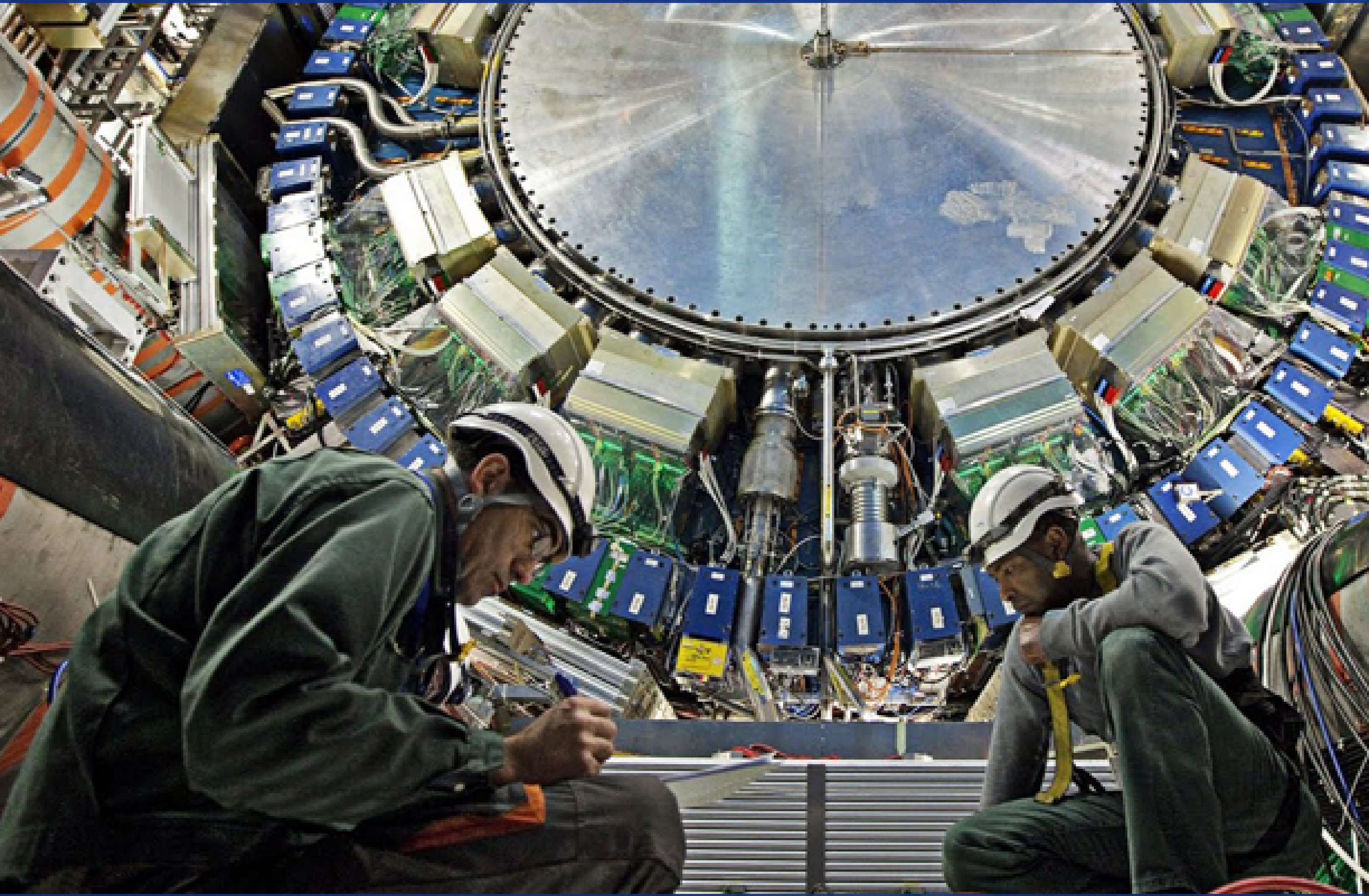
Nuclear
Physics and Engineering



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Semi-empirical Mass Formula and Nuclear Shell 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 based partly on theory and partly on empirical measurements; the theory is based on the **liquid drop model**, which 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 the nucleus, 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

$$m = Zm_p + Nm_n - \frac{E_B}{c^2}$$

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:

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z)$$

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 $\frac{A(A-1)}{2}$, 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 neighbours 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 $\frac{3}{5}A\epsilon_F$, with ε_F the Fermi energy which is estimated as 38 MeV. Thus the expected value of a_V in this model is $E_b - \frac{3}{5}\epsilon_F \sim 17\text{ MeV}$, 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 $a_C \frac{Z(Z-1)}{A^{1/3}}$ 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

$$E = \frac{3}{5}\left(\frac{1}{4\pi\epsilon_0}\right)\frac{Q^2}{R}$$

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:

Empirical nuclear radius:

$$R = r_0 A^{\frac{1}{3}}.$$

Quantum charge integers:

$$Q = Ze$$
$$Z^2 = Z(Z-1)\ .$$

Integration by substitution:

$$E = \frac{3}{5}\left(\frac{1}{4\pi\epsilon_0}\right)\frac{Q^2}{R} = \frac{3}{5}\left(\frac{1}{4\pi\epsilon_0}\right)\frac{(Ze)^2}{(r_0 A^{\frac{1}{3}})} = \frac{3e^2Z^2}{20\pi\epsilon_0 r_0 A^{\frac{1}{3}}} = \frac{3e^2Z(Z-1)}{20\pi\epsilon_0 r_0 A^{\frac{1}{3}}} = a_C\frac{Z(Z-1)}{A^{1/3}}$$

Potential energy of charge distribution:

$$E = \frac{3e^2Z(Z-1)}{20\pi\epsilon_0 r_0 A^{\frac{1}{3}}}$$

Electrostatic Coulomb constant:

$$a_C = \frac{3e^2}{20\pi\epsilon_0 r_0}$$

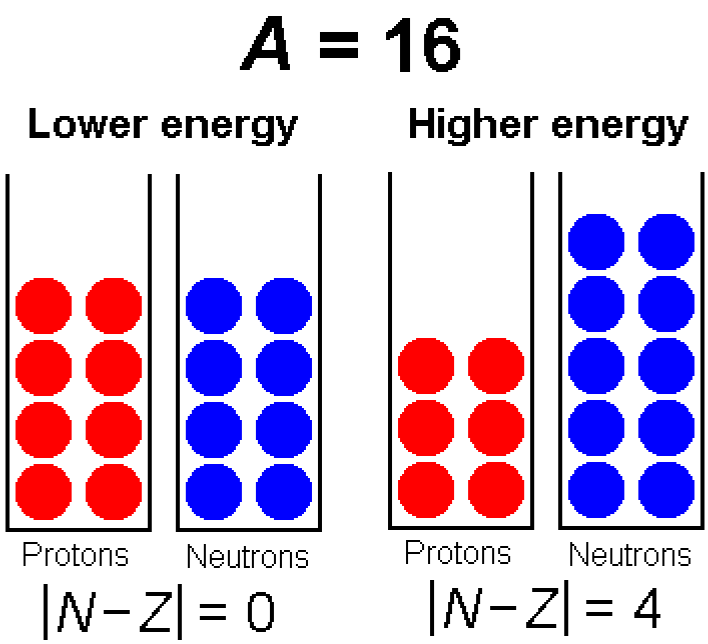
The value of a_C using the fine structure constant:

$$a_C = \frac{3}{5}\left(\frac{\hbar c \alpha}{r_0}\right)$$

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.

$$a_C = 0.691 \text{ MeV}$$

Asymmetry term



The term $a_A \frac{(A-2Z)^2}{A}$ 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 modelling the nucleus as a Fermi ball of protons and neutrons. Its total kinetic energy is

$$E_k = \frac{3}{5}(N_p\epsilon_{Fp} + N_n\epsilon_{Fn})$$

where N_p, N_n are the numbers of protons and neutrons and ϵ_{Fp}, ϵ_{Fn} are their Fermi energies. Since the latter are proportional to ${N_p}^{2/3}$ and ${N_n}^{2/3}$, respectively, one gets

$$E_k = C(N_p^{5/3} + N_n^{5/3})$$ for some constant C.

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

$$E_k = \frac{C}{2^{2/3}}\left((N_p + N_n)^{5/3} + \frac{5}{9}\frac{(N_n - N_p)^2}{(N_p + N_n)^{1/3}}\right) + O((N_n - N_p)^2).$$

At the zeroth order expansion the kinetic energy is just the Fermi energy $\epsilon_F \equiv \epsilon_{Fp} = \epsilon_{Fn}$ multiplied by $\frac{3}{5}(N_p + N_n)^{2/3}$. Thus we get

$$E_k = \frac{3}{5}\epsilon_F(N_p{+}N_n)^{2/3}{+}\frac{1}{3}\epsilon_F\frac{(N_n - N_p)^2}{(N_p + N_n)}{+}O((N_n{-}N_p)^4) = \frac{3}{5}\epsilon_F A^{2/3}{+}\frac{1}{3}\epsilon_F\frac{(A - 2Z)^2}{A}{+}O((A{-}2Z)^4).$$

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:

$$\delta(A,Z) = \begin{cases} +\delta_0 & Z,N \text{ even } (A \text{ even}) \\ 0 & A \text{ odd} \\ -\delta_0 & Z,N \text{ odd } (A \text{ even}) \end{cases}$$

where

$$\delta_0 = \frac{a_P}{A^{1/2}}.$$

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 a 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}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

$$Z \approx \frac{1}{2}\frac{A}{1+A^{2/3}\frac{a_C}{4a_A}}.$$

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 and nuclear chemistry, 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, playing a role in the search of the so-called island of stability. There have been found some semimagic numbers, notably Z=40. 16 may also be a magic number.

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 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	1/2
			-1/2
1	1	0	1/2
			-1/2
		-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 $\frac{(n+1)(n+2)}{2}$. Due to the spin, the degeneracy is doubled and is $(n + 1)(n + 2)$.
> Thus the magic numbers would be
> $$\sum_{n=0}^{k}(n+1)(n+2) = \frac{(k+1)(k+2)(k+3)}{3}$$
> 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 $\vec{s}$ is parallel to $\vec{l}$, the interaction energy is negative; and in this case $j = l + s = l + 1/2$. When $\vec{s}$ is anti-parallel to $\vec{l}$ (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.

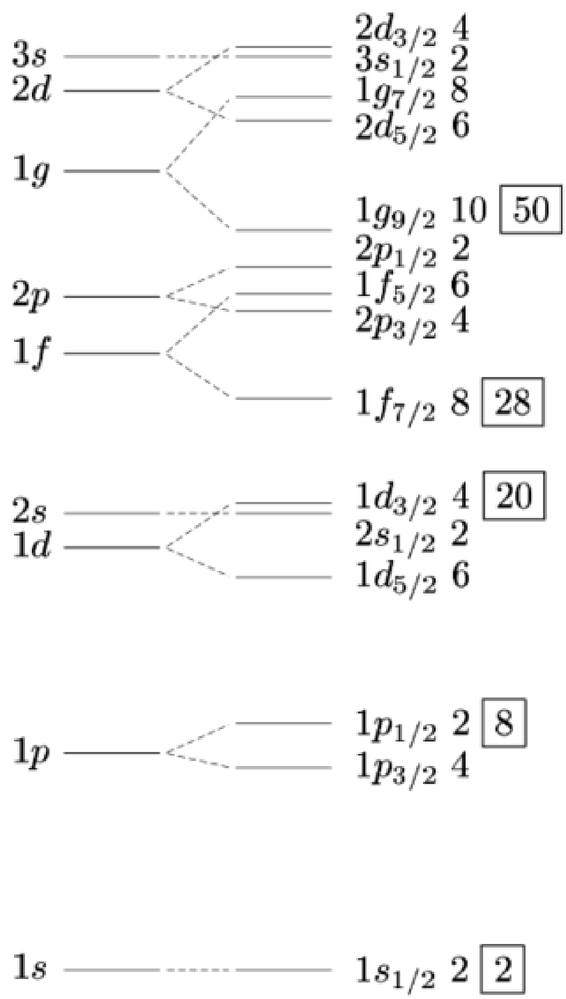
For example, consider the states at level 4:

- 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 $\hbar^2 l(l+1)/2mr^2$ in the Laplace operator of 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 l^2 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 $^{17}{}_{8}O^{9}$ 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 $^{17}{}_{8}O^{9}$ 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 form 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.

Chapter-2

Radioactive Decay

Radioactive decay is the process by which an unstable atomic nucleus loses energy by emitting ionizing particles or radiation. The emission is spontaneous in that the nucleus decays without collision with another particle. This decay, or loss of energy, results in an atom of one type, called the *parent radionuclide*, 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 stochastic process on the atomic level, in that according to quantum mechanics it is impossible to predict when a given atom will decay. However given a large number of similar atoms the decay rate, on average, is predictable.

The SI unit of activity 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 GBq (gigabecquerel, 1×10^9 decays per second) or TBq (terabecquerel, 1×10^{12} decays per second) are commonly used. Another unit of radioactivity is the curie, Ci, which was originally defined as the amount of radium emanation (radon-222) in equilibrium with 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.

Nuclides produced as daughters are also called radiogenic nuclides, whether they themselves are stable or not. A number of naturally occurring radionuclides are short-lived radiogenic nuclides that are daughters of radioactive primordial nuclides. Other naturally-occurring radioactive nuclides are cosmogenic nuclides, formed by cosmic ray bombardment of material in the Earth's atmosphere or crust. For a summary table showing the number of stable nuclides and of radioactive nuclides in each category.

Explanation

The trefoil symbol is used to indicate radioactive material

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 radioactive 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 salts 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 become black.

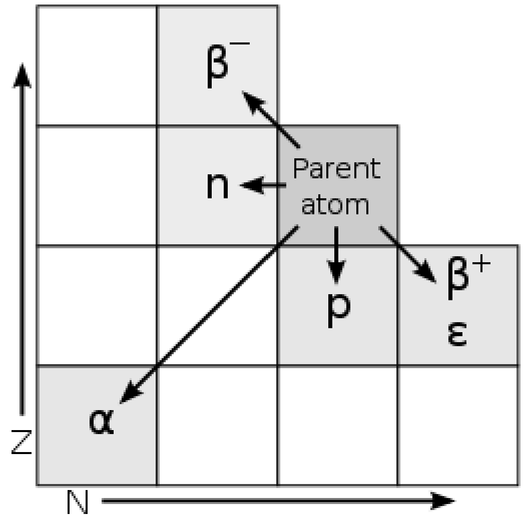
At first it seemed that the new radiation was similar to the then recently discovered X-rays. Further research by Becquerel, Marie Curie, Pierre Curie, Ernest Rutherford and others discovered that radioactivity was significantly more complicated. Different types of decay can occur, but Rutherford was 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.

