety of ICF drivers are being explored. Lasers have improved dramatically since the 1970s, scaling up in energy and power from a few joules and kilowatts to megajoules (see NIF laser) and hundreds of terawatts, using mostly frequency doubled or tripled light from neodymium glass amplifiers.

Heavy ion beams are particularly interesting for commercial generation, as they are easy to create, control, and focus. On the downside, it is very difficult to achieve the very high energy densities required to implode a target efficiently, and most ion-beam systems

require the use of a hohlraum surrounding the target to smooth out the irradiation, reducing the overall efficiency of the coupling of the ion beam's energy to that of the imploding target further.

Brief history of ICF

The first laser-driven "ICF" experiments (though strictly speaking, these were only high intensity laser-hydrogen plasma interaction experiments) were carried out using ruby lasers soon after these were invented in the 1960s. It was realized that the power available from existing lasers was far too low to be truly useful in achieving significant fusion reactions, but were useful in establishing preliminary theories describing high intensity light and plasma interactions.

A major step in the ICF program took place in 1972, when John Nuckolls of the Lawrence Livermore National Laboratory (LLNL) published a seminal article in *Nature* that predicted that ignition could be achieved with laser energies about 1 kJ, while "high gain" would require energies around 1 MJ.

But already back in 1964, it was proposed by Winterberg that ignition could be achieved by an intense beam of microparticles accelerated to a velocity of 1000 km/s. And in 1968, Winterberg proposed to use intense electron and ion beams, generated by Marx generators, for the same purpose.

The primary problems in making a practical ICF device would be building a laser of the required energy and making its beams uniform enough to collapse a fuel target evenly. At first it was not obvious that the energy issue could ever be addressed, but a new generation of laser devices first invented in the late 1960s pointed to ways to build devices of the required power. Starting in the early-1970s several labs started experiments with such devices, including krypton fluoride excimer lasers at the Naval Research Laboratory (NRL) and the solid-state lasers (Nd:glass lasers) at Lawrence Livermore National Laboratory (LLNL). What followed was a series of advances followed by seemingly intractable problems that characterized fusion research in general.

High energy ICF experiments (multi-hundred joules per shot and greater experiments) began in earnest in the early-1970s, when lasers of the required energy and power were first designed. This was some time after the successful design of magnetic confinement fusion systems, and around the time of the particularly successful tokamak design that was introduced in the early '70s. Nevertheless, high funding for fusion research stimulated by the multiple energy crises during the mid to late 1970s produced rapid gains in performance, and inertial designs were soon reaching the same sort of "below break-even" conditions of the best magnetic systems.

LLNL was, in particular, very well funded and started a major laser fusion development program. Their Janus laser started operation in 1974, and validated the approach of using Nd:glass lasers to generate very high power devices. Focusing problems were explored in the Long path laser and Cyclops laser, which led to the larger Argus laser. None of these

were intended to be practical ICF devices, but each one advanced the state of the art to the point where there was some confidence the basic approach was valid. At the time it was believed that making a much larger device of the Cyclops type could both compress and heat the ICF targets, leading to ignition in the "short term". This was a misconception based on extrapolation of the fusion yields seen from experiments utilizing the so called "exploding pusher" type of fuel capsules. During the period spanning the years of the late '70s and early '80s the estimates for laser energy on target needed to achieve ignition doubled almost yearly as the various plasma instabilities and laser-plasma energy coupling loss modes were gradually understood. The realization that the simple exploding pusher target designs and mere few kilojoule (kJ) laser irradiation intensities would never scale to high gain fusion yields led to the effort to increase laser energies to the hundred kJ level in the UV and to the production of advanced ablator and cryogenic DT ice target designs.

One of the earliest serious and large scale attempts at an ICF driver design was the **Shiva laser**, a 20-beam neodymium doped glass laser system built at the Lawrence Livermore National Laboratory (LLNL) that started operation in 1978. Shiva was a "proof of concept" design intended to demonstrate compression of fusion fuel capsules to many times the liquid density of hydrogen. In this, Shiva succeeded and compressed its pellets to 100 times the liquid density of deuterium. However, due to the laser's strong coupling with hot electrons, premature heating of the dense plasma (ions) was problematic and fusion yields were low. This failure by Shiva to efficiently heat the compressed plasma pointed to the use of optical frequency multipliers as a solution which would frequency triple the infrared light from the laser into the ultraviolet at 351 nm. Newly discovered schemes to efficiently frequency triple high intensity laser light discovered at the Laboratory for Laser Energetics in 1980 enabled this method of target irradiation to be experimented with in the 24 beam OMEGA laser and the NOVETTE laser, which was followed by the Nova laser design with 10 times the energy of Shiva, the first design with the specific goal of reaching ignition conditions.

Nova also failed in its goal of achieving ignition, this time due to severe variation in laser intensity in its beams (and differences in intensity between beams) caused by filamentation which resulted in large non-uniformity in irradiation smoothness at the target and asymmetric implosion. The techniques pioneered earlier could not address these new issues. But again this failure led to a much greater understanding of the process of implosion, and the way forward again seemed clear, namely the increase in uniformity of irradiation, the reduction of hot-spots in the laser beams through beam smoothing techniques to reduce Rayleigh–Taylor instability imprinting on the target and increased laser energy on target by at least an order of magnitude. Funding for fusion research was severely constrained in the 80's, but Nova nevertheless successfully gathered enough information for a next generation machine.

The resulting design, now known as the National Ignition Facility, started construction at LLNL in 1997. NIF's main objective will be to operate as the flagship experimental device of the so called nuclear stewardship program, supporting LLNL's traditional bomb-

making role. Originally intended to start construction in the early 1990s, NIF is now scheduled for fusion experiments starting in 2009 when the remaining lasers in the 192-beam array are installed. The facility was completed in March 2009. The first credible attempts at ignition are scheduled for 2010.

A more recent development is the concept of "fast ignition", which may offer a way to directly heat the high density fuel after compression, thus decoupling the heating and compression phases of the implosion. In this approach the target is first compressed "normally" using a driver laser system, and then when the implosion reaches maximum density (at the stagnation point or "bang time"), a second ultra-short pulse ultra-high power petawatt (PW) laser delivers a single pulse focused on one side of the core, dramatically heating it and hopefully starting fusion ignition. The two types of fast ignition are the "plasma bore-through" method and the "cone-in-shell" method. In the first method the petawatt laser is simply expected to bore straight through the outer plasma of an imploding capsule and to impinge on and heat the dense core, whereas in the cone-in-shell method, the capsule is mounted on the end of a small high-z cone such that the tip of the cone projects into the core of the capsule. In this second method, when the capsule is imploded, the petawatt has a clear view straight to the high density core and does not have to waste energy boring through a 'corona' plasma; however, the presence of the cone affects the implosion process in significant ways that are not fully understood. Several projects are currently underway to explore the fast ignition approach, including upgrades to the OMEGA laser at the University of Rochester, the GEKKO XII device in Japan, and an entirely new £500m facility, known as HiPER, proposed for construction in the European Union. If successful, the fast ignition approach could dramatically lower the total amount of energy needed to be delivered to the target; whereas NIF uses UV beams of 2 MJ, HiPER's driver is 200 kJ and heater 70 kJ, yet the predicted fusion gains are nevertheless even higher than on NIF.

Finally, using a different approach entirely is the z-pinch device. Z-pinch uses massive amounts of electrical current which is switched into a small number of extremely fine wires. The wires heat and vaporize so quickly they fill the target with x-rays, which implode the fuel pellet. In order to direct the x-rays onto the pellet the target consists of a cylindrical metal capsule with the wiring and fuel within. Challenges to this approach include relatively low drive temperatures, resulting in slow implosion velocities and potentially large instability growth, and preheat caused by high-energy x-rays.

Most recently, Winterberg has proposed the ignition of a deuterium microexplosion, with a gigavolt super-Marx generator, which is a Marx Generator driven by up to 100 ordinary Marx generators

Inertial confinement fusion as an energy source

Practical power plants built using ICF have been studied since the late 1970s when ICF experiments were beginning to ramp up to higher powers; they are known as **inertial fusion energy**, or **IFE** plants. These devices would deliver a successive stream of targets

to the reaction chamber, several a second typically, and capture the resulting heat and neutron radiation from their implosion and fusion to drive a conventional steam turbine.

Laser driven systems were initially believed to be able to generate commercially useful amounts of energy. However, as estimates of the energy required to reach ignition grew dramatically during the 1970s and '80s, these hopes were abandoned. Given the low efficiency of the laser amplification process (about 1 to 1.5%), and the losses in generation (steam-driven turbine systems are typically about 35% efficient), fusion gains would have to be on the order of 350 just to break even. These sorts of gains appeared to be impossible to generate, and ICF work turned primarily to weapons research. With the recent introduction of fast ignition, things have changed dramatically. In this approach gains of 100 are predicted in the first experimental device, HiPER. Given a gain of about 100 and a laser efficiency of about 1%, HiPER produces about the same amount of *fusion* energy as electrical energy was needed to create it.

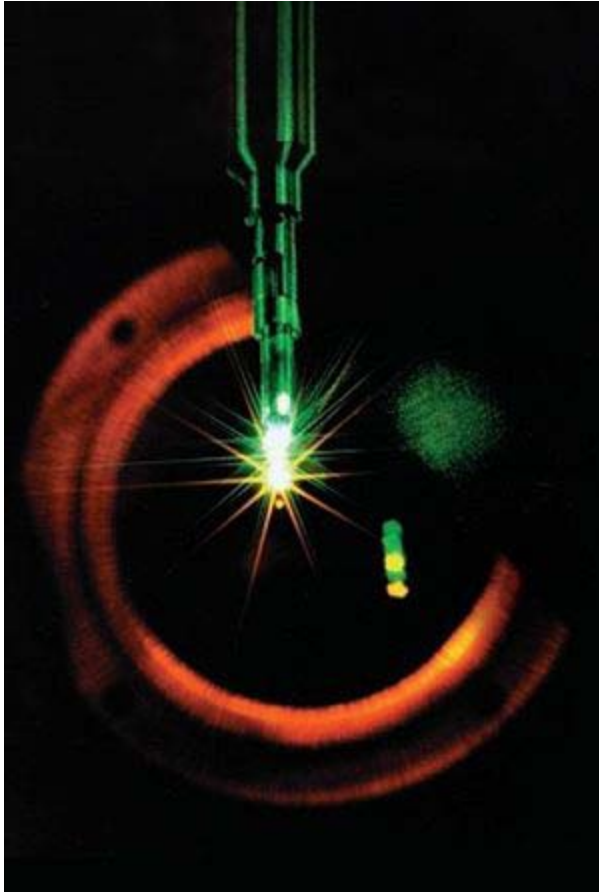
Additionally newer laser devices appear to be able to greatly improve driver efficiency. Current designs use xenon flash lamps to produce an intense flash of white light, some of which is absorbed by the Nd:glass that produces the laser power. In total about 1 to 1.5% of the electrical power fed into the flash tubes is turned into useful laser light. Newer designs replace the flash lamps with laser diodes that are tuned to produce most of their energy in a frequency range that is strongly absorbed. Initial experimental devices offer efficiencies of about 10%, and it is suggested that 20% is a real possibility with some additional development.

With "classical" devices like NIF about 330 MJ of electrical power are used to produce the driver beams, producing an expected yield of about 20 MJ, with the maximum credible yield of 45 MJ. Using the same sorts of numbers in a reactor combining fast ignition with newer lasers would offer dramatically improved performance. HiPER requires about 270 kJ of laser energy, so assuming a first-generation diode laser driver at 10% the reactor would require about 3 MJ of electrical power. This is expected to produce about 30 MJ of fusion power. Even a very poor conversion to electrical energy appears to offer real-world power output, and incremental improvements in yield and laser efficiency appear to be able to offer a commercially useful output.

ICF systems face some of the same secondary power extraction problems as magnetic systems in generating useful power from their reactions. One of the primary concerns is how to successfully remove heat from the reaction chamber without interfering with the targets and driver beams. Another serious concern is that the huge number of neutrons released in the fusion reactions react with the plant, causing them to become intensely radioactive themselves, as well as mechanically weakening metals. Fusion plants built of conventional metals like steel would have a fairly short lifetime and the core containment vessels will have to be replaced frequently.

One current concept in dealing with both of these problems, as shown in the **HYLIFE-II** baseline design, is to use a "waterfall" of *flibe*, a molten mix of fluorine, lithium and beryllium salts, which both protect the chamber from neutrons, as well as carrying away

heat. The flibe is then passed into a heat exchanger where it heats water for use in the turbines. Another, **Sombrero**, uses a reaction chamber built of carbon fibre which has a very low neutron cross section. Cooling is provided by a molten ceramic, chosen because of its ability to stop the neutrons from traveling any further, while at the same time being an efficient heat transfer agent.



An inertial confinement fusion implosion in Nova, creating "microsun" conditions of tremendously high density and temperature rivaling even those found at the core of our Sun.

As a power source, even the best IFE reactors would be hard-pressed to deliver the same economics as coal, although they would have advantages in terms of less pollution and global warming. Coal can simply be dug up and burned for little financial cost, one of the main costs being shipping. In terms of the turbomachinery and generators, an IFE plant would likely cost the same as a coal plant of similar power, and one might suggest that the "combustion chamber" in an IFE plant would be similar to those for a coal plant. On the other hand, a coal plant has no equivalent to the driver laser, which would make the IFE plant much more expensive. Additionally, extraction of deuterium and its formation into useful fuel pellets is considerably more expensive than coal processing, although the cost of shipping it is much lower (in terms of energy per unit mass). It is generally estimated that an IFE plant would have long-term operational costs about the same as

coal, discounting development. HYLIFE-II claims to be about 40% less expensive than a coal plant of the same size, but considering the problems with NIF, it is simply too early to tell if this is realistic or not.

The various phases of such a project are the following, the sequence of inertial confinement fusion development follows much the same outline:

- **burning demonstration:** reproducible achievement of some fusion energy release (not necessarily a Q factor of >1).
- **high gain demonstration:** experimental demonstration of the feasibility of a reactor with a sufficient energy gain.
- **industrial demonstration:** validation of the various technical options, and of the whole data needed to define a commercial reactor.
- **commercial demonstration:** demonstration of the reactor ability to work over a long period, while respecting all the requirements for safety, liability and cost.

At the moment, according to the available data, inertial confinement fusion experiments have not gone beyond the first phase, although Nova and others have repeatedly demonstrated operation within this realm.

In the short term a number of new systems are expected to reach the second stage. NIF is expected to be able to quickly reach this sort of operation when it starts, but the date for the start of fusion experiments is currently suggested to be somewhere between 2010 and 2014. Laser Mégajoule would also operate within the second stage, and was initially expected to become operational in 2010. Fast ignition systems work well within this range. Finally, the z-pinch machine, not using lasers, is expected to obtain a high fusion energy gain, as well as capability for repetitive working, starting around 2010.

For a true industrial demonstration, further work is required. In particular, the laser systems need to be able to run at high operating frequencies, perhaps one to ten times a second. Most of the laser systems mentioned in this article have trouble operating even as much as once a day. Parts of the HiPER budget are dedicated to research in this direction as well. Because they convert electricity into laser light with much higher efficiency, diode lasers also run cooler, which in turn allows them to be operated at much higher frequencies. HiPER is currently studying devices that operate at 1 MJ at 1 Hz, or alternately 100 kJ at 10 Hz.

Inertially confined fusion and the nuclear weapons program

The very hot and dense conditions encountered during an Inertial Confinement Fusion experiment are similar to those created in a thermonuclear weapon, and have applications to the nuclear weapons program. ICF experiments might be used, for example, to help determine how warhead performance will degrade as it ages, or as part of a program of designing new weapons. Retaining knowledge and corporate expertise in the nuclear

weapons program is another motivation for pursuing ICF. Funding for the NIF facility in the United States is sourced from the 'Nuclear Weapons Stockpile Stewardship' program, and the goals of the program are oriented accordingly. It has been argued that some aspects of ICF research may violate the Comprehensive Test Ban Treaty or the Nuclear Non-Proliferation Treaty. In the long term, despite the formidable technical hurdles, ICF research might potentially lead to the creation of a "pure fusion weapon".