Danger of radioactive substances

The danger classification sign of radioactive materials

Ionizing radiation hazard symbol (recently introduced)



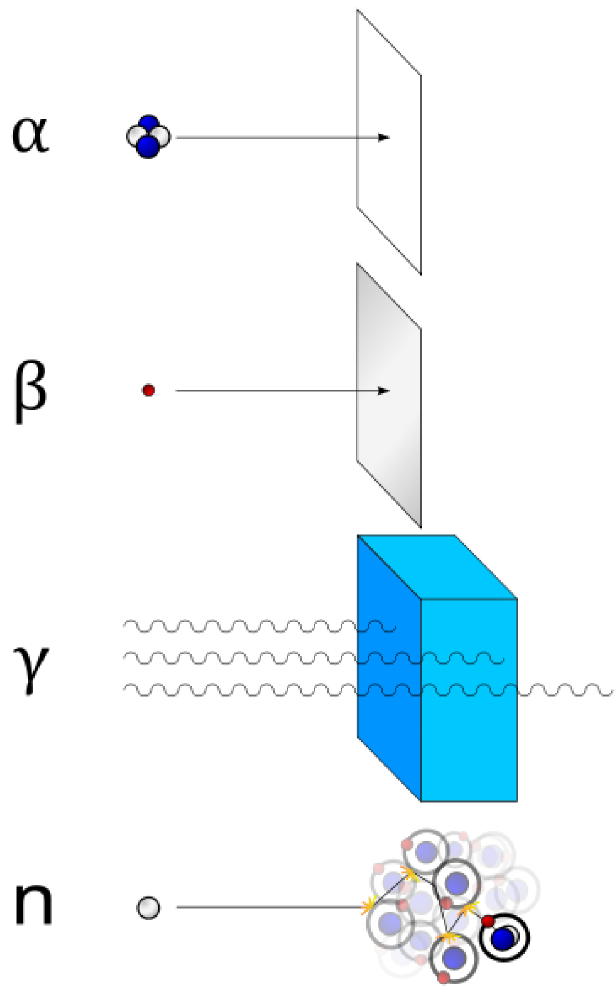
Different types of decay of a radionuclide. Vertical: atomic number Z, Horizontal: neutron number N

Ionizing radiation consists of subatomic particles or electromagnetic waves energetic enough to detach electrons from atoms or molecules, thus ionizing them. The degree and nature of such ionization depends on the energy of the individual particles or waves, and not on their number. An intense flood of particles or waves will not cause ionization if these particles or waves do not carry enough energy to be ionizing. Roughly speaking, particles or photons with energies above a few electron volts (eV) are ionizing.

Examples of ionizing particles are energetic alpha particles, beta particles, and neutrons. The ability of an electromagnetic wave (photons) to ionize an atom or molecule depends on its frequency. Radiation on the short-wavelength end of the electromagnetic spectrum—high frequency ultraviolet, x-rays, and gamma rays—is ionizing. Lower-energy radiation such as visible light, microwaves, and radio waves are not.

Ionizing radiation is ubiquitous in the environment, and also comes from radioactive materials, x-ray tubes, and particle accelerators. It is invisible and not directly detectable by human senses, so instruments such as Geiger counters are usually required to detect its presence. In some cases it may lead to secondary emission of visible light upon interaction with matter, as in Cherenkov radiation and radioluminescence. It has many practical uses in medicine, research, construction, and other areas, but presents a health hazard if used improperly. Exposure to radiation causes damage to living tissue, and high doses can result in Mutation, radiation sickness, cancer and death.

Types of radiation



Alpha (**α**) radiation consists of a fast moving Helium-4 (^{4}He) nucleus and is stopped by a sheet of paper. Beta (**β**) radiation, consisting of electrons, is halted by an aluminium plate. Gamma (**γ**) radiation, consisting of energetic photons, is eventually absorbed as it penetrates a dense material. Neutron (**n**) radiation consists of free neutrons which are blocked using light elements, like hydrogen, which slow and/or capture them.

Various types of ionizing radiation may be produced by radioactive decay, nuclear fission and nuclear fusion, and by particle accelerators.

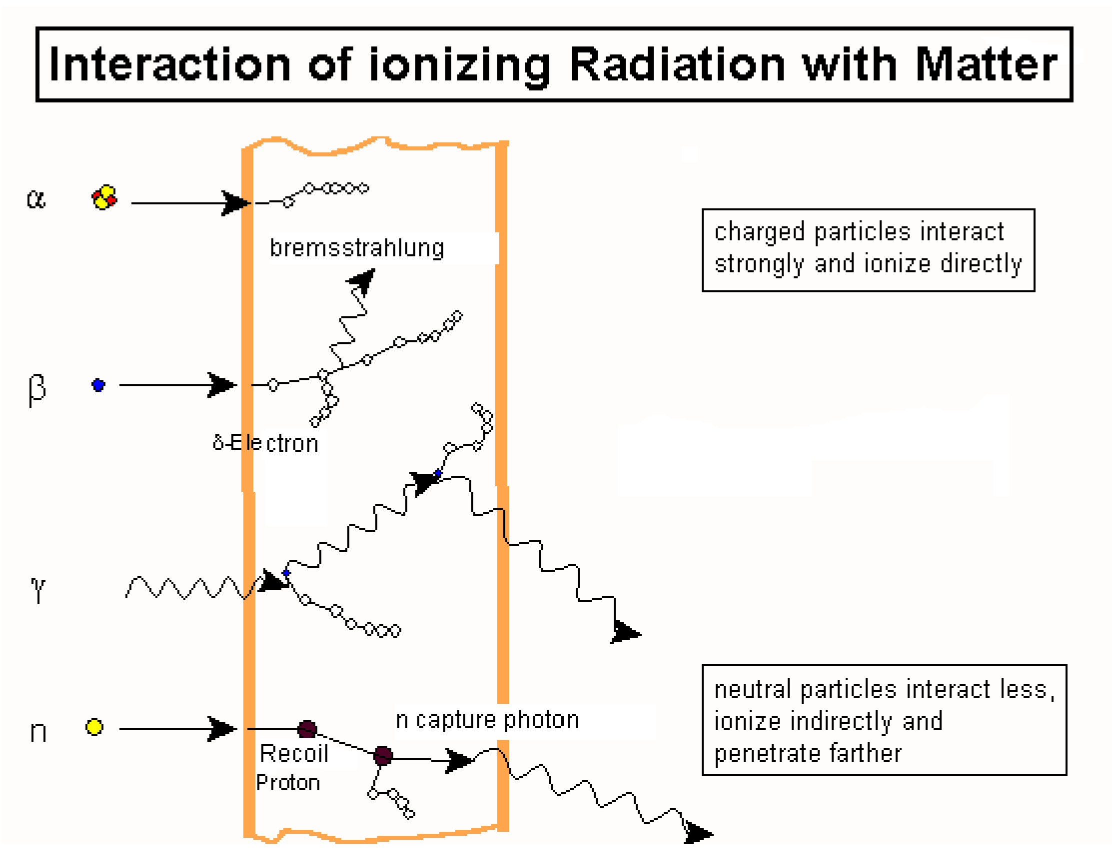
In order for a particle to be ionizing, it must both have a high enough energy and interact with the atoms of a target.

Photons interact electromagnetically with charged particles, so photons of sufficiently high energy also are ionizing. The energy at which this begins to happen with photons (light) is in the high frequency end of the ultraviolet region of the electromagnetic spectrum.

Charged particles such as electrons, positrons, and alpha particles also interact electromagnetically with electrons of an atom or molecule.

Neutrons, on the other hand, having zero electrical charge, do not interact electromagnetically with electrons, and so they cannot directly cause ionization by this mechanism. However, fast neutrons will interact with the protons in hydrogen (in the manner of a billiard ball hitting another, head on, sending it away with all of the first ball's energy of motion), and this mechanism produces proton radiation (fast protons). These protons are ionizing because they are charged, and interact with the electrons in matter.

A neutron can also interact with other atomic nuclei, depending on the nucleus and the neutron's velocity; these reactions happen with fast neutrons and slow neutrons, depending on the situation. Neutron interactions in this manner often produce radioactive nuclei, which produce ionizing radiation when they decay, then they can produce chain reactions in the mass that is decaying, sometimes causing a larger effect of ionization.



Types of radiation - gamma rays are represented by wavy lines, charged particles and neutrons by straight lines. The little circles show where ionization processes occur.

An ionization event normally produces a positive atomic ion and an electron. High-energy beta particles may produce bremsstrahlung when passing through matter, or secondary electrons (δ-electrons); both can ionize in turn. Energetic Beta-particles. like those emitted by ^{32}P, are quickly decelerated when passing through matter. The energy lost to deceleration is emitted in the form of X-rays called "Bremsstrahlung" which translates "Braking Radiation". Bremsstrahlung is of concern when shielding beta emitters. The intensity of bremsstrahlung increases with the increase in energy of the electrons or the atomic number of the absorbing medium.

Unlike alpha or beta particles, gamma rays do not ionize all along their path, but rather interact with matter in one of three ways: the photoelectric effect, the Compton effect, and pair production. By way of example, the figure shows Compton effect: two Compton scatterings that happen sequentially. In every scattering event, the gamma ray transfers energy to an electron, and it continues on its path in a different direction and with reduced energy.

In the same figure, the neutron collides with a proton of the target material, and then becomes a fast recoil proton that ionizes in turn. At the end of its path, the neutron is captured by a nucleus in an (n,γ)-reaction that leads to a neutron capture photon.

The negatively-charged electrons and positively charged ions created by ionizing radiation may cause damage in living tissue. If the dose is sufficient, the effect may be seen almost immediately, in the form of radiation poisoning. Lower doses may cause cancer or other long-term problems. The effect of the very low doses encountered in normal circumstances (from both natural and artificial sources, like cosmic rays, medical X-rays and nuclear power plants) is a subject of current debate. A 2005 report released by the National Research Council (the BEIR VII report, summarized in) indicated that the overall cancer risk associated with background sources of radiation was relatively low. Some even propose that low-level doses of ionizing radiation are beneficial, by stimulating the immune system and self-repair mechanisms of cells. This hypothesis is called radiation hormesis.

Radioactive materials usually release alpha particles, which are the nuclei of helium, beta particles, which are quickly moving electrons or positrons, or gamma rays. Alpha and beta particles can often be stopped by a piece of paper or a sheet of aluminium, respectively. They cause most damage when they are emitted inside the human body. Gamma rays are less ionizing than either alpha or beta particles, and protection against gammas requires thicker shielding. The damage they produce is similar to that caused by X-rays, and include burns and also cancer, through mutations. Human biology resists germline mutation by either correcting the changes in the DNA or inducing apoptosis in the mutated cell.

Non-ionizing radiation is thought to be essentially harmless below the levels that cause heating. Ionizing radiation is dangerous in direct exposure, although the degree of danger is a subject of debate. Animals (including humans) can also be exposed to ionizing radiation internally: if radioactive isotopes are present in the environment, they may be taken into the body. For example, radioactive iodine is treated as normal iodine by the body and used by the thyroid; its accumulation there often leads to thyroid cancer. Some radioactive elements also bioaccumulate.

Units

Weighting factors W_R for equivalent dose

Radiation	Energy	w_R
x-rays, gamma rays, electrons, positrons, muons		1
neutrons	< 10 keV	5
	10 keV - 100 keV	10
	100 keV - 2 MeV	20
	2 MeV - 20 MeV	10
	> 20 MeV	5
protons	> 2 MeV	2
alpha particles, fission fragments, heavy nuclei		20

The units used to measure ionizing radiation are rather complex. The ionizing effects of radiation are measured by units of exposure:

- The coulomb per kilogram (C/kg) is the SI unit of ionizing radiation exposure, and measures the amount of radiation required to create 1 coulomb of charge of each polarity in 1 kilogram of matter.
- The roentgen (R) is an older traditional unit that is almost out of use, which represented the amount of radiation required to liberate 1 esu of charge of each polarity in 1 cubic centimeter of dry air. 1 Roentgen = 2.58×10^{-4} C/kg

However, the amount of damage done to matter (especially living tissue) by ionizing radiation is more closely related to the amount of energy deposited rather than the charge. This is called the absorbed dose.

- The gray (Gy), with units J/kg, is the SI unit of absorbed dose, which represents the amount of radiation required to deposit 1 joule of energy in 1 kilogram of any kind of matter.
- The rad (radioactivity absorbed dose), is the corresponding traditional unit which is 0.01 J deposited per kg. 100 rad = 1 Gy.

Equal doses of different types or energies of radiation cause different amounts of damage to living tissue. For example, 1 Gy of alpha radiation causes about 20 times as much damage as 1 Gy of x-rays. Therefore the equivalent dose was defined to give an approximate measure of the biological effect of radiation. It is calculated by multiplying the absorbed dose by a weighting factor W_R which is different for each type of radiation (see above table).

- The sievert (Sv) is the SI unit of equivalent dose. Although it has the same units as grays, J/kg, it measures something different. It is the dose of a given type of radiation in Gy that has the same biological effect on a human as 1 Gy of x-rays or gamma radiation.

- The rem (Roentgen equivalent man) is the traditional unit of equivalent dose. 1 sievert = 100 rem. Because the rem is a relatively large unit, typical equivalent dose is measured in millirem (mrem), 10^{-3} rem, or in microsievert (μSv), 10^{-6} Sv. 1 mrem = 10 μSv.
- A unit sometimes used for low level doses of radiation is the BRET (Background Radiation Equivalent Time). This is the number of days of an average person's background radiation exposure the dose is equivalent to. This unit is apparently not standardized, and depends on the value used for the average background radiation dose. Using the 2000 UNSCEAR value (below), one BRET unit is equal to about 6.6 μSv.

For comparison, the average 'background' dose of natural radiation received by a person is around 3.6 mSv (360 mrem) per year. The lethal full-body dose of radiation for a human is around 4 - 5 Sv (400 - 500 rem).

Uses

Ionizing radiation has many uses, such as to kill cancerous cells. However, although ionizing radiation has many applications, overuse can be hazardous to human health. For example, at one time, assistants in shoe shops used X-rays to check a child's shoe size, but this practice was halted when it was discovered that ionizing radiation was dangerous.

Nuclear power

Nuclear reactors produce large quantities of ionizing radiation as a byproduct of fission during operation. In addition, they produce highly radioactive nuclear waste, which will emit ionizing radiation for thousands of years for some of the fission products. The safe disposal of this waste in a way that protects future generations from exposure to its radiation is currently imperfect, a highly controversial and arguably unsolved worldwide problem of this technology. However, radiation emissions from nuclear waste naturally decrease over time. This cannot be said of any hazard associated with any other type of waste byproduct. Waste from nuclear reactors, while highly radioactive, can be contained and stored safely while this natural process occurs. Radioactive emissions from nuclear power plants are significantly lower than radioactive emissions from coal-burning power producers, and do not contain the other toxic substances found in the waste byproducts from fossil-fueled generators.

Industrial measurement

Since ionizing radiations can penetrate matter, they are used for a variety of measuring methods.

Industrial radiography

X-rays and gamma rays are used to make images of the inside of solid products, as a means of nondestructive testing and inspection. The piece to be radiographed is placed between the source and a photographic film in a cassette. After a certain exposure time, the film is developed and it shows internal defects of the material if there are any.

Gauges

Gauges use the exponential absorption law of gamma rays

- Level indicators: Source and detector are placed at opposite sides of a container, indicating the presence or absence of material in the horizontal radiation path. Beta or gamma sources are used, depending on the thickness and the density of the material to be measured. The method is used for containers of liquids or of grainy substances
- Thickness gauges: if the material is of constant density, the signal measured by the radiation detector depends on the thickness of the material. This is useful for continuous production, like of paper, rubber, etc.

Applications using ionization of gases by radiation

- To avoid the build-up of static electricity in production of paper, plastics, synthetic textiles, etc., a ribbon-shaped source of the alpha emitter ^{241}Am can be placed close to the material at the end of the production line. The source ionizes the air to remove electric charges on the material.
- Smoke detector: Two ionisation chambers are placed next to each other. Both contain a small source of ^{241}Am that gives rise to a small constant current. One is closed and serves for comparison, the other is open to ambient air; it has a gridded electrode. When smoke enters the open chamber, the current is disrupted as the smoke particles attach to the charged ions and restore them to a neutral electrical state. This reduces the current in the open chamber. When the current drops below a certain threshold, the alarm is triggered.
- Radioactive tracers for industry: Since radioactive isotopes behave, chemically, mostly like the inactive element, the behavior of a certain chemical substance can be followed by *tracing* the radioactivity. Examples:
    - Adding a gamma tracer to a gas or liquid in a closed system makes it possible to find a hole in a tube.
    - Adding a tracer to the surface of the component of a motor makes it possible to measure wear by measuring the activity of the lubricating oil.

Biological and medical applications

The largest use of ionizing radiation in medicine is in medical radiography to make images of the inside of the human body using x-rays. This is the largest artificial source of radiation exposure for humans. Radiation is also used to treat diseases in radiation therapy. Tracer methods (mentioned above) are used in nuclear medicine to diagnose diseases, and widely used in biological research.

In biology and agriculture, radiation is used to induce mutations to produce new or improved species. Another use in insect control is the sterile insect technique, where male insects are sterilized by radiation and released, so they have no offspring, to reduce the population.

In medicine, biology, and other fields, radiation is used for sterilization of tools and equipment. An advantage is that the object may be sealed in plastic before sterilization. An emerging use in food production is the sterilization of food using food irradiation. This is controversial due to concerns about the health hazards of induced radioactivity. Though a report for the American Council on Science and Health called "Irradiated Foods" says irradiation does not make food radioactive.

"The types of radiation sources approved for the treatment of foods have specific energy levels well below that which would cause any element in food to become radioactive. Food undergoing irradiation does not become any more radioactive than luggage passing through an airport X-ray scanner or teeth that have been X-rayed."

Sources

Natural background radiation

Natural background radiation comes from four primary sources: cosmic radiation, solar radiation, external terrestrial sources, and radon.

Cosmic radiation

The Earth, and all living things on it, are constantly bombarded by radiation from outside our solar system. This cosmic radiation consists of positively-charged ions from protons to iron nuclei. The energy of this radiation can far exceed that which humans can create even in the largest particle accelerators. This radiation interacts in the atmosphere to create secondary radiation that rains down, including x-rays, muons, protons, alpha particles, pions, electrons, and neutrons.

The dose from cosmic radiation is largely from muons, neutrons, and electrons, with a dose rate that varies in different parts of the world and based largely on the geomagnetic field, altitude, and solar cycle. The cosmic-radiation dose rate on airplanes is so high that, according to the United Nations UNSCEAR 2000 Report, airline flight crew workers receive more dose on average than any other worker, including those in nuclear power plants.

External terrestrial sources

Most materials on Earth contain some radioactive atoms, even if in small quantities. Most of the dose received from these sources is from food containing radioactive isotopes, gamma-ray emitters in building materials, or rocks and soil when outside. The major radionuclides of concern for **terrestrial radiation** are isotopes of potassium, uranium, and thorium. Each of these sources has been decreasing in activity since the birth of the Earth so that our present dose from potassium-40 is about ½ what it would have been at the dawn of life on Earth.

Radon

Radon-222 is produced by the decay of radium-226 which is present wherever uranium is found. Since radon is a gas, it seeps out of uranium-containing soils found across most of the world and may accumulate in well-sealed homes. It is often the single largest contributor to an individual's background radiation dose and is certainly the most variable from location to location. Radon gas could be the second largest cause of lung cancer in America, after smoking.

Human-made radiation sources

Natural and artificial radiation sources are similar in their effects on matter. Above the background level of radiation exposure, the U.S. Nuclear Regulatory Commission (NRC) requires that its licensees limit human-made radiation exposure for individual members of the public to 100 mrem (1 mSv) per year, and limit occupational radiation exposure to adults working with radioactive material to 5,000 mrem (50 mSv) per year.

The average exposure for Americans is about 360 mrem (3.6 mSv) per year, 81 percent of which comes from natural sources of radiation. The remaining 19 percent results from exposure to human-made radiation sources such as medical X-rays, most of which is deposited in people who have CAT scans. However, in some areas, the average background dose can be over 1,000 mrem (10 mSv) per year. An important source of natural radiation is radon gas, which seeps continuously from bedrock but can, because of its high density, accumulate in poorly ventilated houses.

The background rate for radiation varies considerably with location, being as low as 1.5 mSv/a (1.5 mSv per year) in some areas and over 100 mSv/a in others. People in some parts of Ramsar, a city in northern Iran, receive an annual absorbed dose from background radiation that is up to 260 mSv/a. Despite having lived for many generations in these high background areas, inhabitants of Ramsar show no significant cytogenetic differences compared to people in normal background areas. This has led to the suggestion that high but steady levels of radiation are easier for humans to sustain than sudden radiation bursts.

Some human-made radiation sources affect the body through direct radiation, while others take the form of radioactive contamination and irradiate the body from within.

Medical procedures, such as diagnostic X-rays, nuclear medicine, and radiation therapy are by far the most significant source of human-made radiation exposure to the general public. Some of the major radionuclides used are I-131, Tc-99, Co-60, Ir-192, and Cs-137. These are rarely released into the environment. The public also is exposed to radiation from consumer products, such as tobacco (polonium-210), building materials, combustible fuels (gas, coal, etc.), ophthalmic glass, televisions, luminous watches and dials (tritium), airport X-ray systems, smoke detectors (americium), road construction materials, electron tubes, fluorescent lamp starters, and lantern mantles (thorium). A typical dose for radiation therapy might be 7 Gy spread daily over two months.

Of lesser magnitude, members of the public are exposed to radiation from the nuclear fuel cycle, which includes the entire sequence from mining and milling of uranium to the disposal of the spent fuel. The effects of such exposure have not been reliably measured due to the extremely low doses involved. Estimates of exposure are low enough that proponents of nuclear power liken them to the mutagenic power of wearing trousers for two extra minutes per year (because heat causes mutation). Opponents use a cancer per dose model to assert that such activities cause several hundred cases of cancer per year, an application of the controversial Linear no-threshold model (LNT).

In a nuclear war, gamma rays from fallout of nuclear weapons would probably cause the largest number of casualties. Immediately downwind of targets, doses would exceed 300 Gy per hour. As a reference, 4.5 Gy (around 15,000 times the average annual background rate) is fatal to half of a normal population, without medical treatment.

Occupationally exposed individuals are exposed according to the sources with which they work. The radiation exposure of these individuals is carefully monitored with the use of pocket-pen-sized instruments called dosimeters.

Some of the radionuclides of concern include cobalt-60, caesium-137, americium-241, and iodine-131. Examples of industries where occupational exposure is a concern include:

- Airline crew (the most exposed population)
- Industrial radiography
- Medical radiology and nuclear medicine
- Uranium mining
- Nuclear power plant and nuclear fuel reprocessing plant workers
- Research laboratories (government, university and private)

Biological effects

The biological effects of radiation are thought of in terms of their effects on living cells. For low levels of radiation, the biological effects are so small they may not be detected in epidemiological studies. The body repairs many types of radiation and chemical damage. Biological effects of radiation on living cells may result in a variety of outcomes, including:

1. Cells experience DNA damage and are able to detect and repair the damage.
2. Cells experience DNA damage and are unable to repair the damage. These cells may go through the process of programmed cell death, or apoptosis, thus eliminating the potential genetic damage from the larger tissue.
3. Cells experience a nonlethal DNA mutation that is passed on to subsequent cell divisions. This mutation may contribute to the formation of a cancer.
4. Cells experience "irreparable DNA damage." Low level ionizing radiation may induce irreparable DNA damage (leading to replicational and transcriptional errors needed for neoplasia or may trigger viral interactions) leading to pre-mature aging and cancer.

Other observations at the tissue level are more complicated. These include:

1. In some cases, a small radiation dose reduces the impact of a subsequent, larger radiation dose. This has been termed an 'adaptive response' and is related to hypothetical mechanisms of hormesis.

Chronic radiation exposure

Exposure to ionizing radiation over an extended period of time is called chronic exposure. The natural background radiation is chronic exposure, but a normal level is difficult to determine due to variations. Geographic location and occupation often affect chronic exposure.

Acute radiation exposure

Acute radiation exposure is an exposure to ionizing radiation which occurs during a short period of time. There are routine brief exposures, and the boundary at which it becomes significant is difficult to identify. Extreme examples include

- Instantaneous flashes from nuclear explosions.
- Exposures of minutes to hours during handling of highly radioactive sources.
- Laboratory and manufacturing accidents.
- Intentional and accidental high medical doses.

The effects of acute events are more easily studied than those of chronic exposure.

Radiation levels

The associations between ionizing radiation exposure and the development of cancer are mostly based on populations exposed to relatively high levels of ionizing radiation, such as Japanese atomic bomb survivors, and recipients of selected diagnostic or therapeutic medical procedures.

Cancers associated with high dose exposure include leukemia, thyroid, breast, bladder, colon, liver, lung, esophagus, ovarian, multiple myeloma, and stomach cancers. United

States Department of Health and Human Services literature also suggests a possible association between ionizing radiation exposure and prostate, nasal cavity/sinuses, pharyngeal and laryngeal, and pancreatic cancer.

The period of time between radiation exposure and the detection of cancer is known as the latent period. Those cancers that may develop as a result of radiation exposure are indistinguishable from those that occur naturally or as a result of exposure to other chemical carcinogens. Furthermore, National Cancer Institute literature indicates that other chemical and physical hazards and lifestyle factors, such as smoking, alcohol consumption, and diet, significantly contribute to many of these same diseases.

Although radiation may cause cancer at high doses and high dose rates, public health data regarding lower levels of exposure, below about 1,000 mrem (10 mSv), are harder to interpret. To assess the health impacts of lower radiation doses, researchers rely on models of the process by which radiation causes cancer; several models have emerged which predict differing levels of risk.

Studies of occupational workers exposed to chronic low levels of radiation, above normal background, have provided mixed evidence regarding cancer and transgenerational effects. Cancer results, although uncertain, are consistent with estimates of risk based on atomic bomb survivors and suggest that these workers do face a small increase in the probability of developing leukemia and other cancers. One of the most recent and extensive studies of workers was published by Cardis, *et al.* in 2005.

The linear dose-response model suggests that any increase in dose, no matter how small, results in an incremental increase in risk. The linear no-threshold model (LNT) hypothesis is accepted by the Nuclear Regulatory Commission (NRC) and the EPA and its validity has been reaffirmed by a National Academy of Sciences Committee. Under this model, about 1% of a population would develop cancer in their lifetime as a result of ionizing radiation from background levels of natural and man-made sources.

Ionizing radiation damages tissue by causing ionization, which disrupts molecules directly and also produces highly reactive free radicals, which attack nearby cells. The net effect is that biological molecules suffer local disruption; this may exceed the body's capacity to repair the damage and may also cause mutations in cells currently undergoing replication.

Two widely studied instances of large-scale exposure to high doses of ionizing radiation are: atomic bomb survivors in 1945; and emergency workers responding to the 1986 Chernobyl accident.

Approximately 134 plant workers and fire fighters engaged at the Chernobyl power plant received high radiation doses (70,000 to 1,340,000 mrem or 700 to 13,400 mSv) and suffered from acute radiation sickness. Of these, 28 died from their radiation injuries.

Longer term effects of the Chernobyl accident have also been studied. There is a clear link between the Chernobyl accident and the unusually large number, approximately 1,800, of thyroid cancers reported in contaminated areas, mostly in children. These were fatal in some cases. Other health effects of the Chernobyl accident are subject to current debate.

Ionizing radiation level examples

Recognized effects of acute radiation exposure are described in the article on radiation poisoning. The exact units of measurement vary, but light radiation sickness begins at about 50–100 rad (0.5–1 gray (Gy), 0.5–1 Sv, 50–100 rem, 50,000–100,000 mrem).

Although the SI unit of radiation dose equivalent is the sievert, chronic radiation levels and standards are still often given in millirems, 1/1000th of a rem (1 mrem = 0.01 mSv).

Table A.2 presents a scale of dose levels, with an example of the type of exposure that may cause such a dose, or the special significance of such a dose.

Hormesis

Radiation hormesis is the unproven theory that a low level of ionizing radiation (i.e. near the level of Earth's natural background radiation) helps "immunize" cells against DNA damage from other causes (such as free radicals or larger doses of ionizing radiation), and decreases the risk of cancer. The theory proposes that such low levels activate the body's DNA repair mechanisms, causing higher levels of cellular DNA-repair proteins to be present in the body, improving the body's ability to repair DNA damage. This assertion is very difficult to prove in humans (using, for example, statistical cancer studies) because the effects of very low ionizing radiation levels are too small to be statistically measured amid the "noise" of normal cancer rates.

The idea of radiation hormesis is considered unproven by regulatory bodies, which generally use the standard "linear, no threshold" (LNT) model. The LNT model, however, also remains unproven, and was originally created as an administrative convenience, to simplify the process of developing safety standards. The LNT states that risk of cancer is directly proportional to the dose level of ionizing radiation, even at very low levels. The LNT model is perceived to be safer for regulatory purposes because it assumes worst-case damage due to ionizing radiation. Once this assumption is made, the conclusion is that regulations based on it will ensure the protection of workers - that they might be over-protected, but never be under-protected. However, if the LNT does not apply at low levels, it is conceivable that regulations based on it will prevent or limit the hormetic effect, and thus have a negative impact on health.

Monitoring and controlling exposure

Radiation has always been present in the environment and in our bodies. The human body cannot sense ionizing radiation, but a range of instruments exists which are capable of detecting even very low levels of radiation from natural and man-made sources.

Dosimeters measure an absolute dose received over a period of time. Ion-chamber dosimeters resemble pens, and can be clipped to one's clothing. Film-badge dosimeters enclose a piece of photographic film, which will become exposed as radiation passes through it. Ion-chamber dosimeters must be periodically recharged, and the result logged. Film-badge dosimeters must be developed as photographic emulsion so the exposures can be counted and logged; once developed, they are discarded. Another type of dosimeter is the TLD (Thermoluminescent Dosimeter). These dosimeters contain crystals that emit visible light when heated, in direct proportion to their total radiation exposure. Like ion-chamber dosimeters, TLDs can be re-used after they have been 'read'.

Geiger counters and scintillation counters measure the dose rate of ionizing radiation directly.

Limiting exposure

There are four standard ways to limit exposure:

Time: For people who are exposed to radiation in addition to natural background radiation, limiting or minimizing the exposure time will reduce the dose from the radiation source.

Distance: Radiation intensity decreases sharply with distance x, according to an inverse square law (in an absolute vacuum). practically i = Io e^(-ux)

Air substantially attenuates alpha and beta radiation.

Shielding: Barriers of lead, concrete, or water give effective protection from radiation formed of energetic particles such as gamma rays and neutrons. Some radioactive materials are stored or handled underwater or by remote control in rooms constructed of thick concrete or lined with lead. There are special plastic shields which stop beta particles and air will stop alpha particles. The effectiveness of a material in shielding radiation is determined by its halve value thicknesses, the thickness of material that reduces the radiation by half. This value is a function of the material itself and the energy and type of ionizing radiation.

Containment: Radioactive materials are confined in the smallest possible space and kept out of the environment. Radioactive isotopes for medical use, for example, are dispensed in closed handling facilities, while nuclear reactors operate within closed systems with multiple barriers which keep the radioactive materials contained. Rooms have a reduced air pressure so that any leaks occur into the room and not out of it.