Inertial confinement fusion as a neutron source

Inertial confinement fusion has the potential to produce orders of magnitude more neutrons than spallation. Neutrons are capable of locating hydrogen atoms in molecules, resolving atomic thermal motion and studying collective excitations of photons more effectively than X-rays. Neutron scattering studies of molecular structures could resolve problems associated with protein folding, diffusion through membranes, proton transfer mechanisms, dynamics of molecular motors, etc. by modulating thermal neutrons into beams of slow neutrons. In combination with fissionable materials, neutrons produced by ICF can potentially be used in Hybrid Nuclear Fusion designs to produce electric power.

A third confinement principle is to apply a rapid pulse of energy to a large part of the surface of a pellet of fusion fuel, causing it to simultaneously "implode" and heat to very high pressure and temperature. If the fuel is dense enough and hot enough, the fusion reaction rate will be high enough to burn a significant fraction of the fuel before it has dissipated. To achieve these extreme conditions, the initially cold fuel must be explosively compressed. Inertial confinement is used in the hydrogen bomb, where the driver is x-rays created by a fission bomb. Inertial confinement is also attempted in "controlled" nuclear fusion, where the driver is a laser, ion, or electron beam, or a Z-pinch. Another method is to use conventional high explosive material to compress a fuel to fusion conditions. The UTIAS explosive-driven-implosion facility was used to produce stable, centered and focused hemispherical implosions to generate neutrons from D-D reactions. The simplest and most direct method proved to be in a predetonated stoichiometric mixture of deuterium-oxygen. The other successful method was using a miniature Voitenko compressor, where a plane diaphragm was driven by the implosion wave into a secondary small spherical cavity that contained pure deuterium gas at one atmosphere.

Some confinement principles have been investigated, such as muon-catalyzed fusion, the Farnsworth-Hirsch fusor and Polywell (inertial electrostatic confinement), and bubble fusion.

Production methods

A variety of methods are known to effect nuclear fusion. Some are "cold" in the strict sense that no part of the material is hot (except for the reaction products), some are "cold" in the limited sense that the bulk of the material is at a relatively low temperature and

pressure but the reactants are not, and some are "hot" fusion methods that create macroscopic regions of very high temperature and pressure.

Locally cold fusion

Muon-catalyzed fusion is a well-established and reproducible fusion process that occurs at ordinary temperatures. It was studied in detail by Steven Jones in the early 1980s. It has not been reported to produce net energy. Net energy production from this reaction is not believed to be possible because of the energy required to create muons, their 2.2 μ s half-life, and the chance that a muon will bind to the new alpha particle and thus stop catalyzing fusion.

Generally cold, locally hot fusion

Accelerator based light-ion fusion. Using particle accelerators it is possible to achieve particle kinetic energies sufficient to induce many light ion fusion reactions. Accelerating light ions is relatively easy, cheap, and can be done in an efficient manner – all it takes is a vacuum tube, a pair of electrodes, and a high-voltage transformer; fusion can be observed with as little as 10 kilovolt between electrodes. The key problem with accelerator-based fusion (and with cold targets in general) is that fusion cross sections are many orders of magnitude lower than Coulomb interaction cross sections. Therefore vast majority of ions ends up expending their energy on bremsstrahlung and ionization of atoms of the target. Devices referred to as sealed-tube neutron generators are particularly relevant to this discussion. These small devices are miniature particle accelerators filled with deuterium and tritium gas in an arrangement which allows ions of these nuclei to be accelerated against hydride targets, also containing deuterium and tritium, where fusion takes place. Hundreds of neutron generators are produced annually for use in the petroleum industry where they are used in measurement equipment for locating and mapping oil reserves. Despite periodic reports in the popular press by scientists claiming to have invented "table-top" fusion machines, neutron generators have been around for half a century. The sizes of these devices vary but the smallest instruments are often packaged in sizes smaller than a loaf of bread. These devices do not produce a net power output.

In sonoluminescence, acoustic shock waves create temporary bubbles that collapse shortly after creation, producing very high temperatures and pressures. In 2002, Rusi P. Taleyarkhan reported the possibility that bubble fusion occurs in those collapsing bubbles (aka sonofusion). As of 2005, experiments to determine whether fusion is occurring give conflicting results. If fusion is occurring, it is because the local temperature and pressure are sufficiently high to produce hot fusion. In an episode of Horizon, on BBC television, results were presented showing that, although temperatures were reached which could initiate fusion on a large scale, no fusion was occurring, and inaccuracies in the measuring system were the cause of anomalous results.

The Farnsworth-Hirsch Fusor is a tabletop device in which fusion occurs. This fusion comes from high effective temperatures produced by electrostatic acceleration of ions. The device can be built inexpensively, but it too is unable to produce a net power output.

The Polywell is a concept for a tabletop device in which fusion occurs. The device is a non-thermodynamic equilibrium machine which uses electrostatic confinement to accelerate ions into a center where they fuse together.

Antimatter-initialized fusion uses small amounts of antimatter to trigger a tiny fusion explosion. This has been studied primarily in the context of making nuclear pulse propulsion feasible. This is not near becoming a practical power source, due to the cost of manufacturing antimatter alone.

Pyroelectric fusion was reported in April 2005 by a team at UCLA. The scientists used a pyroelectric crystal heated from -34 to 7°C (-30 to 45°F), combined with a tungsten needle to produce an electric field of about 25 gigavolts per meter to ionize and accelerate deuterium nuclei into an erbium deuteride target. Though the energy of the deuterium ions generated by the crystal has not been directly measured, the authors used 100 keV (a temperature of about 10^9 K) as an estimate in their modeling. At these energy levels, two deuterium nuclei can fuse together to produce a helium-3 nucleus, a 2.45 MeV neutron and bremsstrahlung. Although it makes a useful neutron generator, the apparatus is not intended for power generation since it requires far more energy than it produces.

Hot fusion

In "standard" "hot" fusion, the fuel reaches tremendous temperature and pressure inside a fusion reactor or nuclear weapon.

The methods in the second group are examples of non-equilibrium systems, in which very high temperatures and pressures are produced in a relatively small region adjacent to material of much lower temperature. In his doctoral thesis for MIT, Todd Rider did a theoretical study of all quasineutral, isotropic, non-equilibrium fusion systems. He demonstrated that all such systems will leak energy at a rapid rate due to bremsstrahlung produced when electrons in the plasma hit other electrons or ions at a cooler temperature and suddenly decelerate. The problem is not as pronounced in a hot plasma because the range of temperatures, and thus the magnitude of the deceleration, is much lower. Note that Rider's work does not apply to non-neutral and/or anisotropic non-equilibrium plasmas.

Important reactions

Astrophysical reaction chains

The most important fusion process in nature is that which powers the stars. The net result is the fusion of four protons into one alpha particle, with the release of two positrons, two

neutrinos (which changes two of the protons into neutrons), and energy, but several individual reactions are involved, depending on the mass of the star. For stars the size of the sun or smaller, the proton-proton chain dominates. In heavier stars, the CNO cycle is more important. Both types of processes are responsible for the creation of new elements as part of stellar nucleosynthesis.

At the temperatures and densities in stellar cores the rates of fusion reactions are notoriously slow. For example, at solar core temperature ($T \approx 15$ MK) and density (160 g/cm^3), the energy release rate is only $276 \text{ } \mu\text{W/cm}^3$ —about a quarter of the volumetric rate at which a resting human body generates heat. Thus, reproduction of stellar core conditions in a lab for nuclear fusion power production is completely impractical. Because nuclear reaction rates strongly depend on temperature ($\exp(-E/kT)$), then in order to achieve reasonable rates of energy production in terrestrial fusion reactors 10–100 times higher temperatures (compared to stellar interiors) are required $T \approx 0.1\text{--}1.0$ GK.

Criteria and candidates for terrestrial reactions

In man-made fusion, the primary fuel is not constrained to be protons and higher temperatures can be used, so reactions with larger cross-sections are chosen. This implies a lower Lawson criterion, and therefore less startup effort. Another concern is the production of neutrons, which activate the reactor structure radiologically, but also have the advantages of allowing volumetric extraction of the fusion energy and tritium breeding. Reactions that release no neutrons are referred to as *aneutronic*.

In order to be useful as a source of energy, a fusion reaction must satisfy several criteria. It must

- **be exothermic:** This may be obvious, but it limits the reactants to the low Z (number of protons) side of the curve of binding energy. It also makes helium ^4He the most common product because of its extraordinarily tight binding, although ^3He and ^3H also show up;
- **involve low Z nuclei:** This is because the electrostatic repulsion must be overcome before the nuclei are close enough to fuse;
- **have two reactants:** At anything less than stellar densities, three body collisions are too improbable. It should be noted that in inertial confinement, both stellar densities and temperatures are exceeded to compensate for the shortcomings of the third parameter of the Lawson criterion, ICF's very short confinement time;
- **have two or more products:** This allows simultaneous conservation of energy and momentum without relying on the electromagnetic force;
- **conserve both protons and neutrons:** The cross sections for the weak interaction are too small.

Few reactions meet these criteria. The following are those with the largest cross sections:

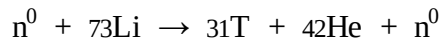
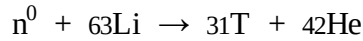
(1)	$^{21}\text{D} + ^{31}\text{T} \rightarrow ^{42}\text{He} \left(\frac{3.5 \text{ Me}}{\text{V}} \right) + \text{n}^0 \left(\frac{14.1 \text{ Me}}{\text{V}} \right)$	
(2i)	$^{21}\text{D} + ^{21}\text{D} \rightarrow ^{31}\text{T} \left(\frac{1.01 \text{ Me}}{\text{V}} \right) + \text{p}^+ \left(\frac{3.02 \text{ Me}}{\text{V}} \right)$	50 %
(2ii)	$\rightarrow ^{32}\text{He} \left(\frac{0.82 \text{ Me}}{\text{V}} \right) + \text{n}^0 \left(\frac{2.45 \text{ Me}}{\text{V}} \right)$	50 %
(3)	$^{21}\text{D} + ^{32}\text{H}_\text{e} \rightarrow ^{42}\text{He} \left(\frac{3.6 \text{ Me}}{\text{V}} \right) + \text{p}^+ \left(\frac{14.7 \text{ Me}}{\text{V}} \right)$	
(4)	$^{31}\text{T} + ^{31}\text{T} \rightarrow ^{42}\text{He} + 2 \text{n}^0$	+ 11.3 Me V
(5)	$^{32}\text{H}_\text{e} + ^{32}\text{H}_\text{e} \rightarrow ^{42}\text{He} + 2 \text{p}^+$	+ 12.9 Me V
(6i)	$^{32}\text{H}_\text{e} + ^{31}\text{T} \rightarrow ^{42}\text{He} + \text{p}^+ + \text{n}^0$	+ 12.1 Me V
(6ii)	$\rightarrow ^{42}\text{He} \left(\frac{4.8 \text{ Me}}{\text{V}} \right) + ^{21}\text{D} \left(\frac{9.5 \text{ Me}}{\text{V}} \right)$	43 %
(6iii)	$\rightarrow ^{42}\text{He} \left(\frac{0.5 \text{ Me}}{\text{V}} \right) + \text{n}^0 \left(\frac{1.9 \text{ Me}}{\text{V}} \right) + \text{p}^+ \left(\frac{11.9 \text{ Me}}{\text{V}} \right)$	6%
(7i)	$^{21}\text{D} + ^{63}\text{Li}_\text{e} \rightarrow 2 ^{42}\text{H} + \frac{22.4 \text{ Me}}{\text{V}}$	
(7ii)	$\rightarrow ^{32}\text{He} + ^{42}\text{He} + \text{n}^0$	+ 2.56 Me V
(7iii)	$\rightarrow ^{73}\text{Li} + \text{p}^+$	+ 5.0 Me V
(7iv)	$\rightarrow ^{74}\text{Be} + \text{n}^0$	+ 3.4 Me V
(8)	$\text{p}^+ + ^{63}\text{Li} \rightarrow ^{42}\text{He} \left(\frac{1.7 \text{ Me}}{\text{V}} \right) + ^{32}\text{H}_\text{e} \left(\frac{2.3 \text{ Me}}{\text{V}} \right)$	
(9)	$^{32}\text{H}_\text{e} + ^{63}\text{Li} \rightarrow 2 ^{42}\text{H} + \text{p}^+$	+ 16.9 Me V
(10)	$\text{p}^+ + ^{115}\text{B}_\text{e} \rightarrow 3 ^{42}\text{H}$	+ 8.7 Me V

For reactions with two products, the energy is divided between them in inverse proportion to their masses, as shown. In most reactions with three products, the distribution of energy varies. For reactions that can result in more than one set of products, the branching ratios are given.

Some reaction candidates can be eliminated at once. The $\text{D}-^6\text{Li}$ reaction has no advantage compared to $\text{p}^+-^{115}\text{B}$ because it is roughly as difficult to burn but produces substantially more neutrons through $^{21}\text{D}-^{21}\text{D}$ side reactions. There is also a p^+-^7Li reaction, but the cross section is far too low, except possibly when $T_i > 1 \text{ MeV}$, but at such high temperatures an endothermic, direct neutron-producing reaction also becomes very

significant. Finally there is also a $p^+ - {}^{94}\text{Be}$ reaction, which is not only difficult to burn, but ${}^{94}\text{Be}$ can be easily induced to split into two alpha particles and a neutron.

In addition to the fusion reactions, the following reactions with neutrons are important in order to "breed" tritium in "dry" fusion bombs and some proposed fusion reactors:



To evaluate the usefulness of these reactions, in addition to the reactants, the products, and the energy released, one needs to know something about the cross section. Any given fusion device will have a maximum plasma pressure that it can sustain, and an economical device will always operate near this maximum. Given this pressure, the largest fusion output is obtained when the temperature is chosen so that $\langle \sigma v \rangle / T^2$ is a maximum. This is also the temperature at which the value of the triple product $nT\tau$ required for ignition is a minimum, since that required value is inversely proportional to $\langle \sigma v \rangle / T^2$ (see Lawson criterion). (A plasma is "ignited" if the fusion reactions produce enough power to maintain the temperature without external heating.) This optimum temperature and the value of $\langle \sigma v \rangle / T^2$ at that temperature is given for a few of these reactions in the following table.

fuel	T [keV]	$\langle \sigma v \rangle / T^2$ [$\text{m}^3/\text{s/keV}^2$]
${}^{21}\text{D} - {}^3\text{T}$	13.6	1.24×10^{-24}
${}^{21}\text{D} - {}^{21}\text{D}$	15	1.28×10^{-26}
${}^{21}\text{D} - {}^{32}\text{He}$	58	2.24×10^{-26}
$p^+ - {}^{63}\text{Li}$	66	1.46×10^{-27}
$p^+ - {}^{115}\text{B}$	123	3.01×10^{-27}

Note that many of the reactions form chains. For instance, a reactor fueled with ${}^3\text{T}$ and ${}^{32}\text{He}$ will create some ${}^{21}\text{D}$, which is then possible to use in the ${}^{21}\text{D} - {}^{32}\text{He}$ reaction if the energies are "right". An elegant idea is to combine the reactions (8) and (9). The ${}^{32}\text{He}$ from reaction (8) can react with ${}^{63}\text{Li}$ in reaction (9) before completely thermalizing. This produces an energetic proton which in turn undergoes reaction (8) before thermalizing. A detailed analysis shows that this idea will not really work well, but it is a good example of a case where the usual assumption of a Maxwellian plasma is not appropriate.

Neutronicity, confinement requirement, and power density



The only fusion reactions thus far produced by humans to achieve ignition are those which have been created in hydrogen bombs, the first of which, Ivy Mike, is shown here.

Any of the reactions above can in principle be the basis of fusion power production. In addition to the temperature and cross section discussed above, we must consider the total energy of the fusion products E_{fus} , the energy of the charged fusion products E_{ch} , and the atomic number Z of the non-hydrogenic reactant.

Specification of the $21\text{D}-21\text{D}$ reaction entails some difficulties, though. To begin with, one must average over the two branches (2) and (3). More difficult is to decide how to treat the 31T and 32He products. 31T burns so well in a deuterium plasma that it is almost impossible to extract from the plasma. The $21\text{D}-32\text{He}$ reaction is optimized at a much higher temperature, so the burnup at the optimum $21\text{D}-21\text{D}$ temperature may be low, so it seems reasonable to assume the 31T but not the 32He gets burned up and adds its energy to the net reaction. Thus we will count the $21\text{D}-21\text{D}$ fusion energy as $E_{\text{fus}} = (4.03 + 17.6 + 3.27)/2 = 12.5 \text{ MeV}$ and the energy in charged particles as $E_{\text{ch}} = (4.03 + 3.5 + 0.82)/2 = 4.2 \text{ MeV}$.