In a nuclear war, an effective fallout shelter reduces human exposure at least 1,000 times. Other civil defense measures can help reduce exposure of populations by reducing ingestion of isotopes and occupational exposure during war time. One of these available measures could be the use of potassium iodide (KI) tablets which effectively block the uptake of radioactive iodine into the human thyroid gland.

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 electrical engineer and physicist 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

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, tellurium, 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.

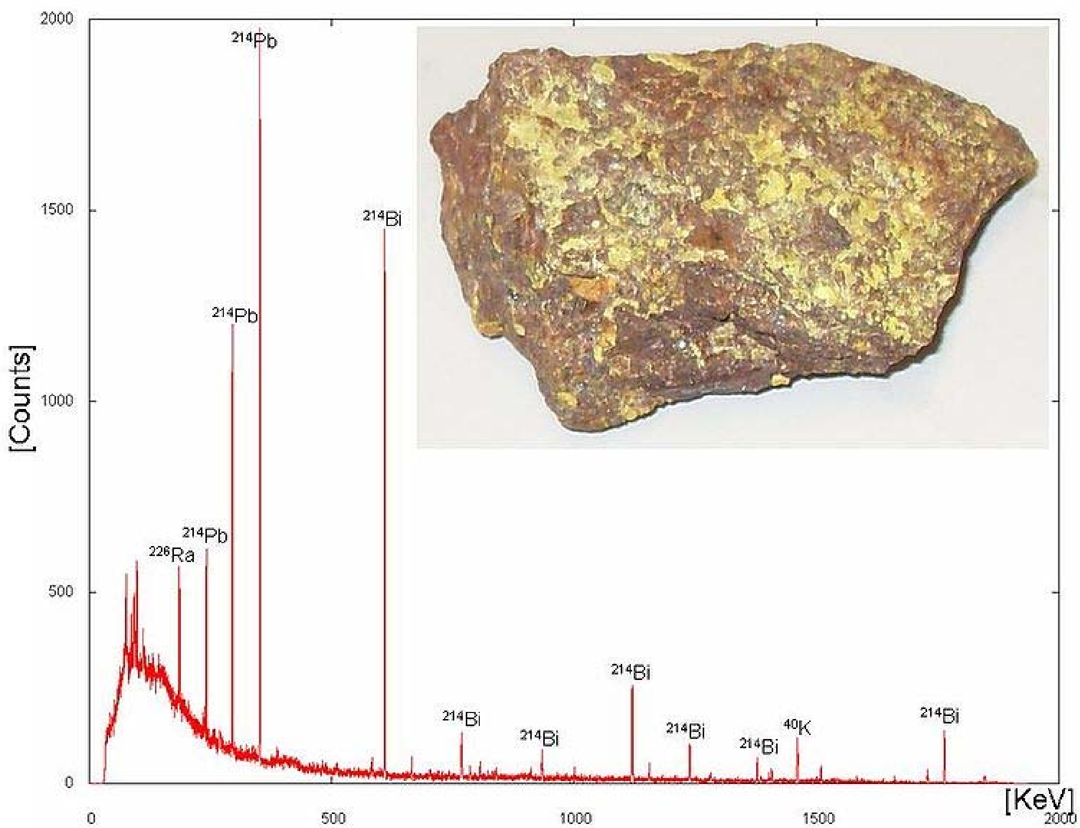
Mode of decay	Participating particles	Daughter nucleus
Decays with emission of nucleons:		
Alpha decay	An alpha particle ($A = 4$, $Z = 2$) emitted from nucleus	($A - 4$, $Z - 2$)
Proton emission	A proton ejected from nucleus	($A - 1$, $Z - 1$)
Neutron emission	A neutron ejected from nucleus	($A - 1$, 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:		
β^- decay	A nucleus emits an electron and an electron antineutrino	(A, $Z + 1$)
Positron emission (β^+	A nucleus emits a positron and a electron neutrino	(A, $Z - 1$)

decay)		
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 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*.



Gamma-ray energy spectrum of ^{238}U (inset). Gamma-rays are emitted by decaying nuclides, and the gamma-ray energy can be used to characterize the decay (which nuclide is decaying to which). Here, using the gamma-ray spectrum, several nuclides which are typical of the decay chain have been identified: ^{226}Ra, ^{214}Pb, ^{214}Bi.

An example is the natural decay chain of ^{238}U 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:

$$t_{1/2} = \frac{\ln(2)}{\lambda} = \tau \ln(2)$$
$$A = -\frac{dN}{dt} = \lambda N$$
$$S_A a_0 = -\frac{dN}{dt}\bigg|_{t=0} = \lambda N_0$$

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

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:

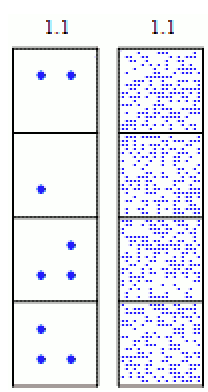
$$\left(-\frac{dN}{N}\right) = \lambda \cdot dt.$$

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:

$$N(t) = N_0\, e^{-\lambda t} = N_0\, e^{-t/\tau}.$$

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:

$$\tau = \frac{1}{\lambda}.$$



Simulation of many identical atoms undergoing radioactive decay, starting with either 4 atoms (left) or 400 (right). The number at the top indicates how many half-lives have elapsed. Note the law of large numbers: With more atoms, the overall decay is less random.

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:

$$t_{1/2} = \frac{\ln 2}{\lambda} = \tau \ln 2.$$

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 **ln2** 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 = about 36.8% remains) rather than the "1/2" life of a radionuclide where 50% remains (thus, **τ** is longer than $\mathbf{t}_{½}$). Thus, the following equation can easily be shown to be valid.

$$N(t) = N_0\, e^{-t/\tau} = N_0\, 2^{-t/t_{1/2}}.$$

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 $\mathbf{t}_{½}$ 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.

Example

A sample of C^{14}, whose half life is 5730 years, has a decay rate of 14 disintegration per minute (dpm) per gram of natural C. An artifact is found to have radioactivity of 4 dpm per gram of its present C, how old is the artifact?

Using the above equation, we have:

$$N = N_0 \, e^{-t/\tau}$$

Where: $\frac{N}{N_0} = 4/14 = 0.286$

$$\tau = \frac{T_{1/2}}{ln(2)} = 8267$$ years

$$t = -\tau \, ln(\frac{N}{N_0}) = 10360$$ years

Changing decay rates

The radioactive decay modes of electron capture and internal conversion are usually known to be slightly sensitive to chemical and environmental effects which change the electronic structure of the atom, which in turn affects the presence of **1s** and **2s** electrons which participate in the decay process. A small number of mostly light nuclides are affected. For example chemical bonds can affect the rate of electron capture to a small degree (generally less than 1%) depending on the proximity of electrons to the nucleus in beryllium. In ^{7}Be, a difference of 0.9% has been observed between half-lives in metallic and insulating environments. This relatively large effect is because beryllium is a small atom whose valence electrons are in **2s** atomic orbitals which have a large degree of penetration very close to the nucleus, and thus are subject to electron capture.

Rhenium 187 is a more spectacular example. ^{187}Re normally beta decays to ^{187}Os with a half life of 41.6×10^9 y, but studies using fully ionised ^{187}Re atoms (bare nuclei) have found that this can decrease to only 33 y. This is attributed to "bound-state β^- decay" of the fully ionised atom — the electron is emitted into the K-shell (1s orbital), which cannot occur for neutral atoms in which all low-lying bound states are occupied.

A number of experiments have found that decay rates of other modes of artificial and naturally-occurring radioisotopes are, to a high degree of precision, unaffected by external conditions such as temperature, pressure, the chemical environment and electric, magnetic or gravitational fields. Comparison of laboratory experiments over the last century, studies of the Oklo natural nuclear reactor (which exemplified the effects of thermal neutrons on nuclear decay rates), and astrophysical observations of the luminosity decays of distant supernovae (which occurred long ago so the light has taken a great deal of time to reach us), for example, strongly indicate that decay rates have been constant (at least to within the limitations of small experimental errors) as a function of time as well.

On the other hand, some recent results suggest the possibility that decay rates might have a weak dependence (0.5% or less) on environmental factors. It has been suggested that measurements of decay rates of silicon-32, manganese-54 and radium-226 exhibit small seasonal variations (of the order of 0.1%), proposed to be related to either solar flare activity or distance from the sun. However, such measurements are highly susceptible to systematic errors, and a subsequent paper has found no evidence for such correlations in a half-dozen isotopes, and sets upper limits on the size of any such effects. However, research at Purdue University indicates that the rate of radioactive decay may not be truly constant, but slightly influenced by solar flares due to variations in solar neutrino flux.

Chapter-3

Nuclear Fusion

In nuclear physics, nuclear chemistry, and astrophysics, **nuclear fusion** is the process in which two or more atomic nuclei join together to form a single heavier nucleus. This is usually accompanied by the release or absorption of large quantities of energy. Large scale thermonuclear fusion processes, involving many nuclei fusing at once, must occur in matter at very high densities and temperatures.

The fusion of two nuclei with lower masses 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. The opposite is true for the reverse process, nuclear fission.

In the simplest case of hydrogen fusion, two protons have to be brought close enough for the weak nuclear force to convert either of the identical protons into a neutron forming the hydrogen isotope deuterium. In more complex cases of heavy ion fusion involving two or more nucleons, the reaction mechanism is different, but the same result occurs - one of combining smaller nuclei into larger nuclei.

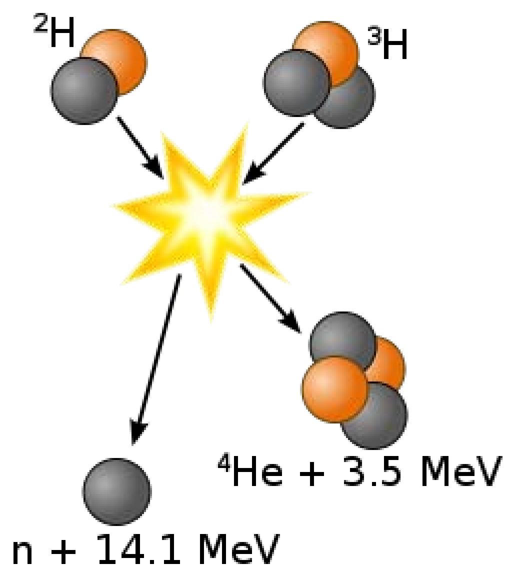
Nuclear fusion occurs naturally in all active stars. Synthetic fusion as a result of human actions has also been achieved, although this has not yet been completely controlled as a source of nuclear power. In the laboratory, successful nuclear physics experiments have been carried out that involve the fusion of many different varieties of nuclei, but the energy output has been negligible in these studies. In fact, the amount of energy put into the process has always exceeded the energy output.

Uncontrolled nuclear fusion has been carried out many times in nuclear weapons testing, which always results in a deliberate explosion. These explosions have always used the heavy isotopes of hydrogen, deuterium (H-2) and tritium (H-3), and never the much more common isotope of hydrogen (H-1), sometimes called "protium".

Building upon the nuclear transmutation experiments by Ernest Rutherford, carried out several years earlier, the fusion of the light nuclei (hydrogen isotopes) was first accomplished by Mark Oliphant in 1932. Then, the steps of the main cycle of nuclear fusion in stars were first 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 this was not accomplished until 1951, and nuclear fusion on a large scale in an explosion was first carried out on November 1, 1952, in the Ivy Mike hydrogen bomb test. Research into developing controlled thermonuclear fusion for civil purposes also began in the 1950s, and it continues to this day.

Overview



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 $E = \Delta mc^2$.

Fusion reactions power the stars and produce virtually all elements in a process called nucleosynthesis. Although the fusion of lighter elements in stars releases energy, production of elements heavier than iron 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. Non-self sustaining reactions 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 that theoretically will deliver ten times more fusion energy than the amount needed to heat up plasma to required temperatures were originally scheduled to be operational in 2018, however this has been delayed and a new date has not been stated.

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 National Ignition Facility, which uses laser-driven inertial confinement fusion, is thought to be capable of break-even fusion. The first large-scale laser target experiments were performed in June 2009 and ignition experiments will begin in 2010.

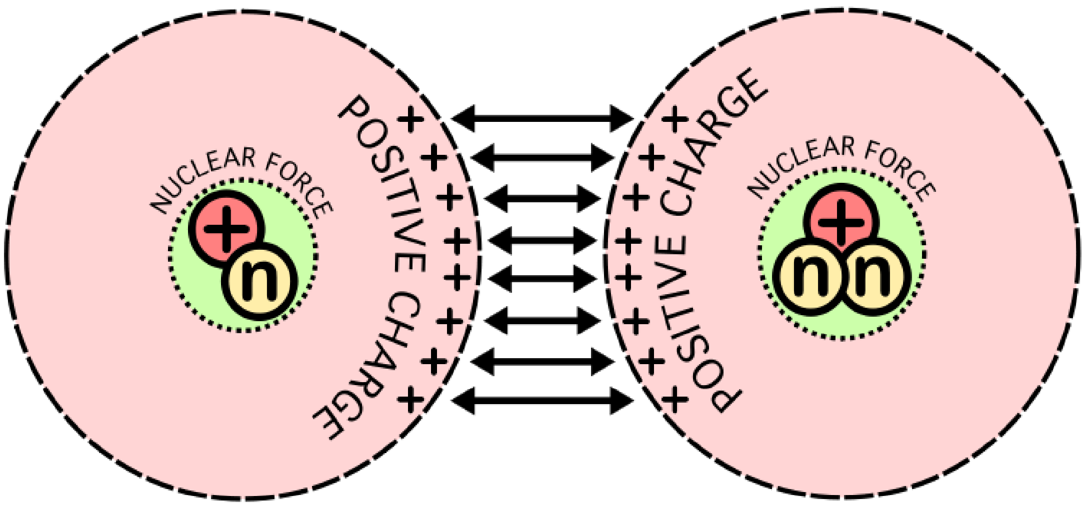
The energy released in most nuclear reactions is much larger than that in chemical reactions, because the binding energy that holds a nucleus together is far greater than the energy that holds electrons to a nucleus. For example, the ionization energy gained by adding an electron to a hydrogen nucleus is 13.6 eV—less than one-millionth of the 17 MeV released in the deuterium–tritium (D–T) reaction shown in the diagram to the right. Fusion reactions have an energy density many times greater than nuclear fission; 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 nuclear 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. It is important to keep in mind that the above picture is a toy model because nucleons are quantum objects, and so, for example, since two neutrons in a nucleus are identical to each other, distinguishing one from the other, such as which one is in the interior and which is on the surface, is in fact meaningless, and the inclusion of quantum mechanics is necessary for proper calculations.

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.

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.