Another unique aspect of the $21\text{D}-21\text{D}$ reaction is that there is only one reactant, which must be taken into account when calculating the reaction rate.

With this choice, we tabulate parameters for four of the most important reactions

fuel	Z	E_{fus} [MeV]	E_{ch} [MeV]	neutronicity
$21\text{D}-31\text{T}$	1	17.6	3.5	0.80
$21\text{D}-21\text{D}$	1	12.5	4.2	0.66
$21\text{D}-32\text{He}$	2	18.3	18.3	~ 0.05
p^+-115B	5	8.7	8.7	~ 0.001

The last column is the **neutronicity** of the reaction, the fraction of the fusion energy released as neutrons. This is an important indicator of the magnitude of the problems associated with neutrons like radiation damage, biological shielding, remote handling, and safety. For the first two reactions it is calculated as $(E_{\text{fus}} - E_{\text{ch}})/E_{\text{fus}}$. For the last two reactions, where this calculation would give zero, the values quoted are rough estimates based on side reactions that produce neutrons in a plasma in thermal equilibrium.

Of course, the reactants should also be mixed in the optimal proportions. This is the case when each reactant ion plus its associated electrons accounts for half the pressure.

Assuming that the total pressure is fixed, this means that density of the non-hydrogenic ion is smaller than that of the hydrogenic ion by a factor $2/(Z+1)$. Therefore the rate for these reactions is reduced by the same factor, on top of any differences in the values of $\langle\sigma v\rangle/T^2$. On the other hand, because the 21D-21D reaction has only one reactant, the rate is twice as high as if the fuel were divided between two hydrogenic species.

Thus there is a "penalty" of $(2/(Z+1))$ for non-hydrogenic fuels arising from the fact that they require more electrons, which take up pressure without participating in the fusion reaction. (It is usually a good assumption that the electron temperature will be nearly equal to the ion temperature. Some authors, however discuss the possibility that the electrons could be maintained substantially colder than the ions. In such a case, known as a "hot ion mode", the "penalty" would not apply.) There is at the same time a "bonus" of a factor 2 for 21D-21D because each ion can react with any of the other ions, not just a fraction of them.

We can now compare these reactions in the following table.

fuel	$\langle\sigma v\rangle/T^2$	penalty/bonus	reactivity	Lawson criterion	power density (W/m ³ /kPa ²)	relation of power density
21D-31T	1.24×10^{-24}	1	1	1	34	1
21D-21D	1.28×10^{-26}	2	48	30	0.5	68
21D-32He	2.24×10^{-26}	2/3	83	16	0.43	80
p ⁺ -63Li	1.46×10^{-27}	1/2	1700		0.005	6800
p ⁺ -115B	3.01×10^{-27}	1/3	1240	500	0.014	2500

The maximum value of $\langle\sigma v\rangle/T^2$ is taken from a previous table. The "penalty/bonus" factor is that related to a non-hydrogenic reactant or a single-species reaction. The values in the column "reactivity" are found by dividing 1.24×10^{-24} by the product of the second and third columns. It indicates the factor by which the other reactions occur more slowly

than the ${}^{21}\text{D}-{}^{31}\text{T}$ reaction under comparable conditions. The column "Lawson criterion" weights these results with E_{ch} and gives an indication of how much more difficult it is to achieve ignition with these reactions, relative to the difficulty for the ${}^{21}\text{D}-{}^{31}\text{T}$ reaction. The last column is labeled "power density" and weights the practical reactivity with E_{fus} . It indicates how much lower the fusion power density of the other reactions is compared to the ${}^{21}\text{D}-{}^{31}\text{T}$ reaction and can be considered a measure of the economic potential.

Bremsstrahlung losses in quasineutral, isotropic plasmas

The ions undergoing fusion in many systems will essentially never occur alone but will be mixed with electrons that in aggregate neutralize the ions' bulk electrical charge and form a plasma. The electrons will generally have a temperature comparable to or greater than that of the ions, so they will collide with the ions and emit x-ray radiation of 10-30 keV energy (Bremsstrahlung). The Sun and stars are opaque to x-rays, but essentially any terrestrial fusion reactor will be optically thin for x-rays of this energy range. X-rays are difficult to reflect but they are effectively absorbed (and converted into heat) in less than mm thickness of stainless steel (which is part of a reactor's shield). The ratio of fusion power produced to x-ray radiation lost to walls is an important figure of merit. This ratio is generally maximized at a much higher temperature than that which maximizes the power density (see the previous subsection). The following table shows the rough optimum temperature and the power ratio at that temperature for several reactions.

fuel	T_i (keV)	$P_{\text{fusion}}/P_{\text{Bremsstrahlung}}$
${}^{21}\text{D}-{}^{31}\text{T}$	50	140
${}^{21}\text{D}-{}^{21}\text{D}$	500	2.9
${}^{21}\text{D}-{}^{32}\text{He}$	100	5.3
${}^{32}\text{He}-{}^{32}\text{He}$	1000	0.72
$\text{p}^+-{}^{63}\text{Li}$	800	0.21
$\text{p}^+-{}^{115}\text{B}$	300	0.57

The actual ratios of fusion to Bremsstrahlung power will likely be significantly lower for several reasons. For one, the calculation assumes that the energy of the fusion products is transmitted completely to the fuel ions, which then lose energy to the electrons by collisions, which in turn lose energy by Bremsstrahlung. However because the fusion products move much faster than the fuel ions, they will give up a significant fraction of their energy directly to the electrons. Secondly, the plasma is assumed to be composed purely of fuel ions. In practice, there will be a significant proportion of impurity ions, which will lower the ratio. In particular, the fusion products themselves *must* remain in the plasma until they have given up their energy, and *will* remain some time after that in any proposed confinement scheme. Finally, all channels of energy loss other than Bremsstrahlung have been neglected. The last two factors are related. On theoretical and experimental grounds, particle and energy confinement seem to be closely related. In a confinement scheme that does a good job of retaining energy, fusion products will build

up. If the fusion products are efficiently ejected, then energy confinement will be poor, too.

The temperatures maximizing the fusion power compared to the Bremsstrahlung are in every case higher than the temperature that maximizes the power density and minimizes the required value of the fusion triple product. This will not change the optimum operating point for ${}^{21}\text{D}$ - ${}^{31}\text{T}$ very much because the Bremsstrahlung fraction is low, but it will push the other fuels into regimes where the power density relative to ${}^{21}\text{D}$ - ${}^{31}\text{T}$ is even lower and the required confinement even more difficult to achieve. For ${}^{21}\text{D}$ - ${}^{21}\text{D}$ and ${}^{21}\text{D}$ - ${}^{32}\text{He}$, Bremsstrahlung losses will be a serious, possibly prohibitive problem. For ${}^{32}\text{He}$ - ${}^{32}\text{He}$, p^+ - ${}^{63}\text{Li}$ and p^+ - ${}^{115}\text{B}$ the Bremsstrahlung losses appear to make a fusion reactor using these fuels with a quasineutral, anisotropic plasma impossible. Some ways out of this dilemma are considered—and rejected—in *Fundamental limitations on plasma fusion systems not in thermodynamic equilibrium* by Todd Rider. This limitation does not apply to non-neutral and anisotropic plasmas; however, these have their own challenges to contend with.

A Math Book

Chapter-4

Nuclear fission

Nuclear fission

An induced fission reaction. A slow-moving neutron is absorbed by the nucleus of a uranium-235 atom, which in turn splits into fast-moving lighter elements (fission products) and three free neutrons.

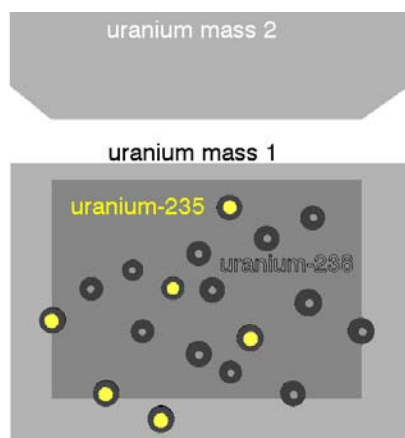
In nuclear physics and nuclear chemistry, **nuclear fission** is a nuclear reaction in which the nucleus of an atom splits into smaller parts, often producing free neutrons and lighter nuclei, which may eventually produce photons (in the form of gamma rays). Fission of heavy elements is an exothermic reaction which can release large amounts of energy both as electromagnetic radiation and as kinetic energy of the fragments (heating the bulk material where fission takes place). For fission to produce energy, the total binding energy of the resulting elements has to be higher than that of the starting element. Fission is a form of nuclear transmutation because the resulting fragments are not the same element as the original atom.

Nuclear fission produces energy for nuclear power and to drive the explosion of nuclear weapons. Both uses are made possible because certain substances called nuclear fuels undergo fission when struck by free neutrons and in turn generate neutrons when they break apart. This makes possible a self-sustaining chain reaction that releases energy at a controlled rate in a nuclear reactor or at a very rapid uncontrolled rate in a nuclear weapon.

The amount of free energy contained in nuclear fuel is millions of times the amount of free energy contained in a similar mass of chemical fuel such as gasoline, making nuclear fission a very tempting source of energy; however, the products of nuclear fission are radioactive and remain so for significant amounts of time, giving rise to a nuclear waste problem. Concerns over nuclear waste accumulation and over the destructive potential of nuclear weapons may counterbalance the desirable qualities of fission as an energy source, and give rise to ongoing political debate over nuclear power.

Physical overview

Mechanics



A 3D representation of an induced nuclear fission event where a slow-moving neutron is absorbed by the nucleus of a uranium-235 atom, which fissions into two fast-moving lighter elements (fission products) and additional neutrons. Most of the energy released is in the form of the kinetic velocities of the fission products and the neutrons. Also shown is the capture of a neutron by uranium-238 to become uranium-239.

Occasionally nuclear fission occurs without neutron bombardment, as a type of radioactive decay, but this type of fission (called spontaneous fission) is rare except in a few heavy isotopes. Most nuclear fission occurs as a "nuclear reaction"—a bombardment-driven process that results from the collision of two subatomic particles. In nuclear reactions, a subatomic particle collides with an atomic nucleus and causes changes to it. Nuclear reactions are thus driven by the mechanics of bombardment, not by the relatively constant exponential decay and half-life characteristic of spontaneous radioactive processes.

A great many nuclear reactions are known. Nuclear fission differs importantly from other types of nuclear reactions in that it can be amplified and sometimes controlled via a nuclear chain reaction. In such a reaction, free neutrons released by each fission event can trigger yet more events, which in turn release more neutrons and cause more fissions.

The chemical element isotopes that can sustain a fission chain reaction are called nuclear fuels, and are said to be fissile. The most common nuclear fuels are ^{235}U (the isotope of uranium with an atomic mass of 235 and of use in nuclear reactors) and ^{239}Pu (the isotope of plutonium with an atomic mass of 239). These fuels break apart into a bimodal range of chemical elements with atomic masses centering near 95 and 135 u (fission products). Most nuclear fuels undergo spontaneous fission only very slowly, decaying instead mainly via an alpha/beta decay chain over periods of millennia to eons. In a nuclear reactor or nuclear weapon, the overwhelming majority of fission events are induced by bombardment with another particle, a neutron, which is itself produced by prior fission events.

Energetics

Typical fission events release about two hundred million eV of energy for each fission event. By contrast, most chemical oxidation reactions (such as burning coal or TNT) release at most a few eV per event, so nuclear fuel contains at least ten million times more usable energy than does chemical fuel. The energy of nuclear fission is released as kinetic energy of the fission products and fragments, and as electromagnetic radiation in the form of gamma rays; in a nuclear reactor, the energy is converted to heat as the particles and gamma rays collide with the atoms that make up the reactor and its working fluid, usually water or occasionally heavy water.

When a uranium nucleus fissions into two daughter nuclei fragments, an energy of ~ 200 MeV is released. For uranium-235 (total mean fission energy 202.5 MeV), typically ~ 169 MeV appears as the kinetic energy of the daughter nuclei, which fly apart at about 3% of the speed of light, due to Coulomb repulsion. Also, an average of 2.5 neutrons are emitted with a kinetic energy of ~ 2 MeV each (total of 4.8 MeV). The fission reaction also releases ~ 7 MeV in prompt gamma ray photons.

This energy amounts to about 181 MeV, or $\sim 89\%$ of the total energy. The remaining $\sim 11\%$ is released in beta decays which have various half-lives, but begin as a process in the fission products immediately; and in delayed gamma emissions associated with these beta decays. For example, in uranium-235 this delayed energy is divided into about 6.5 MeV in betas, 8.8 MeV in antineutrinos (released at the same time as the betas), and finally, an additional 6.3 MeV in delayed gamma emission from the excited beta-decay products (for a mean total of ~ 10 gamma ray emissions per fission, in all).

The $8.8 \text{ MeV} / 202.5 \text{ MeV} = 4.3\%$ of the energy which is released as antineutrinos is not captured by the reactor material as heat, and escapes directly through all materials (including the Earth) at nearly the speed of light, and into interplanetary space. Almost all of the remaining radiation is converted to heat, either in the reactor core or its shielding.

Some processes involving neutrons are notable for absorbing or finally yielding energy—for example neutron kinetic energy does not yield heat immediately if the neutron is captured by a uranium-238 atom to breed plutonium-239, but this energy is emitted if the plutonium-239 is later fissioned. On the other hand, so called "delayed neutrons" emitted as radioactive decay products with half-lives up to a minute, from fission-daughters, are very important to reactor control because they give a characteristic "reaction" time for the total nuclear reaction to double in size, if the reaction is run in a "delayed-critical" zone which deliberately relies on these neutrons for a supercritical chain-reaction (one in which each fission cycle yields more neutrons than it absorbs). Without their existence, the nuclear chain-reaction would be prompt critical and increase in size faster than it could be controlled by human intervention. In this case, the first experimental atomic reactors would have run away to a dangerous and messy "prompt critical reaction" before their operators could have shut them down. If these neutrons are captured without producing fissions, they produce heat as well.

Product nuclei and binding energy

In fission there is a preference to yield fragments with even proton numbers, which is called the odd-even effect on the fragments charge distribution. However, no odd-even effect is observed on fragment **mass number** distribution. This result is attributed to nucleon pair breaking.

In nuclear fission events the nuclei may break into any combination of lighter nuclei, but the most common event is not fission to equal mass nuclei of about mass 120; the most common event (depending on isotope and process) is a slightly unequal fission in which one daughter nucleus has a mass of about 90 to 100 **u** and the other the remaining 130 to 140 **u**. Unequal fissions are energetically more favorable because this allows one product to be closer to the energetic minimum near mass 60 **u** (only a quarter of the average fissionable mass), while the other nucleus with mass 135 **u** is still not far out of the range of the most tightly bound nuclei (another statement of this, is that the atomic binding energy curve is slightly steeper to the left of mass 120 **u** than to the right of it).

Origin of the active energy and the curve of binding energy

Nuclear fission of heavy elements produces energy because the specific binding energy (binding energy per mass) of intermediate-mass nuclei with atomic numbers and atomic masses close to ^{62}Ni and ^{56}Fe is greater than the nucleon-specific binding energy of very heavy nuclei, so that energy is released when heavy nuclei are broken apart.

The total rest masses of the fission products (**M_p**) from a single reaction is less than the mass of the original fuel nucleus (**M**). The excess mass $\Delta m = M - M_p$ is the invariant mass of the energy that is released as photons (gamma rays) and kinetic energy of the fission fragments, according to the mass-energy equivalence formula $E = mc^2$. The variation in specific binding energy with atomic number is due to the interplay of the two fundamental forces acting on the component nucleons (protons and neutrons) that make up the nucleus. Nuclei are bound by an attractive strong interaction between nucleons, which overcomes the electrostatic repulsion between protons. However, the strong nuclear force acts only over extremely short ranges, since it follows a Yukawa potential. For this reason large nuclei are less tightly bound per unit mass than small nuclei, and breaking a very large nucleus into two or more intermediate-sized nuclei releases energy.