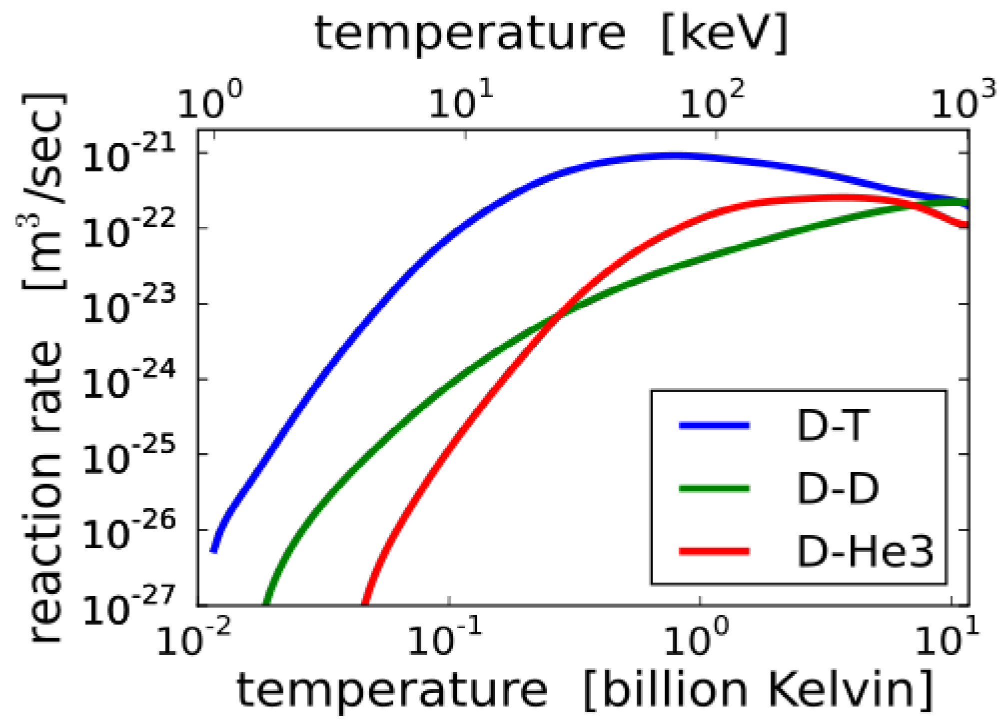
The situation is similar if two nuclei are brought together. As they approach each other, all the protons in one nucleus repel all the protons in the other. Not until the two nuclei actually come in contact can the strong nuclear force take over. Consequently, even when the final energy state is lower, 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}He nucleus, which immediately ejects a neutron with 14.1 MeV. The recoil energy of the remaining ^{4}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, the process is called *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 kelvin shows that the barrier would be overcome at a temperature in excess of 120 million kelvins.

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 kelvin) 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 <σv> times the product of the reactant number densities:

$$f = n_1 n_2 \langle \sigma v \rangle.$$

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 $(1/2)n^2$.

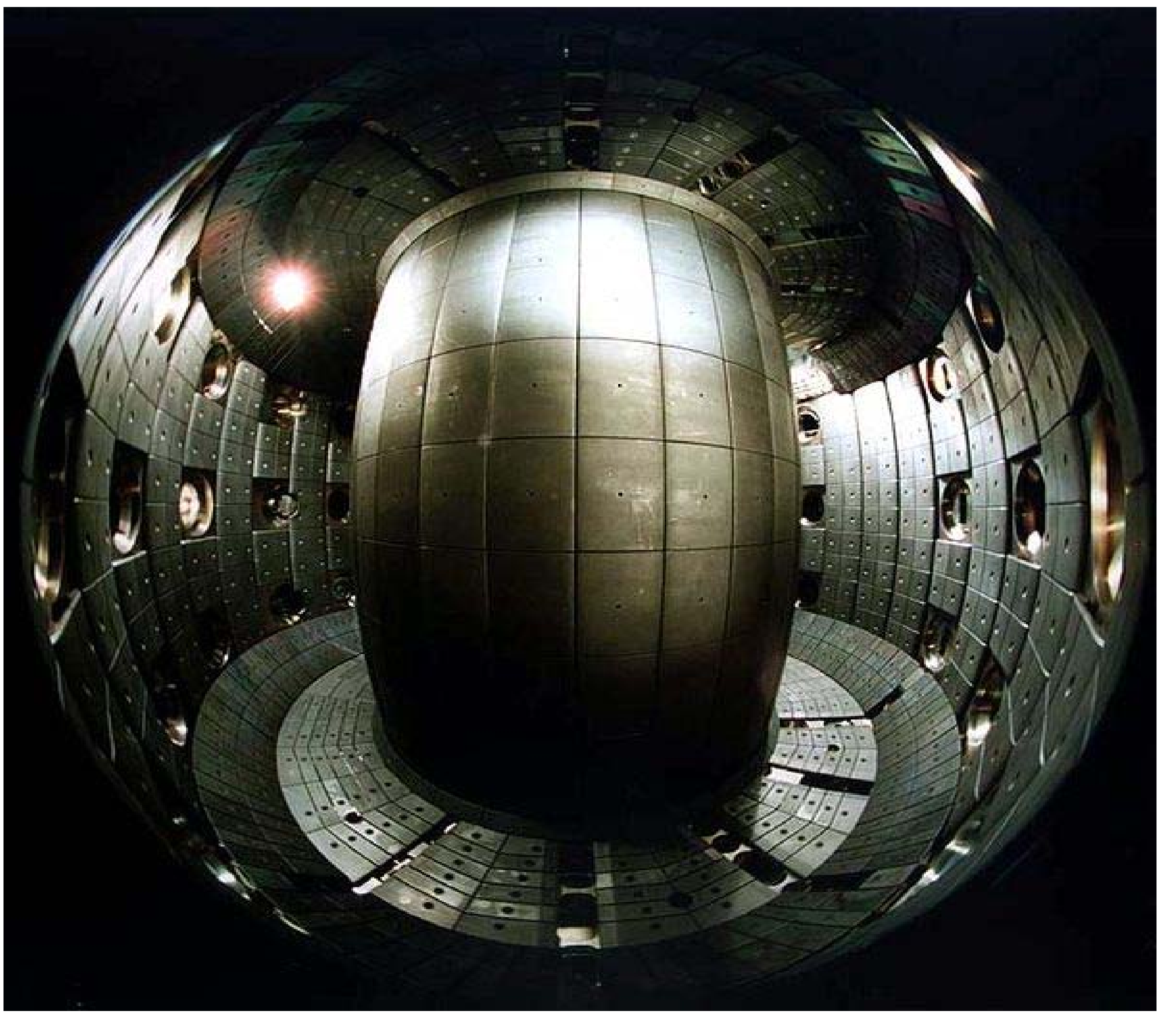
$\langle \sigma v \rangle$ increases from virtually zero at room temperatures up to meaningful magnitudes at temperatures of 10–100 keV. At these temperatures, well above typical ionization energies (13.6 eV in the hydrogen case), the fusion reactants exist in a plasma state.

The significance of $\langle \sigma v \rangle$ 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 least massive of which that are capable of fusion are red 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



TCV inner view, with graphite-claded torus

Magnetic confinement fusion is an approach to generating fusion energy that uses magnetic fields to confine the hot 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.

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.

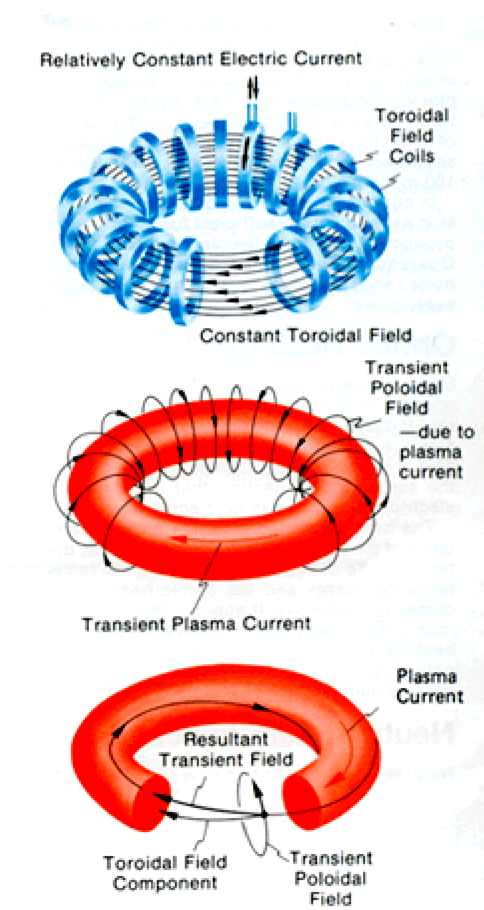
There are two approaches to solving this problem. One is to try to stop up the ends with a magnetic mirror, the other is to eliminate the ends altogether by bending the field lines around to close on themselves. A simple toroidal field, however, provides poor confinement because the radial gradient of 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 Mirror Fusion Test Facility (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.



Tokamak magnetic fields

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

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.

Muon-catalyzed 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 cannot occur because of the energy required to create muons, their 2.2 μs 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 is a technique using particle accelerators to achieve particle kinetic energies sufficient to induce light-ion fusion reactions. Accelerating light ions is relatively easy, 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 kV 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 the vast majority of ions end 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 that 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.

Sonofusion or bubble fusion, a controversial variation on the sonoluminescence theme, suggests that acoustic shock waves, creating temporary bubbles (cavitation) that expand and collapse shortly after creation, can produce temperatures and pressures sufficient for nuclear fusion.

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 that 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, and pure fusion bombs 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 (−29 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.

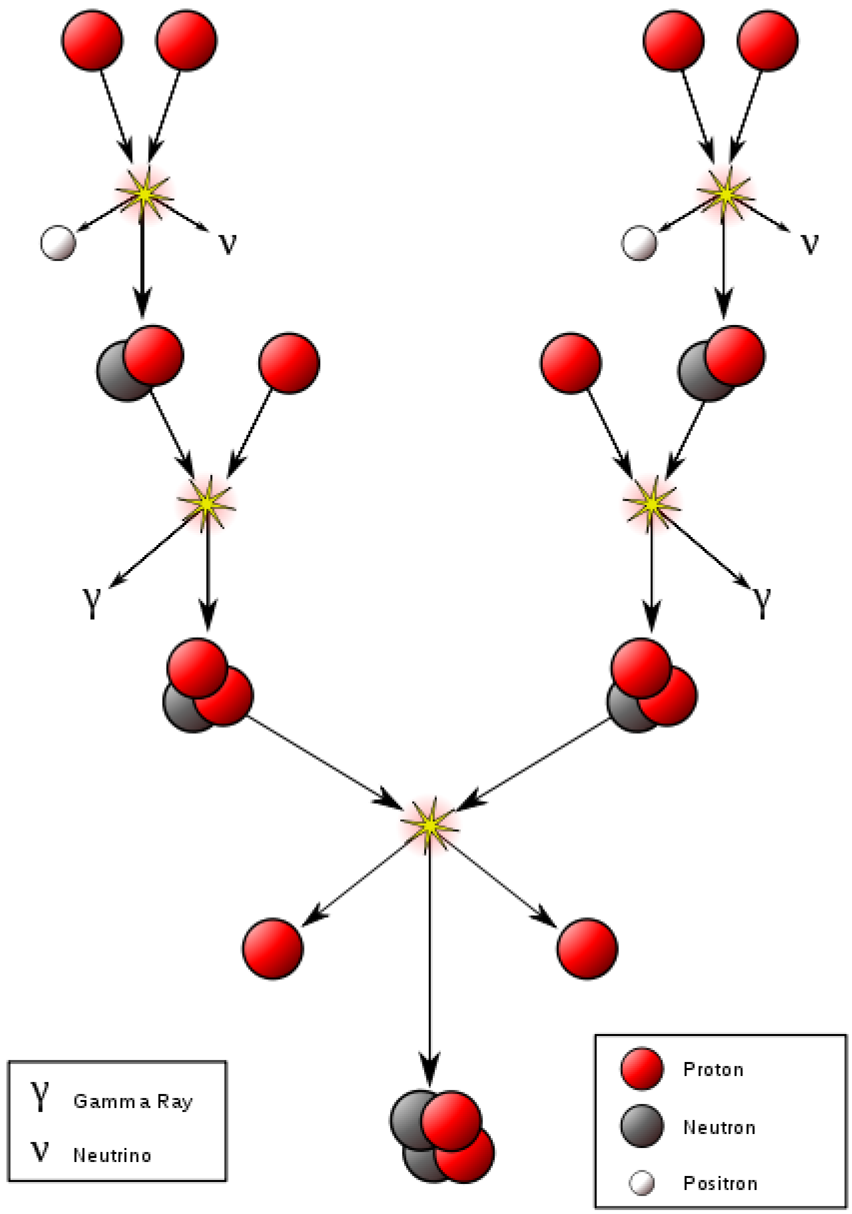
Hot fusion

In hot fusion, the fuel reaches tremendous temperature and pressure inside a fusion reactor or nuclear weapon (or star).

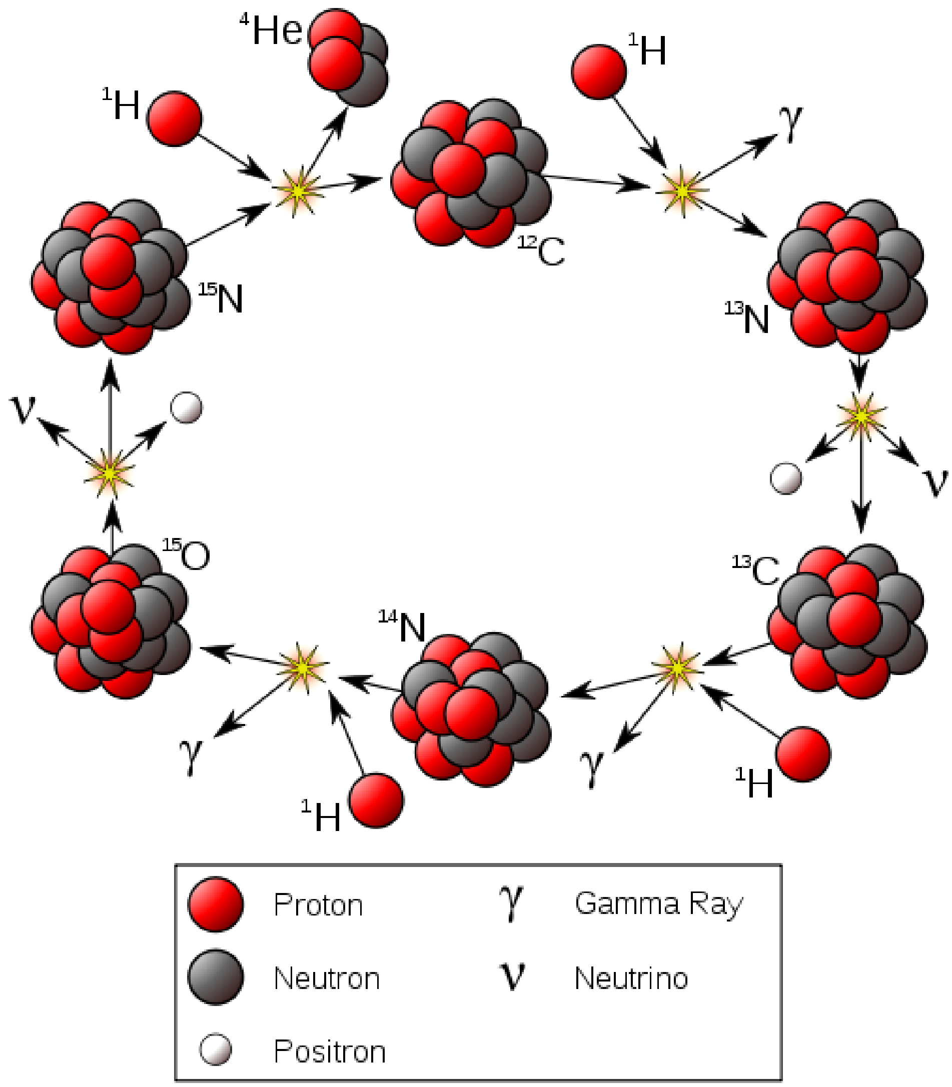
The methods in the second group are examples of non-equilibrium systems, in which very high temperatures and pressures are produced in a relatively small region adjacent to material of much lower temperature. In his doctoral thesis for MIT, Todd Rider did a theoretical study of all quasineutral, isotropic, 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 proton-proton chain dominates in stars the size of the Sun or smaller



The CNO cycle dominates in stars heavier than the Sun

The most important fusion process in nature is the one that powers 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/cm³), the energy release rate is only 276 μW/cm³—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*)), achieving reasonable energy production rates in terrestrial fusion reactors requires 10–100 times higher temperatures (compared to stellar interiors): $T \approx 0.1$–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*.

To be a useful energy source, 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 ^{4}He the most common product because of its extraordinarily tight binding, although ^{3}He and ^{3}H 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. 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.

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 D-^{6}Li reaction has no advantage compared to p^+-115B because it is roughly as difficult to burn but produces substantially more neutrons through 21D-21D side reactions. There is also a p^+-73Li reaction, but the cross section is far too low, except possibly when $T_i > 1$ MeV, but at such high temperatures an endothermic, direct neutron-producing reaction also becomes very significant. Finally there is also a p^+-94Be reaction, which is not only difficult to burn, but 94Be 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:

$$n^0 + {}^{6}_{3}Li \rightarrow {}^{3}_{1}T + {}^{4}_{2}He$$

$$n^0 + {}^{7}_{3}Li \rightarrow {}^{3}_{1}T + {}^{4}_{2}He + n^0$$

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 has a maximum plasma pressure it can sustain, and an economical device would 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 $\langle\sigma v\rangle/T^2$. (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]**	**$\langle\sigma v\rangle/T^2$ [m³/s/keV²]**
${}^{2}_{1}D$-${}^{3}_{1}T$	13.6	1.24×10^{-24}
${}^{2}_{1}D$-${}^{2}_{1}D$	15	1.28×10^{-26}
${}^{2}_{1}D$-${}^{3}_{2}He$	58	2.24×10^{-26}
p^+-${}^{6}_{3}Li$	66	1.46×10^{-27}
p^+-${}^{11}_{5}B$	123	3.01×10^{-27}

Note that many of the reactions form chains. For instance, a reactor fueled with ${}^{3}_{1}T$ and ${}^{3}_{2}He$ creates some ${}^{2}_{1}D$, which is then possible to use in the ${}^{2}_{1}D$-${}^{3}_{2}He$ reaction if the energies are "right". An elegant idea is to combine the reactions (8) and (9). The ${}^{3}_{2}He$ from reaction (8) can react with ${}^{6}_{3}Li$ in reaction (9) before completely thermalizing. This produces an energetic proton, which in turn undergoes reaction (8) before thermalizing. Detailed analysis shows that this idea would not 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 man-made fusion device yet to achieve ignition is the hydrogen bomb. The detonation of the first device, 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 $^{2}_{1}$D-$^{2}_{1}$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 $^{3}_{1}$T and $^{3}_{2}$He products. $^{3}_{1}$T burns so well in a deuterium plasma that it is almost impossible to extract from the plasma. The $^{2}_{1}$D-$^{3}_{2}$He reaction is optimized at a much higher temperature, so the burnup at the optimum $^{2}_{1}$D-$^{2}_{1}$D temperature may be low, so it seems reasonable to assume the $^{3}_{1}$T but not the $^{3}_{2}$He gets burned up and adds its energy to the net reaction. Thus we count the $^{2}_{1}$D-$^{2}_{1}$D fusion energy as $E_{\mathrm{fus}} = (4.03+17.6+3.27)/2 = 12.5$ MeV and the energy in charged particles as $E_{\mathrm{ch}} = (4.03+3.5+0.82)/2 = 4.2$ MeV.

Another unique aspect of the $^{2}_{1}$D-$^{2}_{1}$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
${}^{2}_{1}$D-${}^{3}_{1}$T	1	17.6	3.5	0.80
${}^{2}_{1}$D-${}^{2}_{1}$D	1	12.5	4.2	0.66
${}^{2}_{1}$D-${}^{3}_{2}$He	2	18.3	18.3	~0.05
p^{+}-${}^{11}_{5}$B	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 $(E_{fus}-E_{ch})/E_{fus}$. 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 ${}^{2}_{1}$D-${}^{2}_{1}$D 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 ${}^{2}_{1}$D-${}^{2}_{1}$D 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
${}^{2}_{1}$D-${}^{3}_{1}$T	1.24×10^{-24}	1	1	1	34	1
${}^{2}_{1}$D-${}^{2}_{1}$D	1.28×10^{-26}	2	48	30	0.5	68
${}^{2}_{1}$D-${}^{3}_{2}$He	2.24×10^{-26}	2/3	83	16	0.43	80
p^{+}-	1.46×10^{-27}	1/2	1700		0.005	6800

$^{6}_{3}$Li						
p^{+}-$^{11}_{5}$B	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 $^{2}_{1}$D-$^{3}_{1}$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 $^{2}_{1}$D-$^{3}_{1}$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 $^{2}_{1}$D-$^{3}_{1}$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. The following table shows the rough optimum temperature and the power ratio at that temperature for several reactions.

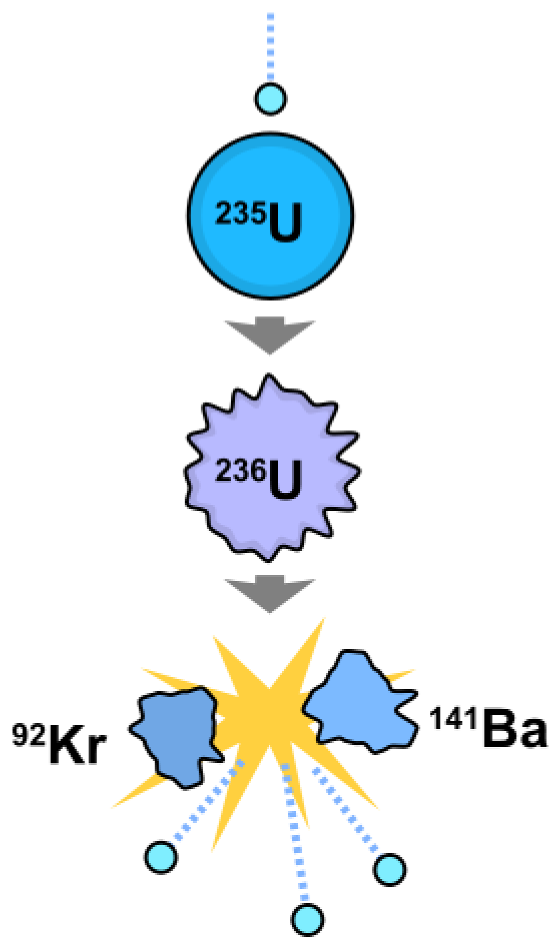
fuel	T_i (keV)	$P_{fusion}/P_{Bremsstrahlung}$
$^{2}_{1}$D-$^{3}_{1}$T	50	140
$^{2}_{1}$D-$^{2}_{1}$D	500	2.9
$^{2}_{1}$D-$^{3}_{2}$He	100	5.3
$^{3}_{2}$He-$^{3}_{2}$He	1000	0.72
p^{+}-$^{6}_{3}$Li	800	0.21
p^{+}-$^{11}_{5}$B	300	0.57

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 then 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 $^{2}_{1}D$-$^{3}_{1}T$ very much because the Bremsstrahlung fraction is low, but it will push the other fuels into regimes where the power density relative to $^{2}_{1}D$-$^{3}_{1}T$ is even lower and the required confinement even more difficult to achieve. For $^{2}_{1}D$-$^{2}_{1}D$ and $^{2}_{1}D$-$^{3}_{2}He$, Bremsstrahlung losses will be a serious, possibly prohibitive problem. For $^{3}_{2}He$-$^{3}_{2}He$, p^{+}-$^{6}_{3}Li$ and p^{+}-$^{11}_{5}B$ the Bremsstrahlung losses appear to make a fusion reactor using these fuels with a quasineutral, isotropic 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.

Chapter-4

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 releases three free neutrons.

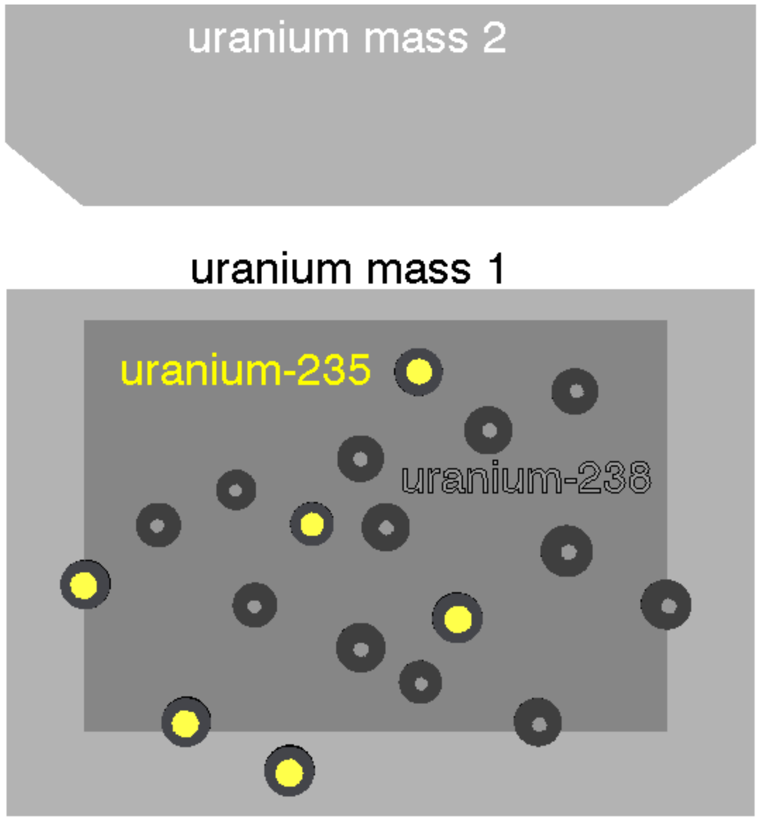
In nuclear physics and nuclear chemistry, **nuclear fission** is a nuclear reaction in which the nucleus of an atom splits into smaller parts (lighter nuclei), often producing free neutrons and photons (in the form of gamma rays), as well. Fission of heavy elements is an exothermic reaction which can 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 lower 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. The products of nuclear fission, however, are on average far more radioactive than the heavy elements which are normally fissioned as fuel, 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 visual 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.

Nuclear fission can occur without neutron bombardment, as a type of radioactive decay. This type of fission (called spontaneous fission) is rare except in a few heavy isotopes. In engineered nuclear devices, essentially all 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 amount of nuclear reactions are known to us till date. 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 (200 MeV) 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 per unit mass 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. The latter figure means that a nuclear fission explosion or criticality accident emits about 3.5% of its energy as gamma rays, less than 2.5% of its energy as fast neutrons (total ~ 6%), and the rest as kinetic energy of fission fragments ("heat"). In an atomic bomb, this heat may serve to raise the temperature of the bomb core to 100 million kelvin and cause secondary emission of soft X-rays, which convert some of this energy to ionizing radiation. However, in nuclear generators, the fission fragment kinetic energy remains as low-temperature heat which causes little or no ionization.

So-called neutron bombs (enhanced radiation weapons) have been constructed which release a larger fraction of their energy as ionizing radiation (specifically, neutrons), but these are all thermonuclear devices which rely on the nuclear fusion stage to produce the extra radiation. The energy dynamics of pure fission bombs always remain at about 6% yield of the total in radiation, as a prompt result of fission.

The total *prompt fission* energy amounts to about 181 MeV, or ~ 89% of the total energy which is eventually released by fission over time. The remaining ~ 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). Thus, an additional 6% of the total energy of fission is also released eventually as non-prompt ionizing radiation, and this is about evenly divided between gamma and beta ray energy. The remainder is antineutrinos.

The 8.8 MeV/202.5 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 (the amount absorbed is miniscule). Neutrino radiation is ordinarily not classed as ionizing radiation, because it is not absorbed and therefore does not produce effects. Almost all of the rest of the radiation (beta and gamma radiation) is eventually converted to heat in a 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 manually shut them down (for this reason, designer Enrico Fermi included radiation-counter-triggered control rods, suspended by electromagnets, which could automatically drop into the center of Chicago Pile-1). If these delayed 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).

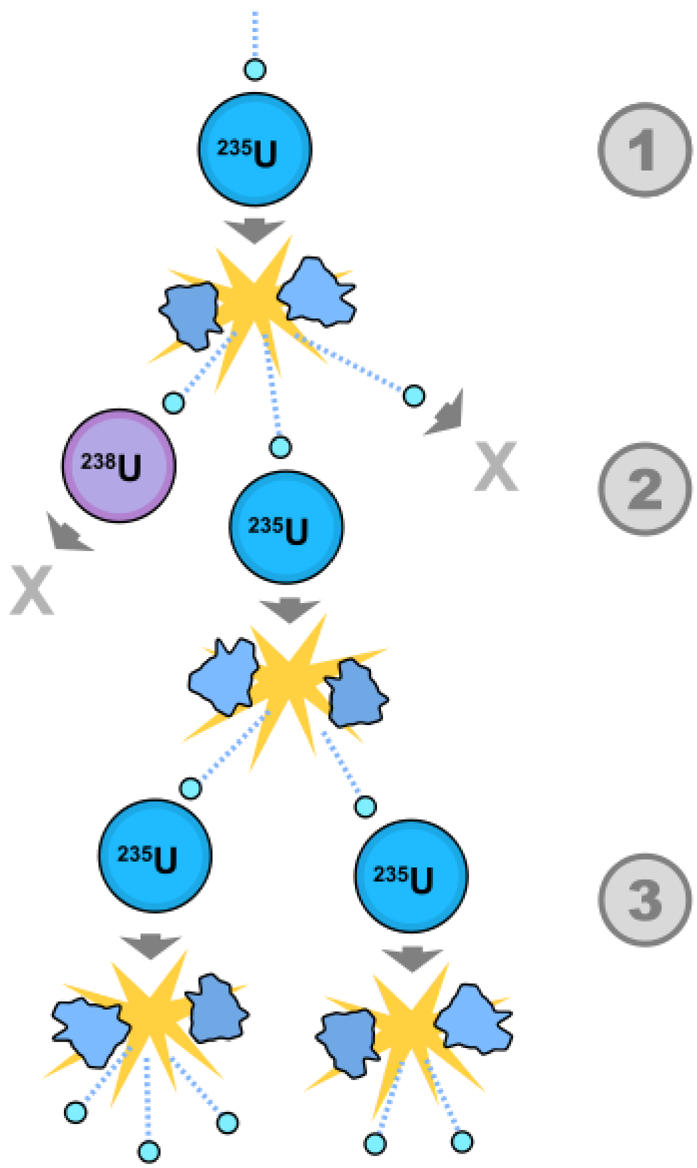
Origin of the active energy and the curve of binding energy

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 (**Mp**) from a single reaction is less than the mass of the original fuel nucleus (**M**). The excess mass **Δm** = **M** – **Mp** 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 nuclear force between nucleons, which overcomes the electrostatic repulsion between protons. However, the nuclear force acts only over relatively short ranges (a few nucleon diameters), since it follows an exponentially decaying Yukawa potential which makes it insignificant at longer distances. The electrostatic repulsion is of longer range, since it decays by an inverse-square rule, so that nuclei larger than about 12 nucleons in diameter reach a point that the total electrostatic repulsion overcomes the nuclear force and causes them to be spontaneously unstable. For the same reason, larger nuclei (more than about eight nucleons in diameter) are less tightly bound per unit mass than are smaller nuclei; breaking a large nucleus into two or more intermediate-sized nuclei, releases energy. The origin of this energy is the nuclear force, which intermediate-sized nuclei allows to act more efficiently, because each nucleon has more neighbors which are within the short range attraction of this force.