Because of the short range of the strong binding force, large nuclei must contain proportionally more neutrons than do light elements, which are most stable with a 1–1 ratio of protons and neutrons. Extra neutrons stabilize heavy elements because they add to strong-force binding without adding to proton-proton repulsion. Fission products have, on average, about the same ratio of neutrons and protons as their parent nucleus, and are therefore usually unstable because they have proportionally too many neutrons compared to stable isotopes of similar mass. This is the fundamental cause of the problem of radioactive high level waste from nuclear reactors. Fission products tend to be beta emitters, emitting fast-moving electrons to conserve electric charge as excess neutrons convert to protons inside the nucleus of the fission product atoms.

Nuclear or "fissile" fuels

The most common nuclear fuels, ^{235}U and ^{239}Pu , are not major radiological hazards by themselves: ^{235}U has a half-life of approximately 700 million years, and although ^{239}Pu has a half-life of only about 24,000 years, it is a pure alpha particle emitter and hence not particularly dangerous unless ingested. Once a fuel element has been used, the remaining fuel material is intimately mixed with highly radioactive fission products that emit energetic beta particles and gamma rays. Some fission products have half-lives as short as seconds; others have half-lives of tens of thousands of years, requiring long-term storage in facilities such as Yucca Mountain nuclear waste repository until the fission products decay into non-radioactive stable isotopes.

Chain reactions

Nuclear chain reaction

A possible nuclear fission chain reaction. 1. A uranium-235 atom absorbs a neutron, and fissions into two new atoms (fission fragments), releasing three new neutrons and a large amount of binding energy. 2. One of those neutrons is absorbed by an atom of uranium-238, and does not continue the reaction. Another neutron leaves the system without being absorbed. However, one neutron does collide with an atom of uranium-235, which then fissions and releases two neutrons and more binding energy. 3. Both of those neutrons collide with uranium-235 atoms, each of which fissions and releases a few neutrons, which can then continue the reaction.

A **nuclear chain reaction** occurs when one nuclear reaction causes an average of one or more nuclear reactions, thus leading to a self-propagating number of these reactions. The specific nuclear reaction may be the fission of heavy isotopes (e.g. ^{235}U) or the fusion of light isotopes (e.g. ^2H and ^3H). The nuclear chain reaction is unique since it releases several million times more energy per reaction than any chemical reaction.

History

The concept of a nuclear chain reaction was first realized by Hungarian scientist Leó Szilárd in 1933. He filed a patent for his idea of a simple nuclear reactor the following year.

The total quantitative chain chemical reactions theory was created by Soviet physicist N.N. Semyonov in 1934. The idea of the chain reactions, developed by Semyonov, is the basis of various high technologies using the incineration of gas mixtures. The idea was also used for the description of the nuclear reaction..

In 1936, Szilárd attempted to create a chain reaction using beryllium and indium, but was unsuccessful. In 1939, Szilárd and Enrico Fermi discovered neutron multiplication in uranium, proving that a chain reaction was indeed possible. This discovery prompted the

letter from Albert Einstein to President Franklin D. Roosevelt warning of the possibility that Nazi Germany might be attempting to build an atomic bomb.

Enrico Fermi created the first artificial self-sustaining nuclear chain reaction, called Chicago Pile-1 (CP-1), in a racquets court below the bleachers of Stagg Field at the University of Chicago on December 2, 1942. Fermi's experiments at the University of Chicago were part of Arthur H. Compton's Metallurgical Laboratory facility, which was part of the Manhattan Project.

In 1956, Paul Kuroda of the University of Arkansas postulated that a natural fission reactor may have once existed. Since nuclear chain reactions only require natural materials (such as water and uranium), it is possible to have these chain reactions occur where there is the right combination of materials within the Earth's crust. Kuroda's prediction was verified with the discovery of evidence of natural self-sustaining nuclear chain reactions in the past at Oklo in Gabon, Africa in September 1972.

Fission chain reaction

Fission chain reactions occur because of interactions between neutrons and fissile isotopes (such as ^{235}U). The chain reaction requires both the release of neutrons from fissile isotopes undergoing nuclear fission and the subsequent absorption of some of these neutrons in fissile isotopes. When an atom undergoes nuclear fission, a few neutrons (the exact number depends on several factors) are ejected from the reaction. These free neutrons will then interact with the surrounding medium, and if more fissile fuel is present, some may be absorbed and cause more fissions. Thus, the cycle repeats to give a reaction that is self-sustaining.

Nuclear power plants operate by precisely controlling the rate at which nuclear reactions occur, and that control is maintained through the use of several redundant layers of safety measures. Moreover, the materials in a nuclear reactor core and the uranium enrichment level make a nuclear explosion impossible, even if all safety measures failed. On the other hand, nuclear weapons are specifically engineered to produce a reaction that is so fast and intense it cannot be controlled after it has started. When properly designed, this uncontrolled reaction can lead to an explosive energy release.

Nuclear fission fuel

Nuclear fission weapons must use an extremely high quality, highly-enriched fuel exceeding the critical size and geometry (critical mass) in order to obtain an explosive chain reaction. The fuel for a nuclear fission reactor is very different, usually consisting of a low-enriched oxide material (e.g. UO_2). It is impossible for a nuclear power plant to undergo an explosive nuclear chain reaction. Chernobyl was a steam explosion, not a nuclear explosion. Furthermore, all power plants licensed in the United States require a negative void coefficient of reactivity, which completely eliminates the possibility of the accident that occurred at Chernobyl (which was due to a positive void coefficient).

Fission reaction products

When a heavy atom undergoes nuclear fission it breaks into two or more fission fragments. Also, several free neutrons, gamma rays, and neutrinos are emitted, and a large amount of energy is released. The sum of the masses of the fission fragments and ejected neutrons is actually less than the mass of original atom and incident neutron. The mass difference is accounted for in the release of energy according to the equation $E=mc^2$:

Due to the extremely large value of the speed of light, c , a small decrease in mass causes a tremendous release in energy. While typical chemical reactions release energies on the order of a few eVs (e.g. the binding energy of the electron to hydrogen is 13.6 eV), nuclear fission reactions typically release energies on the order of hundreds of millions of eVs.

Note that these equations are for fissions caused by slow-moving (thermal) neutrons. The average energy released and number of neutrons ejected is a function of the incident neutron speed. Also, note that these equations exclude energy from neutrinos since these subatomic particles are extremely non-reactive and, therefore, rarely deposit their energy in the system.

Timescales of nuclear chain reactions

Prompt neutron lifetime

The **prompt neutron lifetime**, l , is the average time between the emission of neutrons and either their absorption in the system or their escape from the system. The term lifetime is used because the emission of a neutron is often considered its "birth," and the subsequent absorption is considered its "death." For thermal (slow-neutron) fission reactors, the typical prompt neutron lifetime is on the order of 10^{-4} seconds, and for fast fission reactors, the prompt neutron lifetime is on the order of 10^{-7} seconds. These extremely short lifetimes mean that in 1 second, 10,000 to 10,000,000 neutron lifetimes can pass.

Mean generation time

The **mean generation time**, Λ , is the average time from a neutron emission to a capture that results in fission. The mean generation time is different from the prompt neutron lifetime because the mean generation time only includes neutron absorptions that lead to fission reactions (not other absorption reactions). The two times are related by the following formula:

In this formula, k is the effective neutron multiplication factor, described below.

Effective neutron multiplication factor

The **effective neutron multiplication factor**, k , is the average number of neutrons from one fission that cause another fission. The remaining neutrons either are absorbed in non-fission reactions or leave the system without being absorbed. The value of k determines how a nuclear chain reaction proceeds:

- $k < 1$ (subcriticality): The system cannot sustain a chain reaction, and any beginning of a chain reaction dies out over time. For every fission that is induced in the system, an average *total* of $1/(1 - k)$ fissions occur.
- $k = 1$ (criticality): Every fission causes an average of one more fission, leading to a fission (and power) level that is constant. Nuclear power plants operate with $k = 1$ unless the power level is being increased or decreased.
- $k > 1$ (supercriticality): For every fission in the material, it is likely that there will be " k " fissions after the next *mean generation time*. The result is that the number of fission reactions increases exponentially, according to the equation $e^{(k-1)t/\Lambda}$, where t is the elapsed time. Nuclear weapons are designed to operate under this state. There are two subdivisions of supercriticality: prompt and delayed.

In an infinite medium, the multiplication factor is given by the four factor formula.

Prompt and delayed supercriticality

Not all neutrons are emitted as a direct product of fission, some are instead due to the radioactive decay of some of the fission fragments. The neutrons that occur directly from fission are called "prompt neutrons," and the ones that are a result of radioactive decay of fission fragments are called "delayed neutrons." The fraction of neutrons that are delayed is called β , and this fraction is typically less than 1% of all the neutrons in the chain reaction.

The delayed neutrons allow a nuclear reactor to respond several hundred times more slowly than just prompt neutrons would alone. Without delayed neutrons, changes in reaction rates in nuclear reactors would occur at speeds that are too fast for humans to control.

The region of supercriticality between $k = 1$ and $k = 1/(1-\beta)$ is known as **delayed supercriticality** (or delayed criticality). It is in this region that all nuclear power reactors operate. The region of supercriticality for $k > 1/(1-\beta)$ is known as **prompt supercriticality** (or prompt criticality), which is the region in which nuclear weapons operate.

The change in k needed to go from critical to prompt critical is defined as a dollar.

Neutron multiplication in nuclear weapons

Nuclear fission weapons require a mass of fissile fuel that is prompt supercritical.

For a given mass of fissile material the value of k can be increased by increasing the density. Since the probability per distance traveled for a neutron to collide with a nucleus is proportional to the material density, increasing the density of a fissile material can increase k . This concept is utilized in the implosion method for nuclear weapons. In these devices, the nuclear chain reaction begins after increasing the density of the fissile material with a conventional explosive.

In the gun-type fission weapon two subcritical pieces of fuel are rapidly brought together. The value of k for a combination of two masses is always greater than that of its components. The magnitude of the difference depends on distance, as well as the physical orientation.

The value of k can also be increased by using a neutron reflector surrounding the fissile material

Once the mass of fuel is prompt supercritical, the power increases exponentially. However, the exponential power increase cannot continue for long since k decreases when the amount of fission material that is left decreases (i.e. it is consumed by fissions). Also, the geometry and density are expected to change during detonation since the remaining fission material is torn apart from the explosion.

Predetonation

Detonation of a nuclear weapon involves bringing fissile material into its optimal supercritical state very rapidly. During part of this process, the assembly is supercritical, but not yet in an optimal state for a chain reaction. Free neutrons, in particular from spontaneous fissions, can cause the device to undergo a preliminary chain reaction that destroys the fissile material before it is ready to produce a large explosion, which is known as **predetonation**. To keep the probability of predetonation low, the duration of the non-optimal assembly period is minimized and fissile and other materials are used which have low spontaneous fission rates. In fact, the combination of materials has to be such that it is unlikely that there is even a single spontaneous fission during the period of supercritical assembly. In particular, the gun method cannot be used with plutonium (see nuclear weapon design).

Fusion chain reaction

In a more generalized sense, a nuclear fusion reaction can be considered a nuclear chain reaction: it occurs under extreme pressure and temperature conditions, which are maintained by the energy released in the fusion process.

Fission reactors

Critical fission reactors are the most common type of nuclear reactor. In a critical fission reactor, neutrons produced by fission of fuel atoms are used to induce yet more fissions, to sustain a controllable amount of energy release. Devices that produce engineered but non-self-sustaining fission reactions are *subcritical fission reactors*. Such devices use radioactive decay or particle accelerators to trigger fissions.

Critical fission reactors are built for three primary purposes, which typically involve different engineering trade-offs to take advantage of either the heat or the neutrons produced by the fission chain reaction:

- *power reactors* are intended to produce heat for nuclear power, either as part of a generating station or a local power system such as a nuclear submarine.
- *research reactors* are intended to produce neutrons and/or activate radioactive sources for scientific, medical, engineering, or other research purposes.
- *breeder reactors* are intended to produce nuclear fuels in bulk from more abundant isotopes. The better known fast breeder reactor makes ^{239}Pu (a nuclear fuel) from the naturally very abundant ^{238}U (not a nuclear fuel). Thermal breeder reactors previously tested using ^{232}Th to breed the fissile isotope ^{233}U continue to be studied and developed.

While, in principle, all fission reactors can act in all three capacities, in practice the tasks lead to conflicting engineering goals and most reactors have been built with only one of the above tasks in mind. (There are several early counter-examples, such as the Hanford N reactor, now decommissioned). Power reactors generally convert the kinetic energy of fission products into heat, which is used to heat a working fluid and drive a heat engine that generates mechanical or electrical power. The working fluid is usually water with a steam turbine, but some designs use other materials such as gaseous helium. Research reactors produce neutrons that are used in various ways, with the heat of fission being treated as an unavoidable waste product. Breeder reactors are a specialized form of research reactor, with the caveat that the sample being irradiated is usually the fuel itself, a mixture of ^{238}U and ^{235}U . For a more detailed description of the physics and operating principles of critical fission reactors, see nuclear reactor physics. For a description of their social, political, and environmental aspects, see nuclear reactor.

Fission bombs



The mushroom cloud of the atom bomb dropped on Nagasaki, Japan in 1945 rose some 180 kilometers (110 miles) above the bomb's hypocenter.

One class of nuclear weapon, a *fission bomb* (not to be confused with the *fusion bomb*), otherwise known as an *atomic bomb* or *atom bomb*, is a fission reactor designed to liberate as much energy as possible as rapidly as possible, before the released energy causes the reactor to explode (and the chain reaction to stop). Development of nuclear weapons was the motivation behind early research into nuclear fission: the Manhattan Project of the U.S. military during World War II carried out most of the early scientific work on fission chain reactions, culminating in the Little Boy and Fat Man and Trinity bombs that were exploded over test sites, the cities Hiroshima, and Nagasaki, Japan in August 1945.

Even the first fission bombs were thousands of times more explosive than a comparable mass of chemical explosive. For example, Little Boy weighed a total of about four tons (of which 60 kg was nuclear fuel) and was 11 feet (3.4 m) long; it also yielded an explosion equivalent to about 15 kilotons of TNT, destroying a large part of the city of Hiroshima. Modern nuclear weapons (which include a thermonuclear *fusion* as well as one or more fission stages) are literally hundreds of times more energetic for their weight than the first pure fission atomic bombs, so that a modern single missile warhead bomb weighing less than 1/8th as much as Little Boy (see for example W88) has a yield of 475,000 tons of TNT, and could bring destruction to 10 times the city area.

While the fundamental physics of the fission chain reaction in a nuclear weapon is similar to the physics of a controlled nuclear reactor, the two types of device must be engineered quite differently (see nuclear reactor physics). It is impossible to convert a nuclear reactor to cause a true nuclear explosion, or for a nuclear reactor to explode the way a nuclear explosive does, (though partial fuel meltdowns and steam explosions have occurred), and difficult to extract useful power from a nuclear explosive (though at least one rocket propulsion system, Project Orion, was intended to work by exploding fission bombs behind a massively padded vehicle).

The strategic importance of nuclear weapons is a major reason why the technology of nuclear fission is politically sensitive. Viable fission bomb designs are, arguably, within the capabilities of bright undergraduates (see John Aristotle Phillips) being relatively simple from an engineering viewpoint. However, the difficulty of obtaining fissile nuclear material to realize the designs, is the key to the relative unavailability of nuclear weapons to all but modern industrialized governments with special programs to produce fissile materials (see uranium enrichment and nuclear fuel cycle).

History

Criticality in nature is uncommon. At three ore deposits at Oklo in Gabon, sixteen sites (the so-called Oklo Fossil Reactors) have been discovered at which self-sustaining nuclear fission took place approximately 2 billion years ago.

Ernest Rutherford is credited with splitting the atom in 1917. His team in England bombarded nitrogen with naturally occurring alpha particles from radioactive material and observed a proton emitted with energy higher than the alpha particle. In 1932 his students John Cockcroft and Ernest Walton, working under Rutherford's direction, attempted to split the nucleus by entirely artificial means, using a particle accelerator to bombard lithium with protons, thereby producing two helium nuclei.