Also because of the short range of the strong binding force, large stable nuclei must contain proportionally more neutrons than do the lightest elements, which are most stable with a **1 to 1 ratio** of protons and neutrons. Nuclei which have more than 20 protons cannot be stable unless they have more than an equal number of neutrons. Extra neutrons stabilize heavy elements because they add to strong-force binding (which acts between all nucleons), 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 to beta decay (which changes neutrons to protons) because they have proportionally too many neutrons compared to stable isotopes of similar mass. This tendency for fission product nuclei to beta-decay 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 in the fission-product atoms.

Chain reactions



A schematic 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 some binding energy. 2. One of those neutrons is absorbed by an atom of uranium-238 and does not continue the reaction. Another neutron is simply lost and does not collide with anything, also not continuing the reaction. However one neutron does collide with an atom of uranium-235, which then fissions and releases two neutrons and some binding energy. 3. Both of those neutrons collide with uranium-235 atoms, each of which fissions and releases between one and three 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. ^{2}H and ^{3}H). 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.

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 rest masses of the fission fragments and ejected neutrons is less than the sum of the rest masses of the original atom and incident neutron (of course the fission fragments are not at rest). The mass difference is accounted for in the release of energy according to the equation **$E=\Delta mc^2$**:

mass of released energy = $\frac{E}{c^2} = m_{\text{original}} - m_{\text{final}}$

Due to the extremely large value of the speed of light, c, a small decrease in mass is associated with a tremendous release of active energy (for example, the kinetic energy of the fission fragments). This energy (in the form of radiation and heat) **carries** the missing mass, when it leaves the reaction system (total mass, like total energy, is always conserved). 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.

Two typical fission reactions are shown below with average values of energy released and number of neutrons ejected:

$$^{235}U + \text{neutron} \rightarrow \text{fission fragments} + 2.4\ \text{neutrons} + 192.9\ \text{MeV}$$
$$^{239}Pu + \text{neutron} \rightarrow \text{fission fragments} + 2.9\ \text{neutrons} + 198.5\ \text{MeV}$$

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:

$$\Lambda = \frac{l}{k}$$

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.

When describing kinetics and dynamics of nuclear reactors and also in the practice of reactor operation is used the concept of Reactivity (nuclear), which characterizes the deflection of reactor from the critical state. $\rho=(k-1)/k$.

In a nuclear reactor, *k* will actually oscillate from slightly less than 1 to slightly more than 1, due primarily to thermal effects (as more power is produced, the fuel rods warm and thus expand, lowering their capture ratio, and thus driving *k* lower). This leaves the average value of *k* at exactly 1. Delayed neutrons play an important role in the timing of these oscillations.

In an infinite medium, the multiplication factor may be described by the four factor formula; in a non-infinite medium, the multiplication factor may be described by the six 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 orders of magnitude 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.

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

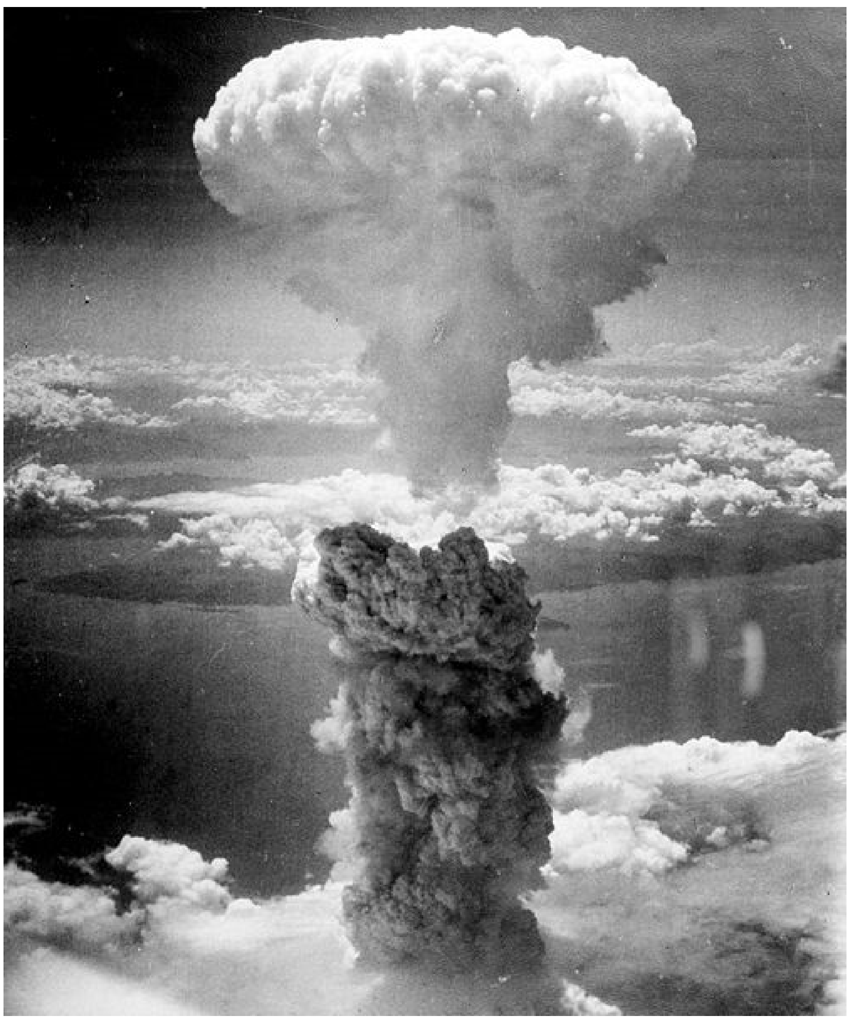
Critical fission reactors are the most common type of nuclear reactor. In a critical fission reactor, neutrons produced by fission of fuel atoms are used to induce yet more fissions, to sustain a controllable amount of energy release. Devices that produce engineered but non-self-sustaining fission reactions 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.

Fission bombs



The mushroom cloud of the atom bomb dropped on Nagasaki, Japan in 1945 rose some 18 kilometers (11 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 Trinity test bomb and the Little Boy and Fat Man bombs that were exploded over 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 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. 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). It is also difficult to extract useful power from a nuclear explosive, although at least one rocket propulsion system, Project Orion, is intended to work by exploding fission bombs behind a massively-padded and shielded 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 many 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.

History

Discovery of fission

The discovery of nuclear fission occurred in 1938, following nearly five decades of work on the science of radioactivity and the elaboration of new nuclear physics that described the components of atoms. In 1911, Ernest Rutherford proposed a model of the atom in which a very small, dense and positively-charged nucleus of protons was surrounded by orbiting, negatively-charged electrons (the Rutherford model). Niels Bohr improved upon this in 1913 by reconciling the quantum behavior of electrons (the Bohr model). Work by

Henri Becquerel, Marie Curie, Pierre Curie, and Rutherford further elaborated that the nucleus, though tightly bound, could undergo different forms of radioactive decay, and thereby transmute into other elements (for example, by losing an alpha particle). All known radioactive processes before fission changed mass of the atomic nucleus by no more than two protons. Albert Einstein's principle of mass–energy equivalence described the amount of energy released in such processes, but this could not be harnessed on a large scale. The possibility of combining two light nuclei in nuclear fusion had been studied in connection with the processes which power stars.

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. Fermi concluded that his experiments had created a new element with 94 protons, which he dubbed Hesperium. However, not all were convinced with Fermi's analysis of his results. The German chemist Ida Noddack notably suggested in 1934 that instead of creating a new, heavier element, that "it is conceivable that the nucleus breaks up into several large fragments." However, Noddack's conclusion was not pursued.

The experimental apparatus with which 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 Berlin. 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. Hahn was unsure of what the physical basis for the results were—barium had an atomic mass 60% less than uranium, and no previously known methods of radioactive decay could account for such a radical difference in the size of the nucleus. In Sweden, 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 short, Meitner had correctly interpreted Hahn's results to mean that the nucleus of uranium had split roughly in half. Frisch named the process "fission" as an analogy to binary fission in the biological sciences.

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 who have documented the history of the discovery of nuclear fission believe Meitner should have been awarded the Nobel Prize with Hahn.

News spread quickly of the new discovery, which was correctly seen as an entirely novel physical effect with great scientific—and potentially practical—possibilities. 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. I.I. 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 experiment involved placing uranium oxide inside of an ionization chamber and irradiating it with neutrons, and measuring the energy thus released. The results confirmed that fission was occurring and hinted strongly that it was the isotope uranium 235 in particular that was fissioning. 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.

During this period, the Hungarian physicist Leo Szilárd, then in the United States, realized that fission could be used to create a nuclear chain reaction, an idea he had first formulated in 1933. If the number of secondary neutrons produced by each fissioning nucleus was greater than one, then each fission reaction could, in theory, trigger two more reactions. Such a system of exponential growth held out the possibility of using uranium fission as a means to generate large amounts of energy, either for civilian (i.e. electric) purposes, or even for military purposes—an atomic bomb. Szilard urged Fermi (in New York) and Frédéric Joliot-Curie (in Paris) to refrain from publishing on the possibility of a chain reaction, lest the Nazi government become aware of the possibilities on the eve of World War II. Fermi agreed to self-censor, with some hesitation. But Joliot-Curie, however, did not, and in April 1939, his team in Paris (Joliot-Curie, Hans von Halban, and Lew Kowarski) reported in *Nature* that the number of neutrons emitted with nuclear fission of ^{235}U was then reported at 3.5 per fission. (They later corrected this to 2.6 per fission.) Simultaneous work by Szilard and Walter Zinn confirmed these results. This appeared to make the possibility of building nuclear reactors, and perhaps nuclear bombs, possible in theory. There was still much unknown about fission and chain reacting systems, however.

The fission chain reaction

"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 considered that neutrons would be ideal for such a situation, since they lacked an electrostatic charge.

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. Fermi had shown much earlier that neutrons were far more effectively captured by atoms if they were of low energy (so-called "slow" or "thermal" neutrons), because for quantum reasons it made the atoms look like much larger targets to the neutrons. Thus to slow down the secondary neutrons released by the fissioning uranium nuclei, Fermi and Szilard proposed a graphite "moderator," against which the fast, high-energy secondary neutrons would collide, effectively slowing them down. With enough uranium, and with pure-enough graphite, their "pile" could theoretically sustain a slow-neutron chain reaction. This would result in the production of heat, as well as the creation of radioactive fission products.

In August 1939, Szilard and fellow Hungarian refugees physicists Teller and Wigner thought that the Germans might make use of the fission chain reaction and were spurred to attempt to attract the attention of the United States government to the issue. Towards this, they persuaded German-Jewish refugee Albert Einstein to lend his name to a letter directed to President Franklin Roosevelt. 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. Roosevelt ordered that a scientific committee be authorized for overseeing uranium work and allocated a small sum of money for pile research.

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. Most of these models were still under the assumption that the bombs would be powered by slow neutron reactions—and thus be similar to a reactor undergoing a meltdown.

In Birmingham, England, Frisch teamed up with Peierls, a fellow German-Jewish refugee. They had the idea of using a purified mass of the uranium isotope ^{235}U, which had a cross section just determined, and which was much larger than that of ^{238}U or natural uranium (which is 99.3% the latter isotope). Assuming that the cross section for fast-neutron fission of ^{235}U was the same as for slow neutron fission, they determined that a pure ^{235}U bomb could have a critical mass of only 6 kg 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, Joseph W. Kennedy, Arthur 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 a fissile material, like ^{235}U.

The possibility of isolating uranium-235 was technically daunting, because uranium-235 and uranium-238 are chemically identical, and vary in their mass by only the weight of three neutrons. However, if a sufficient quantity of uranium-235 could be isolated, it would allow for a fast neutron fission chain reaction. This would be extremely explosive, a true "atomic bomb." The discovery that plutonium-239 could be produced in a nuclear reactor pointed towards another approach to a fast neutron fission bomb. Both approaches were extremely novel and not yet well understood, and there was considerable scientific skepticism at the idea that they could be developed in a short amount of time.

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 to achieve criticality, due to lack of proper materials, or not enough of the proper 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 and ending it prematurely.)

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; and 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 or "Ames" 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—among many others— prevented the Nazis from building a nuclear reactor capable of criticality during the war.

Manhattan Project and beyond

In the United States, an all-out effort for making atomic weapons was begun in late 1942. This work was taken over by the U.S. Army Corps of Engineers in 1943, and known as the Manhattan Engineer District. The top-secret Manhattan Project, as it was colloquially known, was led by General Leslie R. Groves. Among the projects dozens of sites were: Hanford Site in Washington state, which had the first industrial-scale nuclear reactors; Oak Ridge, Tennessee, which was primarily concerned with uranium enrichment; and Los Alamos, in New Mexico, which was the scientific hub for research on bomb development at design. Other sites, notably the Berkeley Radiation Laboratory and the Metallurgical Laboratory at the University of Chicago, played important contributing roles. Overall scientific direction of the project was managed by the physicist J. Robert Oppenheimer.

In July 1945, the first atomic bomb, dubbed "Trinity", was detonated in the New Mexico desert. It was fueled by plutonium created at Hanford. In August 1945, two more atomic bombs—"Little Boy", a uranium-235 bomb, and "Fat Man", a plutonium bomb—were used against the Japanese cities of Hiroshima and Nagasaki.

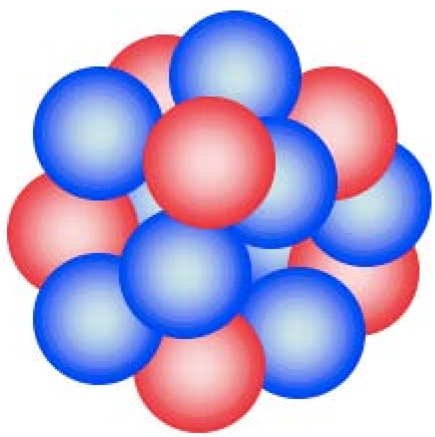
In the years after World War II, many countries were involved in the further development of nuclear fission for the purposes of nuclear reactors and nuclear weapons.

Natural fission chain-reactors on Earth

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. 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 far in the past and would not be possible now. This ancient process was able to use normal water as a moderator only because 2 billion years before the present, 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).

Chapter-5

Nucleon



An atomic nucleus is a compact bundle of the two types of nucleons: Protons (red) and neutrons (blue). In this picture, the protons and neutrons look like little balls stuck together, but an actual nucleus, as understood by modern nuclear physics, does not look like this. An actual nucleus can only be accurately described using quantum mechanics. For example, in a real nucleus, each nucleon is in multiple locations at once, spread throughout the nucleus.

In physics, a **nucleon** is a collective name for two particles: the neutron and the proton. These are the two constituents of the atomic nucleus. Until the 1960s, the nucleons were thought to be elementary particles. Now they are known to be composite particles, each made of three quarks bound together by the so-called strong interaction.