After English physicist James Chadwick discovered the neutron in 1932, Enrico Fermi and his colleagues in Rome studied the results of bombarding uranium with neutrons in 1934. The first person who mentioned the idea of nuclear fission in 1934 was Ida Noddack.



The experimental apparatus with which the team of Lise Meitner, Otto Hahn and Fritz Strassmann discovered Nuclear Fission in 1938

After the Fermi publication, Lise Meitner, Otto Hahn and Fritz Strassmann began performing similar experiments in Germany. Meitner, an Austrian Jew, lost her citizenship with the Anschluss in 1938. She fled and wound up in Sweden, but continued to collaborate by mail and through meetings with Hahn in Sweden. By coincidence her nephew Otto Robert Frisch, also a refugee, was also in Sweden when Meitner received a letter from Hahn describing his chemical proof that some of the product of the

bombardment of uranium with neutrons, was barium and not barium's much heavier chemical sister element radium (barium's atomic weight is about 60% that of uranium). Frisch was skeptical, but Meitner trusted Hahn's ability as a chemist. Marie Curie had been separating barium from radium for many years, and the techniques were well-known. According to Frisch:

Was it a mistake? No, said Lise Meitner; Hahn was too good a chemist for that. But how could barium be formed from uranium? No larger fragments than protons or helium nuclei (alpha particles) had ever been chipped away from nuclei, and to chip off a large number not nearly enough energy was available. Nor was it possible that the uranium nucleus could have been cleaved right across. A nucleus was not like a brittle solid that can be cleaved or broken; George Gamow had suggested early on, and Bohr had given good arguments that a nucleus was much more like a liquid drop. Perhaps a drop could divide itself into two smaller drops in a more gradual manner, by first becoming elongated, then constricted, and finally being torn rather than broken in two? We knew that there were strong forces that would resist such a process, just as the surface tension of an ordinary liquid drop tends to resist its division into two smaller ones. But nuclei differed from ordinary drops in one important way: they were electrically charged, and that was known to counteract the surface tension.

The charge of a uranium nucleus, we found, was indeed large enough to overcome the effect of the surface tension almost completely; so the uranium nucleus might indeed resemble a very wobbly unstable drop, ready to divide itself at the slightest provocation, such as the impact of a single neutron. But there was another problem. After separation, the two drops would be driven apart by their mutual electric repulsion and would acquire high speed and hence a very large energy, about 200 MeV in all; where could that energy come from? ...Lise Meitner... worked out that the two nuclei formed by the division of a uranium nucleus together would be lighter than the original uranium nucleus by about one-fifth the mass of a proton. Now whenever mass disappears energy is created, according to Einstein's formula $E=mc^2$, and one-fifth of a proton mass was just equivalent to 200MeV. So here was the source for that energy; it all fitted!

In December 1938, the German chemists Otto Hahn and Fritz Strassmann sent a manuscript to *Naturwissenschaften* reporting they had detected the element barium after bombarding uranium with neutrons; simultaneously, they communicated these results to Lise Meitner. Meitner, and her nephew Otto Robert Frisch, correctly interpreted these results as being nuclear fission. Frisch confirmed this experimentally on 13 January 1939. In 1944, Hahn received the Nobel Prize for Chemistry for the discovery of nuclear fission. Some historians have documented the history of the discovery of nuclear fission and believe Meitner should have been awarded the Nobel Prize with Hahn.

Meitner's and Frisch's interpretation of the work of Hahn and Strassmann crossed the Atlantic Ocean with Niels Bohr, who was to lecture at Princeton University. Isidor Isaac Rabi and Willis Lamb, two Columbia University physicists working at Princeton, heard the news and carried it back to Columbia. Rabi said he told Enrico Fermi; Fermi gave credit to Lamb. Bohr soon thereafter went from Princeton to Columbia to see Fermi. Not finding Fermi in his office, Bohr went down to the cyclotron area and found Herbert L. Anderson. Bohr grabbed him by the shoulder and said: "Young man, let me explain to you about something new and exciting in physics." It was clear to a number of scientists at Columbia that they should try to detect the energy released in the nuclear fission of

uranium from neutron bombardment. On 25 January 1939, a Columbia University team conducted the first nuclear fission experiment in the United States, which was done in the basement of Pupin Hall; the members of the team were Herbert L. Anderson, Eugene T. Booth, John R. Dunning, Enrico Fermi, G. Norris Glasoe, and Francis G. Slack. The next day, the Fifth Washington Conference on Theoretical Physics began in Washington, D.C. under the joint auspices of the George Washington University and the Carnegie Institution of Washington. There, the news on nuclear fission was spread even further, which fostered many more experimental demonstrations.

Frédéric Joliot-Curie's team in Paris discovered that secondary neutrons are released during uranium fission, thus making a nuclear chain-reaction feasible. The figure of about two neutrons being emitted with nuclear fission of uranium was verified independently by Leo Szilárd and Walter Henry Zinn. The number of neutrons emitted with nuclear fission of ^{235}U was then reported at 3.5/fission, and later corrected to 2.6/fission by Frédéric Joliot-Curie, Hans von Halban and Lew Kowarski.

"Chain reactions" at that time were a known phenomenon in *chemistry*, but the analogous process in nuclear physics, using neutrons, had been foreseen as early as 1933 by Szilárd, although Szilárd at that time had no idea with what materials the process might be initiated (Szilárd thought it might be done with light neutron-rich elements). Szilárd, a Hungarian born Jew, also fled mainland Europe after Hitler's rise, eventually landing in the US.

With the news of fission neutrons from uranium fission, Szilárd immediately understood the possibility of a nuclear chain reaction using uranium. In the summer, Fermi and Szilard proposed the idea of a nuclear reactor (pile) to mediate this process. The pile would use natural uranium as fuel, and graphite as the moderator of neutron energy (it had previously been shown by Fermi that neutrons were far more effectively captured by atoms if they were moving slowly, a process called *moderation* when the neutrons were slowed after being released from a fission event in a nuclear reactor).

In August Hungarian-Jewish refugees Szilard, Teller and Wigner thought that the Germans might make use of the fission chain reaction. They decided to warn President Roosevelt of this possible German menace, and persuaded German-Jewish refugee Albert Einstein to lend his name. The Einstein–Szilárd letter suggested the possibility of a uranium bomb deliverable by ship, which would destroy "an entire harbor and much of the surrounding countryside." The President received the letter on 11 October 1939 — shortly after World War II began in Europe, but two years before U.S. entry into it.

In England, James Chadwick proposed an atomic bomb utilizing natural uranium, based on a paper by Rudolf Peierls with the mass needed for critical state being 30–40 tons. In America, J. Robert Oppenheimer thought that a cube of uranium deuteride 10 cm on a side (about 11 kg of uranium) might "blow itself to hell." In this design it was still thought that a moderator would need to be used for nuclear bomb fission (this turned out not to be the case if the fissile isotope was separated).

In December, Heisenberg delivered a report to the German Ministry of War on the possibility of a uranium bomb.

In Birmingham, England, Frisch teamed up with Rudolf Peierls, another German-Jewish refugee. They had the idea of using a purified mass of the uranium isotope (^{235}U). They determined that an enriched ^{235}U bomb could have a critical mass of only 600 grams, instead of tons, and that the resulting explosion would be tremendous. (The amount actually turned out to be 15 kg, although several times this amount was used in the actual uranium (Little Boy) bomb). In February 1940 they delivered the Frisch-Peierls memorandum. Ironically, they were still officially considered "enemy aliens" at the time.

Glenn Seaborg, Joe Kennedy, Art Wahl and Italian-Jewish refugee Emilio Segrè shortly discovered ^{239}Pu in the decay products of ^{239}U produced by bombarding ^{238}U with neutrons, and determined it to be fissionable like ^{235}U .

On June 28, 1941, the Office of Scientific Research and Development was formed in the U.S. to mobilize scientific resources and apply the results of research to national defense. In September, Fermi assembled his first nuclear "pile" or reactor, in an attempt to create a slow neutron induced chain reaction in uranium, but the experiment failed for lack of proper materials, or not enough of the materials which were available.

Producing a fission chain reaction in natural uranium fuel was found to be far from trivial. Early nuclear reactors did not use isotopically enriched uranium, and in consequence they were required to use large quantities of highly purified graphite as neutron moderation materials. Use of ordinary water (as opposed to heavy water) in nuclear reactors requires enriched fuel — the partial separation and relative enrichment of the rare ^{235}U isotope from the far more common ^{238}U isotope. Typically, reactors also require inclusion of extremely chemically pure neutron moderator materials such as deuterium (in heavy water), helium, beryllium, or carbon, the latter usually as graphite. (The high purity for carbon is required because many chemical impurities such as the boron-10 component of natural boron, are very strong neutron absorbers and thus poison the chain reaction.)

Production of such materials at industrial scale had to be solved for nuclear power generation and weapons production to be accomplished. Up to 1940, the total amount of uranium metal produced in the USA was not more than a few grams, and even this was of doubtful purity; of metallic beryllium not more than a few kilograms; concentrated deuterium oxide (heavy water) not more than a few kilograms. Finally, carbon had never been produced in quantity with anything like the purity required of a moderator.

The problem of producing large amounts of high purity uranium was solved by Frank Spedding using the thermite process. Ames Laboratory was established in 1942 to produce the large amounts of natural (unenriched) uranium metal that would be necessary for the research to come. The critical nuclear chain-reaction success of the Chicago Pile-1 (December 2, 1942) which used unenriched (natural) uranium, like all of the atomic "piles" which produced the plutonium for the atomic bomb, was also due specifically to

Szilard's realization that very pure graphite could be used for the moderator of even natural uranium "piles". In wartime Germany, failure to appreciate the qualities of very pure graphite led to reactor designs dependent on heavy water, which in turn was denied the Germans by Allied attacks in Norway, where heavy water was produced. These difficulties prevented the Nazis from building a nuclear reactor capable of criticality during the war.

Unknown until 1972 (but postulated by Paul Kuroda in 1956), when French physicist Francis Perrin discovered the Oklo Fossil Reactors, it was realized that nature had beaten humans to the punch. Large-scale natural uranium fission chain reactions, moderated by normal water, had occurred some 2 billion years in the past. This ancient process was able to use normal water as a moderator only because 2 billion years in the past, natural uranium was richer in the shorter-lived fissile isotope ^{235}U (about 3%), than natural uranium available today (which is only 0.7%, and must be enriched to 3% to be usable in light-water reactors).

Production of heavy elements

According to the theory, as the Universe cooled after the big bang it eventually became possible for particles as we know them to exist. The most common particles created in the big bang which are still easily observable to us today were protons (hydrogen) and electrons (in equal numbers). Some heavier elements were created as the protons collided with each other, but most of the heavy elements we see today were created inside of stars during a series of fusion stages, such as the proton-proton chain, the CNO cycle and the triple-alpha process. Progressively heavier elements are created during the evolution of a star. Since the binding energy per nucleon peaks around iron, energy is only released in fusion processes occurring below this point. Since the creation of heavier nuclei by fusion costs energy, nature resorts to the process of neutron capture. Neutrons (due to their lack of charge) are readily absorbed by a nucleus. The heavy elements are created by either a slow neutron capture process (the so-called *s* process) or by the rapid, or *r* process. The *s* process occurs in thermally pulsing stars (called AGB, or asymptotic giant branch stars) and takes hundreds to thousands of years to reach the heaviest elements of lead and bismuth. The *r* process is thought to occur in supernova explosions because the conditions of high temperature, high neutron flux and ejected matter are present. These stellar conditions make the successive neutron captures very fast, involving very neutron-rich species which then beta-decay to heavier elements, especially at the so-called waiting points that correspond to more stable nuclides with closed neutron shells (magic numbers). The *r* process duration is typically in the range of a few seconds.

Chapter-5

Nuclear reactor physics

Most nuclear reactors use a chain reaction to induce a controlled rate of nuclear fission in fissile material, releasing both energy and free neutrons. A reactor consists of an assembly of nuclear fuel (a reactor core), usually surrounded by a neutron moderator such as regular water, heavy water, graphite, or zirconium hydride, and fitted with mechanisms such as control rods that control the rate of the reaction.

Nuclear reactor physics is that branch of one, which deals with the study and application of chain reaction to induce controlled rate of fission for energy in reactors.

The physics of nuclear fission has several quirks that affect the design and behavior of nuclear reactors. This article presents a general overview of the physics of nuclear reactors and their behavior.

Criticality

In a nuclear reactor, the neutron population at any instant is a function of the rate of neutron production (due to fission processes) and the rate of neutron losses (via non-fission absorption mechanisms and leakage from the system). When a reactor's neutron population remains steady from one generation to the next (creating as many new neutrons as are lost), the fission chain reaction is self-sustaining and the reactor's condition is referred to as "critical". When the reactor's neutron production exceeds losses, characterized by increasing power level, it is considered "supercritical", and; when losses dominate, it is considered "subcritical" and exhibits decreasing power.

The "six-factor formula" is the neutron life-cycle balance equation, which includes six separate factors, the product of which is equal to the ratio of the number of neutrons in any generation to that of the previous one; this parameter is called the effective multiplication factor (k), a.k.a. K_{eff} . $k = L_f \rho L_{th} f \eta C$, where L_f = "fast non-leakage factor"; ρ = "resonance escape probability"; L_{th} = "thermal non-leakage factor"; f = "thermal fuel utilization factor"; η = "reproduction factor"; C = "fast fission factor".

$k = (\text{Neutrons produced in one generation}) / (\text{Neutrons produced in the previous generation})$ When the reactor is critical, $k = 1$. When the reactor is subcritical, $k < 1$. When the reactor is supercritical, $k > 1$.

"Reactivity" is an expression of the departure from criticality. $\delta k = (k - 1)/k$ When the reactor is critical, $\delta k = 0$. When the reactor is subcritical, $\delta k < 0$. When the reactor is supercritical, $\delta k > 0$. Reactivity is also represented by the lowercase Greek letter rho (ρ). Reactivity is commonly expressed in decimals or percentages or pcm (per cent mille) of

$\Delta k/k$. When reactivity ρ is expressed in units of delayed neutron fraction β , the unit is called the *dollar*.

If we write 'N' for the number of free neutrons in a reactor core and ' τ ' for the average lifetime of each neutron (before it either escapes from the core or is absorbed by a nucleus), then the reactor will follow differential equation (the *evolution equation*)

$$dN / dt = \alpha N / \tau$$

where α is a constant of proportionality, and dN / dt is the rate of change of the neutron count in the core. This type of differential equation describes exponential growth or exponential decay, depending on the sign of the constant α , which is just the expected number of neutrons after one average neutron lifetime has elapsed:

$$\alpha = P_{\text{impact}} P_{\text{fission}} n_{\text{avg}} - P_{\text{absorb}} - P_{\text{escape}}$$

Here, P_{impact} is the probability that a particular neutron will strike a fuel nucleus, P_{fission} is the probability that the neutron, having struck the fuel, will cause that nucleus to undergo fission, P_{absorb} is the probability that it will be absorbed by something other than fuel, and P_{escape} is the probability that it will "escape" by leaving the core altogether. n_{avg} is the number of neutrons produced, on average, by a fission event -- it is between 2 and 3 for both ^{235}U and ^{239}Pu .

If α is positive, then the core is *supercritical* and the rate of neutron production will grow exponentially until some other effect stops the growth. If α is negative, then the core is "subcritical" and the number of free neutrons in the core will shrink exponentially until it reaches an equilibrium at zero (or the background level from spontaneous fission). If α is exactly zero, then the reactor is *critical* and its output does not vary in time ($dN / dt = 0$, from above).

Nuclear reactors are engineered to reduce P_{escape} and P_{absorb} . Small, compact structures reduce the probability of direct escape by minimizing the surface area of the core, and some materials (such as graphite) can reflect some neutrons back into the core, further reducing P_{escape} .

The probability of fission, P_{fission} , depends on the nuclear physics of the fuel, and is often expressed as a cross section. Reactors are usually controlled by adjusting P_{absorb} . Control rods made of a strongly neutron-absorbent material such as cadmium or boron can be inserted into the core: any neutron that happens to impact the control rod is lost from the chain reaction, reducing α . P_{absorb} is also controlled by the recent history of the reactor core itself (see below).

Starter sources

The mere fact that an assembly is supercritical does not guarantee that it contains any free neutrons at all. At least one neutron is required to "strike" a chain reaction, and if the spontaneous fission rate is sufficiently low it may take a long time (in ^{235}U reactors, as long as many minutes) before a chance neutron encounter starts a chain reaction even if the reactor is supercritical. Most nuclear reactors include a "starter" neutron source that ensures there are always a few free neutrons in the reactor core, so that a chain reaction will begin immediately when the core is made critical. A common type of neutron source is a mixture of an alpha particle emitter such as ^{241}Am (Americium-241) with a lightweight isotope such as ^9Be (Beryllium-9). Once the chain reaction is begun, the starter source is removed from the core to prevent damage from the high neutron flux in the operating reactor core.

Subcritical multiplication

Even in a subcritical assembly such as a shut-down reactor core, any stray neutron that happens to be present in the core (for example from spontaneous fission of the fuel, from radioactive decay of fission products, or from a neutron source) will trigger an exponentially decaying chain reaction. Although the chain reaction is not self-sustaining, it acts as a multiplier that increases the equilibrium number of neutrons in the core. This *subcritical multiplication* effect can be used in two ways: as a probe of how close a core is to criticality, and as a way to generate fission power without the risks associated with a critical mass.

As a measurement technique, subcritical multiplication was used during the Manhattan Project in early experiments to determine the minimum critical masses of ^{235}U and of ^{239}Pu . It is still used today to calibrate the controls for nuclear reactors during startup, as many effects (discussed in the following sections) can change the required control settings to achieve criticality in a reactor. As a power-generating technique, subcritical multiplication allows generation of nuclear power for fission where a critical assembly is undesirable for safety or other reasons. A subcritical assembly together with a neutron source can serve as a steady source of heat to generate power from fission.

Including the effect of an external neutron source ("external" to the fission process, not physically external to the core), one can write a modified evolution equation:

$$dN / dt = \alpha N / \tau + R_{ext}$$

where R_{ext} is the rate at which the external source injects neutrons into the core. In equilibrium, the core is not changing and dN/dt is zero, so the equilibrium number of neutrons is given by:

$$N = \tau R_{ext} / (-\alpha)$$

If the core is subcritical, then α is negative so there is an equilibrium with a positive number of neutrons. If the core is close to criticality, then α is very small and thus the final number of neutrons can be made arbitrarily large.

Neutron moderators

To improve $P_{fission}$ and enable a chain reaction, uranium-fueled reactors must include a neutron moderator that interacts with newly produced fast neutrons from fission events to reduce their kinetic energy from several MeV to several eV, making them more likely to induce fission. This is because ^{235}U is much more likely to undergo fission when struck by one of these thermal neutrons than by a freshly-produced neutron from fission.

Neutron moderators are materials that interact weakly with the neutrons but absorb kinetic energy from them. Most moderators rely on either weakly bound hydrogen or a loose crystal structure of another light element such as carbon to transfer kinetic energy from the fast-moving neutrons.

Hydrogen moderators include water (H_2O), heavy water (D_2O), and zirconium hydride (ZrH_2), all of which work because a hydrogen nucleus has nearly the same mass as a free neutron: neutron- H_2O or neutron- ZrH_2 impacts excite rotational modes of the molecules (spinning them around). Deuterium nuclei (in heavy water) absorb kinetic energy less well than do light hydrogen nuclei, but they are much less likely to absorb the impacting neutron. Water or heavy water have the advantage of being transparent liquids, so that, in addition to shielding and moderating a reactor core, they permit direct viewing of the core in operation and can also serve as a working fluid for heat transfer.

Crystal structure moderators rely on a floppy crystal matrix to absorb phonons from neutron-crystal impacts. Graphite is the most common example of such a moderator. It was used in Chicago Pile-1, the world's first man-made critical assembly, and was commonplace in early reactor designs including the Soviet RBMK nuclear power plants, of which the Chernobyl plant was one.

Moderators and reactor design

The amount and nature of neutron moderation affects reactor controllability and hence safety. Because moderators both slow and absorb neutrons, there is an optimum amount of moderator to include in a given geometry of reactor core. Less moderation reduces the effectiveness by reducing the $P_{fission}$ term in the evolution equation, and more moderation reduces the effectiveness by increasing the P_{escape} term.

Most moderators become less effective with increasing temperature, so *under-moderated* reactors are stable against changes in temperature in the reactor core: if the core overheats, then the quality of the moderator is reduced and the reaction tends to slow down (there is a "negative temperature coefficient" in the reactivity of the core). Water is

an extreme case: in extreme heat, it can boil, producing effective voids in the reactor core without destroying the physical structure of the core; this tends to shut down the reaction and reduce the possibility of a fuel meltdown. *Over-moderated* reactors are unstable against changes in temperature (there is a "positive temperature coefficient" in the reactivity of the core), and so are less inherently safe than under-moderated cores.

Most reactors in use today use a combination of moderator materials. For example, TRIGA type research reactors use ZrH_2 moderator mixed with the ^{235}U fuel, an H_2O -filled core, and C (graphite) moderator and reflector blocks around the periphery of the core.

Delayed neutrons and controllability

Fission reactions and subsequent neutron escape happen very quickly; this is important for nuclear weapons, where the object is to make a nuclear core release as much energy as possible before it physically explodes. Most neutrons emitted by fission events are prompt: they are emitted essentially instantaneously. Once emitted, the average neutron lifetime (τ) in a typical core is on the order of a millisecond, so if the exponential factor α is as small as 0.01, then in one second the reactor power will vary by a factor of $(1+0.01)^{1000}$, or more than ten thousand. Nuclear weapons are engineered to maximize the power growth rate, with lifetimes well under a millisecond and exponential factors close to 2; but such rapid variation would render it practically impossible to control the reaction rates in a nuclear reactor.

Fortunately, the *effective* neutron lifetime is much longer than the average lifetime of a single neutron in the core. About 0.65% of the neutrons produced by ^{235}U fission, and about 0.75% of the neutrons produced by ^{239}Pu fission, are not produced immediately, but rather are emitted by radioactive decay of fission products, with an average lifetime of about 15 seconds. These delayed neutrons increase the effective average lifetime of neutrons in the core, to nearly 0.1 seconds, so that a core with α of 0.01 would increase in one second by only a factor of $(1+0.01)^{10}$, or about 1.1 -- a 10% increase. This is a controllable rate of change.

Most nuclear reactors are hence operated in a *prompt subcritical, delayed critical* condition: the prompt neutrons alone are not sufficient to sustain a chain reaction, but the delayed neutrons make up the small difference required to keep the reaction going. This has effects on how reactors are controlled: when a small amount of control rod is slid into or out of the reactor core, the power level changes at first very rapidly due to *prompt subcritical multiplication* and then more gradually, following the exponential growth or decay curve of the delayed critical reaction. Further, *increases* in reactor power can be performed at any desired rate simply by pulling out a sufficient length of control rod -- but *decreases* are limited in speed, because even if the reactor is taken deeply subcritical, the delayed neutrons are produced by ordinary radioactive decay of fission products and that decay cannot be hastened.

Reactor poisons

Nuclear poison

Any element that strongly absorbs neutrons is called a reactor poison, because it tends to shut down (poison) an ongoing fission chain reaction. Some reactor poisons are deliberately inserted into fission reactor cores to control the reaction; boron or cadmium control rods are the best example. Many reactor poisons are produced by the fission process itself, and buildup of neutron-absorbing fission products affects both the fuel economics and the controllability of nuclear reactors.

Long-lived poisons and fuel reprocessing

In practice, buildup of reactor poisons in nuclear fuel is what determines the lifetime of nuclear fuel in a reactor: long before all possible fissions have taken place, buildup of long-lived neutron absorbing fission products damps out the chain reaction. This is the reason that nuclear reprocessing is a useful activity: spent nuclear fuel contains about 99% of the original fissionable material present in newly manufactured nuclear fuel. Chemical separation of the fission products restores the nuclear fuel so that it can be used again.

Nuclear reprocessing is useful economically because chemical separation is much simpler to accomplish than the difficult isotope separation required to prepare nuclear fuel from natural uranium ore, so that in principle chemical separation yields more generated energy for less effort than mining, purifying, and isotopically separating new uranium ore. In practice, both the difficulty of handling the highly radioactive fission products and other political concerns make fuel reprocessing a contentious subject. One such concern is the fact that spent uranium nuclear fuel contains significant quantities of ^{239}Pu , a prime ingredient in nuclear weapons (see breeder reactor).

Short-lived poisons and controllability

Short-lived reactor poisons in fission products strongly affect how nuclear reactors can operate. Unstable fission product nuclei transmute into many different elements (*secondary fission products*) as they undergo a decay chain to a stable isotope. The most important such element is xenon, because the isotope ^{135}Xe , a secondary fission product with a half-life of about 9 hours, is an extremely strong neutron absorber. In an operating reactor, each nucleus of ^{135}Xe is destroyed by neutron capture almost as soon as it is created, so that there is no buildup in the core. However, when a reactor shuts down, the level of ^{135}Xe builds up in the core for about 9 hours before beginning to decay. The result is that, about 6-8 hours after a reactor is shut down, it can become physically impossible to restart the chain reaction until the ^{135}Xe has had a chance to decay over the next several hours; this is one reason why nuclear power reactors are best operated at an even power level around the clock.

^{135}Xe buildup in a reactor core makes it extremely dangerous to operate the reactor a few hours after it has been shut down. Because the ^{135}Xe absorbs neutrons strongly, starting a reactor in a high-Xe condition requires pulling the control rods out of the core much farther than normal. But if the reactor does achieve criticality, then the neutron flux in the core will become quite high and the ^{135}Xe will be destroyed rapidly -- this has the same effect as very rapidly removing a great length of control rod from the core, and can cause the reaction to grow too rapidly or even become prompt critical.

^{135}Xe played a large part in the Chernobyl accident: about eight hours after a scheduled maintenance shutdown, workers tried to bring the reactor to a zero power critical condition to test a control circuit, but because the core was loaded with ^{135}Xe from the previous day's power generation, the reaction rapidly grew uncontrollably, leading to steam explosion in the core, fire, and violent destruction of the facility.

Uranium enrichment

While many fissionable isotopes exist in nature, the only usefully fissile isotope found in any quantity is ^{235}U (see, e.g., the League of Women Voters' "Nuclear Waste Primer"); about 0.7% of the uranium in most ores is the ^{235}U isotope, and about 99.3% is the inert ^{238}U isotope. For most uses as a nuclear fuel, uranium must be *enriched* - purified so that it contains a higher percentage of ^{235}U . Because ^{238}U absorbs fast neutrons, uranium nuclear weapons require their uranium fuel to be ~90% ^{235}U to work. Nuclear reactors with water moderator can operate with only moderate enrichment of ~5% ^{235}U . Nuclear reactors with heavy water moderation can operate with natural uranium, eliminating altogether the need for enrichment and preventing the fuel from being useful for nuclear weapons; the CANDU power reactors used in Canadian power plants are an example of this type.

Uranium enrichment is extremely difficult, because the chemical properties of ^{235}U and ^{238}U are identical, so physical processes such as gas diffusion, Gas centrifugation or mass spectrometry must be used to separate the isotopes based on their slightly different mass. Because enrichment is the main technical hurdle to production of nuclear fuel and simple nuclear weapons, enrichment technology is politically sensitive.

Oklo: a natural nuclear reactor

Natural nuclear fission reactor

Natural nuclear fission reactor

Geological situation in Gabon leading to natural nuclear fission reactors

1. Nuclear reactor zones
2. Sandstone

3. Uranium ore layer
4. Granite

A **natural nuclear fission reactor** is a uranium deposit where analysis of isotope ratios has shown that self-sustaining nuclear chain reactions have occurred. The existence of this phenomenon was discovered in 1972 by French physicist Francis Perrin. The conditions under which a natural nuclear reactor could exist were predicted in 1956 by P. Kuroda. The conditions found at Oklo were very similar to what was predicted.

At the only known location, three ore deposits at Oklo in Gabon, sixteen sites have been discovered at which self-sustaining nuclear fission reactions took place approximately 2 billion years ago, and ran for a few hundred thousand years, averaging 100 kW of power output during that time.

History

In May 1972 at the Pierrelatte uranium enrichment facility in France, routine mass spectrometry comparing UF_6 samples from the Oklo Mine, located in Gabon, Central Africa, showed a discrepancy in the amount of the ^{235}U isotope. Normally the concentration is 0.7202%; these samples had only 0.7171% – a significant difference. This discrepancy required explanation, as all uranium handling facilities must meticulously account for all fissionable isotopes to assure that none are diverted for weapons purposes. Thus the French Commissariat à l'énergie atomique (CEA) began an investigation. A series of measurements of the relative abundances of the two most significant isotopes of the uranium mined at Oklo showed anomalous results compared to those obtained for uranium from other mines. Further investigations into this uranium deposit discovered uranium ore with a ^{235}U to ^{238}U ratio as low as 0.440%. Subsequent examination of other isotopes showed similar anomalies, such as Nd and Ru as described in more detail below.

This loss in ^{235}U is exactly what happens in a nuclear reactor. A possible explanation therefore was that the uranium ore had operated as a natural fission reactor. Other observations led to the same conclusion, and on September 25, 1972, the CEA announced their finding that self-sustaining nuclear chain reactions had occurred on Earth about 2 billion years ago. Later, other natural nuclear fission reactors were discovered in the region.

Fission product isotope signatures

Nd

The isotope signatures of natural neodymium and fission product neodymium from U-235 which had been subjected to thermal neutrons. Note that the Ce-142 (a long

lived beta emitter) has not had time to decay to Nd-142 over the time since the reactors stopped working.

Neodymium and other elements were found with isotopic compositions different from what is customarily found on Earth. For example, natural neodymium contains 27% ^{142}Nd ; the Nd at Oklo contained less than 6% but contained more ^{143}Nd . Subtracting the natural isotopic Nd abundance from the Oklo-Nd, the isotopic composition matched that produced by the fissioning of ^{235}U .

Ru

The isotope signatures of natural ruthenium and fission product ruthenium from U-235 which had been subjected to thermal neutrons. Note that the Mo-100 (a long lived double beta emitter) has not had time to decay to Ru-100 over the time since the reactors stopped working.

Similar investigations into the isotopic ratios of ruthenium at Oklo found a much higher ^{99}Ru concentration than expected (27-30% vs. 12.7%). This anomaly could be explained by the decay of ^{99}Tc to ^{99}Ru . In the bar chart below the normal natural isotope signature of ruthenium is compared with that for fission product ruthenium which is the result of the fission of ^{235}U with thermal neutrons. It is clear that the fission ruthenium has a different isotope signature. The level of ^{100}Ru in the fission product mixture is low because of a long lived (half life = 10^{19} years) isotope of molybdenum. On the time scale of when the reactors were in operation very little decay to ^{100}Ru will have occurred.

Mechanism of the reactors

The natural nuclear reactor formed when a uranium-rich mineral deposit became inundated with groundwater that acted as a neutron moderator, and a nuclear chain reaction took place. The heat generated from the nuclear fission caused the groundwater to boil away, which slowed or stopped the reaction. After cooling of the mineral deposit, short-lived fission product poisons decayed, the water returned and the reaction started again. These fission reactions were sustained for hundreds of thousands of years, until a chain reaction could no longer be supported.

Fission of uranium normally produces five known isotopes of the fission-product gas xenon; all five have been found trapped in the remnants of the natural reactor, in varying concentrations. The concentrations of xenon isotopes, found trapped in mineral formations 2 billion years later, make it possible to calculate the specific time intervals of reactor operation: approximately 2 hours and 30 minutes.

A key factor that made the reaction possible was that, at the time the reactor went critical, the fissile isotope ^{235}U made up about 3% of the natural uranium, which is comparable to the amount used in some of today's reactors. (The remaining 97% was non-fissile ^{238}U .) Because ^{235}U has a shorter half life than ^{238}U , and thus decays more rapidly, the current abundance of ^{235}U in natural uranium is about 0.7%. A natural nuclear reactor is therefore no longer possible on Earth.

The Oklo uranium ore deposits are the only known in which natural nuclear reactors existed. Other rich uranium ore bodies would also have had sufficient uranium to support nuclear reactions at that time, but the combination of uranium, water and physical conditions needed to support the chain reaction was unique to the Oklo ore bodies.

Another factor which probably contributed to the start of the Oklo natural nuclear reactor at 2 billion years, rather than earlier, was the increasing oxygen content in the Earth's atmosphere. Uranium is naturally present in the rocks of the earth, and the abundance of fissionable ^{235}U was at least 3% or higher at all times prior to reactor startup. However, uranium is soluble in water only in the presence of oxygen. Therefore, the rising oxygen levels during the aging of earth may have allowed uranium to be dissolved and transported with groundwater to places where a high enough concentration could accumulate to form rich uranium ore bodies. Without the new aerobic environment available on earth at the time, these concentrations probably couldn't have taken place.

It is estimated that nuclear reactions in the uranium in centimeter- to meter-sized veins consumed about five tons of ^{235}U and elevated temperatures to a few hundred degrees Celsius. Remarkably, most of the non-volatile fission products and actinides have only moved centimeters in the veins during the last 2 billion years. This offers a case study of how radioactive isotopes migrate through the Earth's crust—a significant area of controversy as opponents of geologic nuclear waste disposal fear that releases from stored waste could end up in water supplies or be carried into the environment.

Relation to the atomic fine-structure constant

The natural reactor of Oklo has been used to check if the atomic fine-structure constant α might have changed over the past 2 billion years. That is because α influences the rate of various nuclear reactions. For example, ^{149}Sm captures a neutron to become ^{150}Sm , and since the rate of neutron capture depends on the value of α , the ratio of the two samarium isotopes in samples from Oklo can be used to calculate the value of α from 2 billion years ago.

Several studies have analysed the relative concentrations of radioactive isotopes left behind at Oklo, and most (but not all) have concluded that nuclear reactions then were much the same as they are today, which implies α was the same too.

The ^{149}Sm resonance is sensitive to changes in the proton-to-electron mass ratio, μ , as well as changes in α . It may be that some cancellation occurs between these two, and so a null result does not necessarily mean that both α and μ have been constant over this time period.

Modern deposits of uranium contain only up to $\sim 0.7\%$ ^{235}U (and $\sim 99.3\%$ ^{238}U), which is not enough to sustain a chain reaction moderated by ordinary water. But ^{235}U has a much shorter half-life (700 million years) than ^{238}U (4.5 billion years), so in the distant past the percentage of ^{235}U was much higher. About two billion years ago, a water-saturated uranium deposit (in what is now the Oklo mine in Gabon, West Africa) underwent a naturally occurring chain reaction that was moderated by groundwater and, presumably, controlled by the negative void coefficient as the water boiled from the heat of the reaction. Uranium from the Oklo mine is about 50% depleted compared to other locations: it is only about 0.3% to 0.7% ^{235}U ; and the ore contains traces of stable daughters of long-decayed fission products.

A Math Book

Chapter-6

Nuclear power



The Ikata Nuclear Power Plant, a pressurized water reactor that cools by secondary coolant exchange with the ocean.



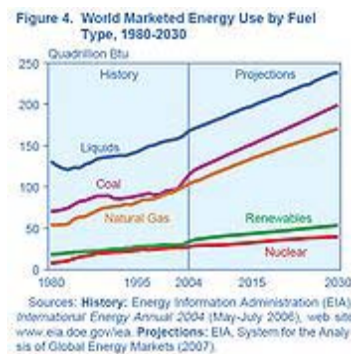
The Susquehanna Steam Electric Station, a boiling water reactor. The reactors are located inside the rectangular containment buildings towards the front of the cooling towers.



Three nuclear powered ships, (top to bottom) nuclear cruisers USS Bainbridge and USS Long Beach with *USS Enterprise* the first nuclear powered aircraft carrier in 1964. Crew members are spelling out Einstein's mass-energy equivalence formula $E=mc^2$ on the flight deck.

Nuclear power is any nuclear technology designed to extract usable energy from atomic nuclei via controlled nuclear reactions. The only method in use today produces power via nuclear fission, though other methods might one day include nuclear fusion and radioactive decay (see below). All utility-scale reactors heat water to produce steam, which is then converted into mechanical work for the purpose of generating electricity or propulsion. In 2007, 14% of the world's electricity came from nuclear power. Also, more than 150 nuclear-powered naval vessels have been built, and a few radioisotope rockets have been produced.

Use



Historical and projected world energy use by energy source, 1980-2030, Source: International Energy Outlook 2007, EIA.

Nuclear power installed capacity and generation, 1980 to 2007 (EIA).

As of 2005, nuclear power provided 2.1% of the world's energy and 15% of the world's electricity, with the U.S., France, and Japan together accounting for 56.5% of nuclear generated electricity. In 2007, the IAEA reported there were 439 nuclear power reactors in operation in the world, operating in 31 countries.

In 2007, nuclear power's share of global electricity generation dropped to 14%. According to the International Atomic Energy Agency, the main reason for this was an earthquake in western Japan on 16 July 2007, which shut down all seven reactors at the Kashiwazaki-Kariwa Nuclear Power Plant. There were also several other reductions and "unusual outages" experienced in Korea and Germany. Also, increases in the load factor for the current fleet of reactors appear to have plateaued.

The United States produces the most nuclear energy, with nuclear power providing 19% of the electricity it consumes, while France produces the highest percentage of its electrical energy from nuclear reactors—78% as of 2006. In the European Union as a whole, nuclear energy provides 30% of the electricity. Nuclear energy policy differs between European Union countries, and some, such as Austria, Estonia, and Ireland, have

no active nuclear power stations. In comparison, France has a large number of these plants, with 16 multi-unit stations in current use.

In the US, while the Coal and Gas Electricity industry is projected to be worth \$85 billion by 2013, Nuclear Power generators are forecast to be worth \$18 billion.

Many military and some civilian (such as some icebreaker) ships use nuclear marine propulsion, a form of nuclear propulsion. A few space vehicles have been launched using full-fledged nuclear reactors: the Soviet RORSAT series and the American SNAP-10A.

International research is continuing into safety improvements such as passively safe plants, the use of nuclear fusion, and additional uses of process heat such as hydrogen production (in support of a hydrogen economy), for desalinating sea water, and for use in district heating systems.

History

Origins

After James Chadwick discovered the neutron in 1932, nuclear fission was first experimentally achieved by Enrico Fermi in 1934 in Rome, when his team bombarded uranium with neutrons. In 1938, German chemists Otto Hahn and Fritz Strassmann, along with Austrian physicists Lise Meitner and Meitner's nephew, Otto Robert Frisch, conducted experiments with the products of neutron-bombarded uranium. They determined that the relatively tiny neutron split the nucleus of the massive uranium atoms into two roughly equal pieces, which was a surprising result. Numerous scientists, including Leo Szilard who was one of the first, recognized that if fission reactions released additional neutrons, a self-sustaining nuclear chain reaction could result. This spurred scientists in many countries (including the United States, the United Kingdom, France, Germany, and the Soviet Union) to petition their government for support of nuclear fission research.

In the United States, where Fermi and Szilard had both emigrated, this led to the creation of the first man-made reactor, known as Chicago Pile-1, which achieved criticality on December 2, 1942. This work became part of the Manhattan Project, which built large reactors at the Hanford Site (formerly the town of Hanford, Washington) to breed plutonium for use in the first nuclear weapons, which were used on the cities of Hiroshima and Nagasaki. A parallel uranium enrichment effort also was pursued.

After World War II, the fear that reactor research would encourage the rapid spread of nuclear weapons and technology, combined with what many scientists thought would be a long road of development, created a situation in which the government attempted to keep reactor research under strict government control and classification. In addition, most reactor research centered on purely military purposes. Actually, there were no secrets to the technology. There was an immediate arms and development race when the United States military refused to follow the advice of its own scientific community to form an

international cooperative to share information and control nuclear materials. By 2006, things have come full circle with the Global Nuclear Energy Partnership (see below.)

Electricity was generated for the first time by a nuclear reactor on December 20, 1951 at the EBR-I experimental station near Arco, Idaho, which initially produced about 100 kW (the Arco Reactor was also the first to experience partial meltdown, in 1955). In 1952, a report by the Paley Commission (*The President's Materials Policy Commission*) for President Harry Truman made a "relatively pessimistic" assessment of nuclear power, and called for "aggressive research in the whole field of solar energy." A December 1953 speech by President Dwight Eisenhower, "Atoms for Peace," emphasized the useful harnessing of the atom and set the U.S. on a course of strong government support for international use of nuclear power.

Early years



Calder Hall nuclear power station in the United Kingdom was the world's first nuclear power station to produce electricity in commercial quantities.



The Shippingport Atomic Power Station in Shippingport, Pennsylvania was the first commercial reactor in the USA and was opened in 1957.

On June 27, 1954, the USSR's Obninsk Nuclear Power Plant became the world's first nuclear power plant to generate electricity for a power grid, and produced around 5 megawatts of electric power.

Later in 1954, Lewis Strauss, then chairman of the United States Atomic Energy Commission (U.S. AEC, forerunner of the U.S. Nuclear Regulatory Commission and the United States Department of Energy) spoke of electricity in the future being "too cheap to meter." The U.S. AEC itself had issued far more conservative testimony regarding

nuclear fission to the U.S. Congress only months before, projecting that "costs can be brought down... [to] ... about the same as the cost of electricity from conventional sources..." Strauss may have been making vague reference to hydrogen fusion - which was secret at the time - rather than uranium fission, but whatever his intent Strauss's statement was interpreted by much of the public as a promise of very cheap energy from nuclear fission. Significant disappointment would develop later on, when the new nuclear plants did not provide energy "too cheap to meter."

In 1955 the United Nations' "First Geneva Conference", then the world's largest gathering of scientists and engineers, met to explore the technology. In 1957 EURATOM was launched alongside the European Economic Community (the latter is now the European Union). The same year also saw the launch of the International Atomic Energy Agency (IAEA).

The world's first commercial nuclear power station, Calder Hall in Sellafield, England was opened in 1956 with an initial capacity of 50 MW (later 200 MW). The first commercial nuclear generator to become operational in the United States was the Shippingport Reactor (Pennsylvania, December, 1957).

One of the first organizations to develop nuclear power was the U.S. Navy, for the purpose of propelling submarines and aircraft carriers. It has a good record in nuclear safety, perhaps because of the stringent demands of Admiral Hyman G. Rickover, who was the driving force behind nuclear marine propulsion as well as the Shippingport Reactor. The U.S. Navy has operated more nuclear reactors than any other entity, including the Soviet Navy, ^[dubious – discuss] with no publicly known major incidents. The first nuclear-powered submarine, USS *Nautilus* (SSN-571), was put to sea in December 1954. Two U.S. nuclear submarines, USS *Scorpion* and USS *Thresher*, have been lost at sea. These vessels were both lost due to malfunctions in systems not related to the reactor plants. Also, the sites are monitored and no known leakage has occurred from the onboard reactors.

The United States Army also had a nuclear power program, beginning in 1954. The SM-1 Nuclear Power Plant, at Ft. Belvoir, Va., was the first power reactor in the US to supply electrical energy to a commercial grid (VEPCO), in April 1957, *before* Shippingport.

Enrico Fermi and Leó Szilárd in 1955 shared U.S. Patent 2,708,656 for the nuclear reactor, belatedly granted for the work they had done during the Manhattan Project.

Development

History of the use of nuclear power (top) and the number of active nuclear power plants (bottom).

Installed nuclear capacity initially rose relatively quickly, rising from less than 1 gigawatt (GW) in 1960 to 100 GW in the late 1970s, and 300 GW in the late 1980s. Since the late

1980s worldwide capacity has risen much more slowly, reaching 366 GW in 2005. Between around 1970 and 1990, more than 50 GW of capacity was under construction (peaking at over 150 GW in the late 70s and early 80s) — in 2005, around 25 GW of new capacity was planned. More than two-thirds of all nuclear plants ordered after January 1970 were eventually cancelled.



Washington Public Power Supply System Nuclear Power Plants 3 and 5 were never completed.

During the 1970s and 1980s rising economic costs (related to extended construction times largely due to regulatory changes and pressure-group litigation) and falling fossil fuel prices made nuclear power plants then under construction less attractive. In the 1980s (U.S.) and 1990s (Europe), flat load growth and electricity liberalization also made the addition of large new baseload capacity unattractive.

The 1973 oil crisis had a significant effect on countries, such as France and Japan, which had relied more heavily on oil for electric generation (39% and 73% respectively) to invest in nuclear power. Today, nuclear power supplies about 80% and 30% of the electricity in those countries, respectively.

A general movement against nuclear power arose during the last third of the 20th century, based on the fear of a possible nuclear accident as well as the history of accidents, fears of radiation as well as the history of radiation of the public, nuclear proliferation, and on the opposition to nuclear waste production, transport and lack of any final storage plans. Perceived risks on the citizens' health and safety, the 1979 accident at Three Mile Island and the 1986 Chernobyl disaster played a part in stopping new plant construction in many countries, although the public policy organization Brookings Institution suggests that new nuclear units have not been ordered in the U.S. because the Institution's research concludes they cost 15–30 % more over their lifetime than conventional coal and natural gas fired plants.

Unlike the Three Mile Island accident, the much more serious Chernobyl accident did not increase regulations affecting Western reactors since the Chernobyl reactors were of the problematic RBMK design only used in the Soviet Union, for example lacking "robust" containment buildings. Many of these reactors are still in use today. However, changes were made in both the reactors themselves (use of low enriched uranium) and in the control system (prevention of disabling safety systems) to reduce the possibility of a duplicate accident.

An international organization to promote safety awareness and professional development on operators in nuclear facilities was created: WANO; World Association of Nuclear Operators.

Opposition in Ireland, and Poland prevented nuclear programs there, while Austria (1978), Sweden (1980) and Italy (1987) (influenced by Chernobyl) voted in referendums to oppose or phase out nuclear power. In July 2009, the Italian Parliament passed a law that canceled the results of an earlier referendum and allowed the immediate start of the Italian nuclear program.

Economics

Economics of new nuclear power plants

The economics of nuclear power plants are primarily influenced by the high initial investment necessary to construct a plant. In 2009, estimates for the cost of a new plant in the U.S. ranged from \$6 to \$10 billion. It is therefore usually more economical to run them as long as possible, or construct additional reactor blocks in existing facilities. In 2008, new nuclear power plant construction costs were rising faster than the costs of other types of power plants.^{[31][32]} A prestigious panel assembled for a 2003 MIT study of the industry found the following:

In deregulated markets, nuclear power is not now cost competitive with coal and natural gas. However, plausible reductions by industry in capital cost, operation and maintenance costs, and construction time could reduce the gap. Carbon emission credits, if enacted by government, can give nuclear power a cost advantage.

—The Future of Nuclear Power

Comparative economics with other power sources are also discussed in the Main article above and in nuclear power debate.

Future of the industry



Diablo Canyon Power Plant in San Luis Obispo County, California, USA

As of 2007, Watts Bar 1, which came on-line in February 7, 1996, was the last U.S. commercial nuclear reactor to go on-line. This is often quoted as evidence of a successful worldwide campaign for nuclear power phase-out. However, even in the U.S. and throughout Europe, investment in research and in the nuclear fuel cycle has continued, and some nuclear industry experts predict electricity shortages, fossil fuel price increases, global warming and heavy metal emissions from fossil fuel use, new technology such as passively safe plants, and national energy security will renew the demand for nuclear power plants.

According to the World Nuclear Association, globally during the 1980s one new nuclear reactor started up every 17 days on average, and by the year 2015 this rate could increase to one every 5 days.

Many countries remain active in developing nuclear power, including Pakistan, Japan, China and India, all actively developing both fast and thermal technology, South Korea and the United States, developing thermal technology only, and South Africa and China, developing versions of the Pebble Bed Modular Reactor (PBMR). Several EU member states actively pursue nuclear programs, while some other member states continue to have a ban for the nuclear energy use. Japan has an active nuclear construction program with new units brought on-line in 2005. In the U.S., three consortia responded in 2004 to the U.S. Department of Energy's solicitation under the Nuclear Power 2010 Program and were awarded matching funds—the Energy Policy Act of 2005 authorized loan guarantees for up to six new reactors, and authorized the Department of Energy to build a reactor based on the Generation IV Very-High-Temperature Reactor concept to produce both electricity and hydrogen. As of the early 21st century, nuclear power is of particular interest to both China and India to serve their rapidly growing economies—both are developing fast breeder reactors. (See also energy development). In the energy policy of the United Kingdom it is recognized that there is a likely future energy supply shortfall, which may have to be filled by either new nuclear plant construction or maintaining existing plants beyond their programmed lifetime.

There is a possible impediment to production of nuclear power plants as only a few companies worldwide have the capacity to forge single-piece containment vessels, which reduce the risk of a radiation leak. Utilities across the world are submitting orders years in advance of any actual need for these vessels. Other manufacturers are examining various options, including making the component themselves, or finding ways to make a similar item using alternate methods. Other solutions include using designs that do not require single-piece forged pressure vessels such as Canada's Advanced CANDU Reactors or Sodium-cooled Fast Reactors.

This graph illustrates the potential rise in CO₂ emissions if base-load electricity currently produced in the U.S. by nuclear power were replaced by coal or natural gas as current reactors go offline after their 60 year licenses expire. Note: graph assumes all 104 American nuclear power plants receive license extensions out to 60 years.

A 2007 status report from the anti-nuclear European Greens claimed that, "even if Finland and France build a European Pressurized water Reactor (EPR), China started an additional 20 plants and Japan, Korea or Eastern Europe added one or the other plant, the overall global trend for nuclear power capacity will most likely be downwards over the next two or three decades. With extremely long lead times of 10 years and more [for plant construction], it is practically impossible to increase or even maintain the number of operating nuclear power plants over the next 20 years, unless operating lifetimes would be substantially increased beyond 40 years on average." In fact, China plans to build more than 100 plants, while in the US the licenses of almost half its reactors have already been extended to 60 years, and plans to build more than 30 new ones are under consideration. Further, the U.S. NRC and the U.S. Department of Energy have initiated research into Light water reactor sustainability which is hoped will lead to allowing extensions of reactor licenses beyond 60 years, in increments of 20 years, provided that safety can be maintained, as the loss in non-CO₂-emitting generation capacity by retiring reactors "may serve to challenge U.S. energy security, potentially resulting in increased greenhouse gas emissions, and contributing to an imbalance between electric supply and demand." In 2008, the International Atomic Energy Agency (IAEA) predicted that nuclear power capacity could double by 2030, though that would not be enough to increase nuclear's share of electricity generation.

Nuclear reactor technology

Nuclear reactor technology

Just as many conventional thermal power stations generate electricity by harnessing the thermal energy released from burning fossil fuels, nuclear power plants convert the energy released from the nucleus of an atom, typically via nuclear fission.

When a relatively large fissile atomic nucleus (usually uranium-235 or plutonium-239) absorbs a neutron, a fission of the atom often results. Fission splits the atom into two or more smaller nuclei with kinetic energy (known as fission products) and also releases gamma radiation and free neutrons. A portion of these neutrons may later be absorbed by other fissile atoms and create more fissions, which release more neutrons, and so on.

This nuclear chain reaction can be controlled by using neutron poisons and neutron moderators to change the portion of neutrons that will go on to cause more fissions. Nuclear reactors generally have automatic and manual systems to shut the fission reaction down if unsafe conditions are detected.

A cooling system removes heat from the reactor core and transports it to another area of the plant, where the thermal energy can be harnessed to produce electricity or to do other useful work. Typically the hot coolant will be used as a heat source for a boiler, and the pressurized steam from that boiler will power one or more steam turbine driven electrical generators.

There are many different reactor designs, utilizing different fuels and coolants and incorporating different control schemes. Some of these designs have been engineered to meet a specific need. Reactors for nuclear submarines and large naval ships, for example, commonly use highly enriched uranium as a fuel. This fuel choice increases the reactor's power density and extends the usable life of the nuclear fuel load, but is more expensive and a greater risk to nuclear proliferation than some of the other nuclear fuels.

A number of new designs for nuclear power generation, collectively known as the Generation IV reactors, are the subject of active research and may be used for practical power generation in the future. Many of these new designs specifically attempt to make fission reactors cleaner, safer and/or less of a risk to the proliferation of nuclear weapons. Passively safe plants (such as the ESBWR) are available to be built and other designs that are believed to be nearly fool-proof are being pursued. Fusion reactors, which may be viable in the future, diminish or eliminate many of the risks associated with nuclear fission.

Life cycle

The Nuclear Fuel Cycle begins when uranium is mined, enriched, and manufactured into nuclear fuel, (1) which is delivered to a nuclear power plant. After usage in the power plant, the spent fuel is delivered to a reprocessing plant (2) or to a final repository (3) for geological disposition. In reprocessing 95% of spent fuel can be recycled to be returned to usage in a power plant (4).
Nuclear fuel cycle

A nuclear reactor is only part of the life-cycle for nuclear power. The process starts with mining (see *Uranium mining*). Uranium mines are underground, open-pit, or in-situ leach mines. In any case, the uranium ore is extracted, usually converted into a stable and compact form such as yellowcake, and then transported to a processing facility. Here, the yellowcake is converted to uranium hexafluoride, which is then enriched using various techniques. At this point, the enriched uranium, containing more than the natural 0.7% U-235, is used to make rods of the proper composition and geometry for the particular reactor that the fuel is destined for. The fuel rods will spend about 3 operational cycles (typically 6 years total now) inside the reactor, generally until about 3% of their uranium has been fissioned, then they will be moved to a spent fuel pool where the short lived isotopes generated by fission can decay away. After about 5 years in a cooling pond, the spent fuel is radioactively and thermally cool enough to handle, and it can be moved to dry storage casks or reprocessed.

Conventional fuel resources

Uranium market and Energy development - Nuclear energy

Uranium is a fairly common element in the Earth's crust. Uranium is approximately as common as tin or germanium in Earth's crust, and is about 35 times more common than

silver. Uranium is a constituent of most rocks, dirt, and of the oceans. The fact that uranium is so spread out is a problem because mining uranium is only economically feasible where there is a large concentration. Still, the world's present measured resources of uranium, economically recoverable at a price of 130 USD/kg, are enough to last for "at least a century" at current consumption rates. This represents a higher level of assured resources than is normal for most minerals. On the basis of analogies with other metallic minerals, a doubling of price from present levels could be expected to create about a tenfold increase in measured resources, over time. However, the cost of nuclear power lies for the most part in the construction of the power station. Therefore the fuel's contribution to the overall cost of the electricity produced is relatively small, so even a large fuel price escalation will have relatively little effect on final price. For instance, typically a doubling of the uranium market price would increase the fuel cost for a light water reactor by 26% and the electricity cost about 7%, whereas doubling the price of natural gas would typically add 70% to the price of electricity from that source. At high enough prices, eventually extraction from sources such as granite and seawater become economically feasible.

Current light water reactors make relatively inefficient use of nuclear fuel, fissioning only the very rare uranium-235 isotope. Nuclear reprocessing can make this waste reusable and more efficient reactor designs allow better use of the available resources.

Breeding

Breeder reactor

As opposed to current light water reactors which use uranium-235 (0.7% of all natural uranium), fast breeder reactors use uranium-238 (99.3% of all natural uranium). It has been estimated that there is up to five billion years' worth of uranium-238 for use in these power plants.

Breeder technology has been used in several reactors, but the high cost of reprocessing fuel safely requires uranium prices of more than 200 USD/kg before becoming justified economically. As of December 2005, the only breeder reactor producing power is BN-600 in Beloyarsk, Russia. The electricity output of BN-600 is 600 MW — Russia has planned to build another unit, BN-800, at Beloyarsk nuclear power plant. Also, Japan's Monju reactor is planned for restart (having been shut down since 1995), and both China and India intend to build breeder reactors.

Another alternative would be to use uranium-233 bred from thorium as fission fuel in the thorium fuel cycle. Thorium is about 3.5 times as common as uranium in the Earth's crust, and has different geographic characteristics. This would extend the total practical fissionable resource base by 450%. Unlike the breeding of U-238 into plutonium, fast breeder reactors are not necessary — it can be performed satisfactorily in more conventional plants. India has looked into this technology, as it has abundant thorium reserves but little uranium.

Fusion

Fusion power advocates commonly propose the use of deuterium, or tritium, both isotopes of hydrogen, as fuel and in many current designs also lithium and boron. Assuming a fusion energy output equal to the current global output and that this does not increase in the future, then the known current lithium reserves would last 3000 years, lithium from sea water would last 60 million years, and a more complicated fusion process using only deuterium from sea water would have fuel for 150 billion years.^[60] Although this process has yet to be realized, many experts and civilians alike believe fusion to be a promising future energy source due to the short lived radioactivity of the produced waste, its low carbon emissions, and its prospective power output.

Water

Like all forms of power generation using steam turbines, nuclear power plants use large amounts of water for cooling. At Sellafield, which is no longer producing electricity, a maximum of 18,184.4 m³ a day (over 4 million gallons) and 6,637,306 m³ a year (figures from the Environment Agency) of fresh water from Wast Water is still abstracted to use on site for various processes. As with most power plants, two-thirds of the energy produced by a nuclear power plant goes into waste heat (see Carnot cycle), and that heat is carried away from the plant in the water (which remains uncontaminated by radioactivity). The emitted water either is sent into cooling towers where it goes up and is emitted as water droplets (literally a cloud) or is discharged into large bodies of water — cooling ponds, lakes, rivers, or oceans. Droughts can pose a severe problem by causing the source of cooling water to run out.

The Palo Verde Nuclear Generating Station near Phoenix, AZ is the only nuclear generating facility in the world that is not located adjacent to a large body of water. Instead, it uses treated sewage from several nearby municipalities to meet its cooling water needs, recycling 20 billion US gallons (76,000,000 m³) of wastewater each year.

Like conventional power plants, nuclear power plants generate large quantities of waste heat which is expelled in the condenser, following the turbine. Colocation of plants that can take advantage of this thermal energy has been suggested by Oak Ridge National Laboratory (ORNL) as a way to take advantage of process synergy for added energy efficiency. One example would be to use the power plant steam to produce hydrogen from water.^[64] (Separation of water into hydrogen and oxygen can use less energy if the water begins at a high temperature.)

Solid waste

The safe storage and disposal of nuclear waste is a significant challenge and yet unresolved problem. The most important waste stream from nuclear power plants is spent fuel. A large nuclear reactor produces 3 cubic metres (25–30 tonnes) of spent fuel each year. It is primarily composed of unconverted uranium as well as significant quantities of transuranic actinides (plutonium and curium, mostly). In addition, about 3% of it is made

of fission products. The actinides (uranium, plutonium, and curium) are responsible for the bulk of the long term radioactivity, whereas the fission products are responsible for the bulk of the short term radioactivity.

High-level radioactive waste

Spent fuel is highly radioactive and needs to be handled with great care and forethought. However, spent nuclear fuel becomes less radioactive over the course of thousands of years of time. After about 5 percent of the rod has reacted the rod is no longer able to be used. Today, scientists are experimenting on how to recycle these rods to reduce waste. In the meantime, after 40 years, the radiation flux is 99.9% lower than it was the moment the spent fuel was removed, although still dangerously radioactive.

Spent fuel rods are stored in shielded basins of water (spent fuel pools), usually located on-site. The water provides both cooling for the still-decaying fission products, and shielding from the continuing radioactivity. After a few decades some on-site storage involves moving the now cooler, less radioactive fuel to a dry-storage facility or dry cask storage, where the fuel is stored in steel and concrete containers until its radioactivity decreases naturally ("decays") to levels safe enough for other processing. This interim stage spans years or decades or millennia, depending on the type of fuel. Most U.S. waste is currently stored in temporary storage sites requiring oversight, while suitable permanent disposal methods are discussed.

As of 2007, the United States had accumulated more than 50,000 metric tons of spent nuclear fuel from nuclear reactors. Underground storage at Yucca Mountain nuclear waste repository in U.S. has been proposed as permanent storage. After 10,000 years of radioactive decay, according to United States Environmental Protection Agency standards, the spent nuclear fuel will no longer pose a threat to public health and safety.

The amount of waste can be reduced in several ways, particularly reprocessing. Even so, the remaining waste will be substantially radioactive for at least 300 years even if the actinides are removed, and for up to thousands of years if the actinides are left in. Even with separation of all actinides, and using fast breeder reactors to destroy by transmutation some of the longer-lived non-actinides as well, the waste must be segregated from the environment for one to a few hundred years, and therefore this is properly categorized as a long-term problem. Subcritical reactors or fusion reactors could also reduce the time the waste has to be stored. It has been argued that the best solution for the nuclear waste is above ground temporary storage since technology is rapidly changing. There is hope that current waste may well become a valuable resource in the future.

According to a 2007 story broadcast on *60 Minutes*, nuclear power gives France the cleanest air of any industrialized country, and the cheapest electricity in all of Europe. France reprocesses its nuclear waste to reduce its mass and make more energy. However, the article continues, "Today we stock containers of waste because currently scientists don't know how to reduce or eliminate the toxicity, but maybe in 100 years perhaps

scientists will ... Nuclear waste is an enormously difficult political problem which to date no country has solved. It is, in a sense, the Achilles heel of the nuclear industry ... If France is unable to solve this issue, says Mandil, then 'I do not see how we can continue our nuclear program.'" Further, reprocessing itself has its critics, such as the Union of Concerned Scientists.

Low-level radioactive waste

The nuclear industry also produces a huge volume of low-level radioactive waste in the form of contaminated items like clothing, hand tools, water purifier resins, and (upon decommissioning) the materials of which the reactor itself is built. In the United States, the Nuclear Regulatory Commission has repeatedly attempted to allow low-level materials to be handled as normal waste: landfilled, recycled into consumer items, et cetera. Most low-level waste releases very low levels of radioactivity and is only considered radioactive waste because of its history.

Comparing radioactive waste to industrial toxic waste

In countries with nuclear power, radioactive wastes comprise less than 1% of total industrial toxic wastes, which remain hazardous indefinitely unless they decompose or are treated so that they are less toxic or, ideally, completely non-toxic. Overall, nuclear power produces far less waste material than fossil-fuel based power plants. Coal-burning plants are particularly noted for producing large amounts of toxic and mildly radioactive ash due to concentrating naturally occurring metals and radioactive material from the coal.

Recent reports claim that coal power actually results in more radioactive waste being released into the environment than nuclear power, and that the population effective dose equivalent from radiation from coal plants is 100 times as much as nuclear plants. However, reputable journals point out that coal ash is not more radioactive than nuclear waste, and the differences in exposure lie in the fact that nuclear plants use heavy shielding to protect the environment from the heavily irradiated reactor vessel, fuel rods, and any radioactive waste on site.

Reprocessing

Reprocessing can potentially recover up to 95% of the remaining uranium and plutonium in spent nuclear fuel, putting it into new mixed oxide fuel. This produces a reduction in long term radioactivity within the remaining waste, since this is largely short-lived fission products, and reduces its volume by over 90%. Reprocessing of civilian fuel from power reactors is currently done on large scale in Britain, France and (formerly) Russia, soon will be done in China and perhaps India, and is being done on an expanding scale in Japan. The full potential of reprocessing has not been achieved because it requires breeder reactors, which are not yet commercially available. France is generally cited as the most successful reprocessor, but it presently only recycles 28% (by mass) of the yearly fuel use, 7% within France and another 21% in Russia.

Unlike other countries, the US stopped civilian reprocessing from 1976 to 1981 as one part of US non-proliferation policy, since reprocessed material such as plutonium could be used in nuclear weapons: however, reprocessing is now allowed in the U.S. Even so, in the U.S. spent nuclear fuel is currently all treated as waste.

In February, 2006, a new U.S. initiative, the Global Nuclear Energy Partnership was announced. It would be an international effort to reprocess fuel in a manner making nuclear proliferation unfeasible, while making nuclear power available to developing countries.

Depleted uranium

Depleted uranium

Uranium enrichment produces many tons of depleted uranium (DU) which consists of U-238 with most of the easily fissile U-235 isotope removed. U-238 is a tough metal with several commercial uses—for example, aircraft production, radiation shielding, and armor—as it has a higher density than lead. Depleted uranium is also useful in munitions as DU penetrators (bullets or APFSDS tips) "self sharpen", due to uranium's tendency to fracture along shear bands.

There are concerns that U-238 may lead to health problems in groups exposed to this material excessively, such as tank crews and civilians living in areas where large quantities of DU ammunition have been used in shielding, bombs, missile warheads, and bullets. In January 2003 the World Health Organization released a report finding that contamination from DU munitions were localized to a few tens of meters from the impact sites and contamination of local