The interaction between two or more nucleons is called internucleon interactions or nuclear force, which is also ultimately caused by the strong interaction. (Before the discovery of quarks, the term "strong interaction" referred to just internucleon interactions.)

Nucleons sit at the boundary where particle physics and nuclear physics overlap. Particle physics, particularly quantum chromodynamics, provides the fundamental equations that explain the properties of quarks and of the strong interaction. These equations explain quantitatively how quarks can bind together into protons and neutrons (and all the other hadrons). However, when multiple nucleons are assembled into an atomic nucleus (nuclide), these fundamental equations become too difficult to solve directly. Instead, nuclides are studied within nuclear physics, which studies nucleons and their interactions by approximations and models, such as the nuclear shell model. These models can successfully explain nuclide properties, for example, whether or not a certain nuclide undergoes radioactive decay.

The proton and neutron are both baryons and both fermions. In the terminology of particle physics, these two particles make up an isospin doublet ($\mathbf{I} = \frac{1}{2}$). This explains why their masses are so similar, with the neutron just 0.1% heavier than the proton.

Nucleon properties

Protons and neutrons are most important and best known for constituting atomic nuclei, but they can also be found on their own, not part of a larger nucleus. A proton on its own is the nucleus of the hydrogen-1 atom (^1H). A neutron on its own is unstable (see below), but they can be found in nuclear reactions and are used in scientific analysis.

Both the proton and neutron are made of three quarks. The proton is made of two up quarks and one down quark, while the neutron is one up quark and two down quarks. The quarks are held together by the strong force. It is also said that the quarks are held together by gluons, but this is just a different way to say the same thing (gluons mediate the strong force).

An up quark has electric charge $+\frac{2}{3}$ e, and a down quark has charge $-\frac{1}{3}$ e, so the total electric charge of the proton and neutron are +e and 0, respectively. The word "neutron" comes from the fact that it is electrically "neutral".

The mass of the proton and neutron is quite similar: The proton is 1.6726×10^{-27} kg or 938.27 MeV/c^2, while the neutron is 1.6749×10^{-27} kg or 939.57 MeV/c^2. The neutron is roughly 0.1% heavier. The similarity in mass is explained by the isospin approximate-symmetry in particle physics (also see below).

The spin of both protons and neutrons is $\frac{1}{2}$. This means they are fermions not bosons, and therefore, like electrons, they are subject to the Pauli exclusion principle. This is a very important fact in nuclear physics: Protons and neutrons in an atomic nucleus cannot all be in the same quantum state, but instead they spread out into nuclear shells analogous to electron shells in chemistry. Another reason that the spin of the proton and neutron is important is because it is the source of nuclear spin in larger nuclei. Nuclear spin is best known for its crucial role in the NMR/MRI technique for chemistry and biochemistry analysis.

The magnetic moment of a proton, denoted μ_p, is 2.79 nuclear magnetons (μ_N), while the magnetic moment of a neutron is $\mu_n = -1.91\ \mu_N$. These parameters are also important in NMR/MRI.

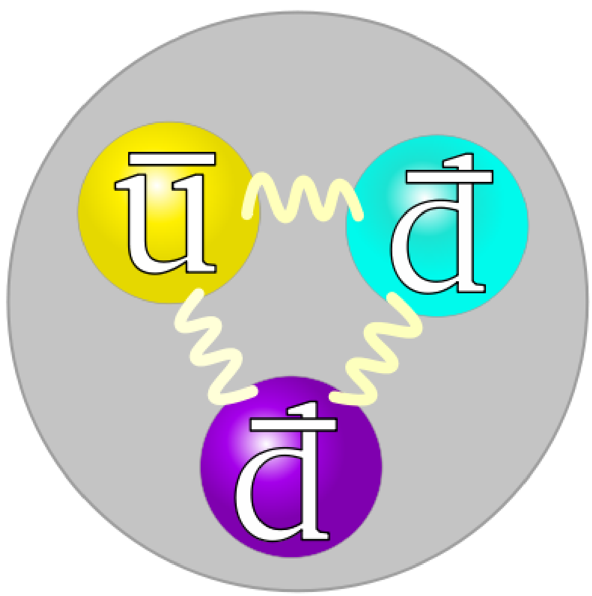
Stability of nucleons

A neutron by itself is an unstable particle: It undergoes β^- decay (a type of radioactive decay) by turning into a proton, electron, and electron antineutrino, with a half-life around ten minutes. A proton by itself is thought to be stable, or at least its lifetime is too long to measure.

Inside a nucleus, on the other hand, both protons and neutrons can be stable or unstable, depending on the nuclide. Inside some nuclides, a neutron can turn into a proton (plus other particles) as described above; inside other nuclides the reverse can happen, where a proton turns into a neutron (plus other particles) through β^+ decay or electron capture; and inside still other nuclides, both protons and neutrons are stable and do not change form.

Antinucleons

Antineutron



The quark structure of the antineutron

The **antineutron** is the antiparticle of the neutron with symbol n. It differs from the neutron only in that some of its properties have equal magnitude but opposite sign. It has the same mass as the neutron, and no net electric charge, but has opposite baryon number (+1 for neutron, −1 for the antineutron). This is because the antineutron is composed of antiquarks, while neutrons are composed of quarks. In particular, the antineutron consists of one up antiquark and two down antiquarks.

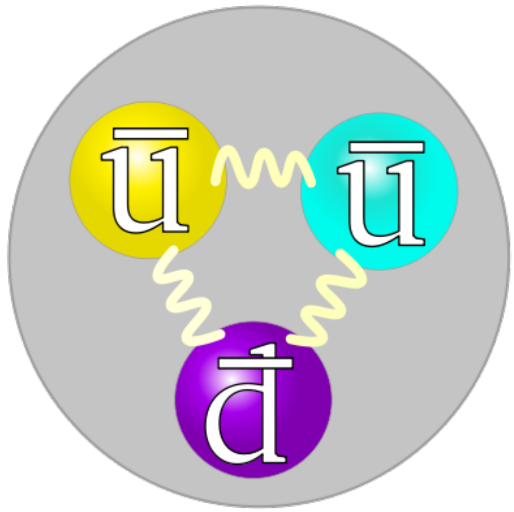
Since the antineutron is electrically neutral, it cannot easily be observed directly. Instead, the products of its annihilation with ordinary matter are observed. In theory, a free antineutron should decay into an antiproton, a positron and a neutrino in a process analogous to the beta decay of free neutrons. There are theoretical proposals that neutron–antineutron oscillations exist, a process which would occur only if there is an undiscovered physical process that violates baryon number conservation.

The antineutron was discovered in proton–proton collisions at the Bevatron (Lawrence Berkeley National Laboratory) by Bruce Cork in 1956, one year after the antiproton was discovered.

Magnetic moment

The magnetic moment of the antineutron is the opposite of that of the neutron. It is 1.91 μ_N for the antineutron but −1.91 μ_N for the neutron (relative to the direction of the spin). Here μ_N is the nuclear magneton.

Antiproton



The quark structure of the antiproton

The **antiproton** (p, pronounced *p-bar*) is the antiparticle of the proton. Antiprotons are stable, but they are typically short-lived since any collision with a proton will cause both particles to be annihilated in a burst of energy.

The existence of the antiproton with -1 electric charge, opposite to the +1 electric charge of the proton, was predicted by Paul Dirac in his 1933 Nobel Prize lecture. Dirac received the Nobel Prize for his previous 1928 publication of his Dirac Equation that predicted the existence of + and - solutions to the Energy Equation (E = mc^2) of Einstein and the existence of the antimatter positive charge electron (e+ positron), the spin opposite of the negative charge electron (e- negatron).

The antiproton was experimentally confirmed in 1955 by University of California, Berkeley physicists Emilio Segrè and Owen Chamberlain, for which they were awarded the 1959 Nobel Prize in Physics. An antiproton consists of two up antiquark and one down antiquark (uud). The properties of the antiproton that have been measured all match the corresponding properties of the proton, with the exception that the antiproton has opposite electric charge and magnetic moment than the proton. The question of ways matter is different from antimatter remains an open problem, in order to explain how our universe survived the Big Bang and why so little remains of antimatter today in our solar system.

Occurrence in nature

Antiprotons have been detected in cosmic rays for over 25 years, first by balloon-borne experiments and more recently by satellite-based detectors. The standard picture for their presence in cosmic rays is that they are produced in collisions of cosmic ray protons with nuclei in the interstellar medium, via the reaction, where A represents a nucleus:

p + A → p+ p +p+ A

The secondary antiprotons (p) then propagate through the galaxy, confined by the galactic magnetic fields. Their energy spectrum is modified by collisions with other atoms in the interstellar medium, and antiprotons can also be lost by "leaking out" of the galaxy.

The antiproton cosmic ray energy spectrum is now measured reliably and is consistent with this standard picture of antiproton production by cosmic ray collisions. This sets upper limits on the number of antiprotons that could be produced in exotic ways, such as from annihilation of supersymmetric dark matter particles in the galaxy or from the evaporation of primordial black holes. This also provides a lower limit on the antiproton lifetime of about 1-10 million years. Since the galactic storage time of antiprotons is about 10 million years, an intrinsic decay lifetime would modify the galactic residence time and distort the spectrum of cosmic ray antiprotons. This is significantly more stringent than the best laboratory measurements of the antiproton lifetime:

- LEAR collaboration at CERN: 0.08 a
- Antihydrogen Penning trap of Gabrielse et al.: 0.28 a
- APEX collaboration at Fermilab: 50,000 yr for p → μ^- + X and 300,000 yr for p → e^- + γ

The properties of the antiproton are predicted by CPT symmetry to be exactly related to those of the proton. In particular, CPT symmetry predicts the mass and lifetime of the antiproton to be the same as those of the proton, and the electric charge and magnetic moment of the antiproton to be opposite in sign and equal in magnitude to those of the proton. CPT symmetry is a basic consequence of quantum field theory and no violations of it have ever been detected.

List of recent antiproton cosmic ray detection experiments

- BESS: balloon-borne experiment, flown in 1993, 1995, 1997, 2000, 2002, 2004(Polar-I) and 2007(Polar-II).
- CAPRICE: balloon-borne experiment, flown in 1994 and 1998.
- HEAT: balloon-borne experiment, flown in 2000.
- AMS: space-based experiment, prototype flown on the space shuttle in 1998, intended for the International Space Station but not yet launched.
- PAMELA: satellite experiment to detect cosmic rays and antimatter from space, launched June 2006.

Modern experiments and applications

Antiprotons are routinely produced at Fermilab for collider physics operations in the Tevatron, where they are collided with protons. The use of antiprotons allows for a higher average energy of collisions between quarks and antiquarks than would be possible in proton-proton collisions. This is because the valence quarks in the proton, and the valence antiquarks in the antiproton, tend to carry the largest fraction of the proton or antiproton's momentum.

Their formation requires energy equivalent to a temperature of 10 trillion K (10^{13} K), and Big Bangs aside, this does not tend to happen naturally. However, at CERN, protons are accelerated in the Proton Synchrotron (PS) to an energy of 26 GeV, and then smashed into an iridium rod. The protons bounce off the iridium nuclei with enough energy for matter to be created. A range of particles and antiparticles are formed, and the antiprotons are separated off using magnets in vacuum.

In mid-June 2006, the ASACUSA experiment at CERN succeeded in determining the mass of the antiproton, which they measured at 1,836.153674(5) times more massive than an electron. This is exactly the same as the mass of a "regular" proton.

Experiments are underway to produce beams of antimatter made of an antiproton and a positron, to see if they are repelled upwards by gravity or if they follow the same trajectory as ordinary matter. results are expected by 2014

Quark model classification

In the quark model with SU(2) flavour, the two nucleons are part of the ground state doublet. The proton has quark content of *uud*, and the neutron, *udd*. In SU(3) flavour, they are part of the ground state octet (**8**) of spin $\frac{1}{2}$ baryons, known as the Eightfold way. The other members of this octet are the hyperons strange isotriplet Σ^+, Σ^0, Σ^-, the Λ and the strange isodoublet Ξ^0, Ξ^-. One can extend this multiplet in SU(4) flavour (with the inclusion of the charm quark) to the ground state **20**-plet, or to SU(6) flavour (with the inclusion of the top and bottom quarks) to the ground state **56**-plet.

The article on isospin provides an explicit expression for the nucleon wave functions in terms of the quark flavour eigenstates.

Models

Although it is known that the nucleon is made from three quarks, as of 2006, it is not known how to solve the equations of motion for quantum chromodynamics. Thus, the study of the low-energy properties of the nucleon are performed by means of models. The only first-principles approach available is to attempt to solve the equations of QCD numerically, using lattice QCD. This requires complicated algorithms and very powerful supercomputers. However, several analytic models also exist:

The Skyrmion models the nucleon as a topological soliton in a non-linear SU(2) pion field. The topological stability of the Skyrmion is interpreted as the conservation of baryon number, that is, the non-decay of the nucleon. The local topological winding number density is identified with the local baryon number density of the nucleon. With the pion isospin vector field oriented in the shape of a hedgehog, the model is readily solvable, and is thus sometimes called the **hedgehog model**. The hedgehog model is able to predict low-energy parameters, such as the nucleon mass, radius and axial coupling constant, to approximately 30% of experimental values.

The MIT bag model confines three non-interacting quarks to a spherical cavity, with the boundary condition that the quark vector current vanish on the boundary. The non-interacting treatment of the quarks is justified by appealing to the idea of asymptotic freedom, whereas the hard boundary condition is justified by quark confinement. Mathematically, the model vaguely resembles that of a radar cavity, with solutions to the Dirac equation standing in for solutions to the Maxwell equations and the vanishing vector current boundary condition standing for the conducting metal walls of the radar cavity. If the radius of the bag is set to the radius of the nucleon, the bag model predicts a nucleon mass that is within 30% of the actual mass. An important failure of the basic bag model is its failure to provide a pion-mediated interaction.

The **chiral bag model** merges the MIT bag model and the Skyrmion model. In this model, a hole is punched out of the middle of the Skyrmion, and replaced with a bag model. The boundary condition is provided by the requirement of continuity of the axial vector current across the bag boundary. Very curiously, the missing part of the topological winding number (the baryon number) of the hole punched into the Skyrmion is exactly made up by the non-zero vacuum expectation value (or spectral asymmetry) of the quark fields inside the bag. As of 2006, this remarkable trade-off between topology and the spectrum of an operator does not have any grounding or explanation in the mathematical theory of Hilbert spaces and their relationship to geometry. Several other properties of the chiral bag are notable: it provides a better fit to the low energy nucleon properties, to within 5–10%, and these are almost completely independent of the chiral bag radius (as long as the radius is less than the nucleon radius). This independence of radius is referred to as the **Cheshire Cat principle**, after the fading to a smile of Lewis Carroll's Cheshire Cat. It is expected that a first-principles solution of the equations of QCD will demonstrate a similar duality of quark-pion descriptions.

Chapter-6

Nuclear Engineering

Nuclear engineering is the branch of engineering concerned with the application of the breakdown of atomic nuclei and/or other sub-atomic physics, based on the principles of nuclear physics. It includes, but is not limited to, the interaction and maintenance of nuclear fission systems and components— specifically, nuclear reactors, nuclear power plants, and/or nuclear weapons. The field also includes the study of nuclear fusion, medical and other applications of (generally ionizing) radiation, nuclear safety, heat/thermodynamics transport, nuclear fuel and/or other related (e.g., waste disposal) technology, nuclear proliferation, and the effect of radioactive waste or radioactivity in the environment.

Professional areas

Nuclear fission

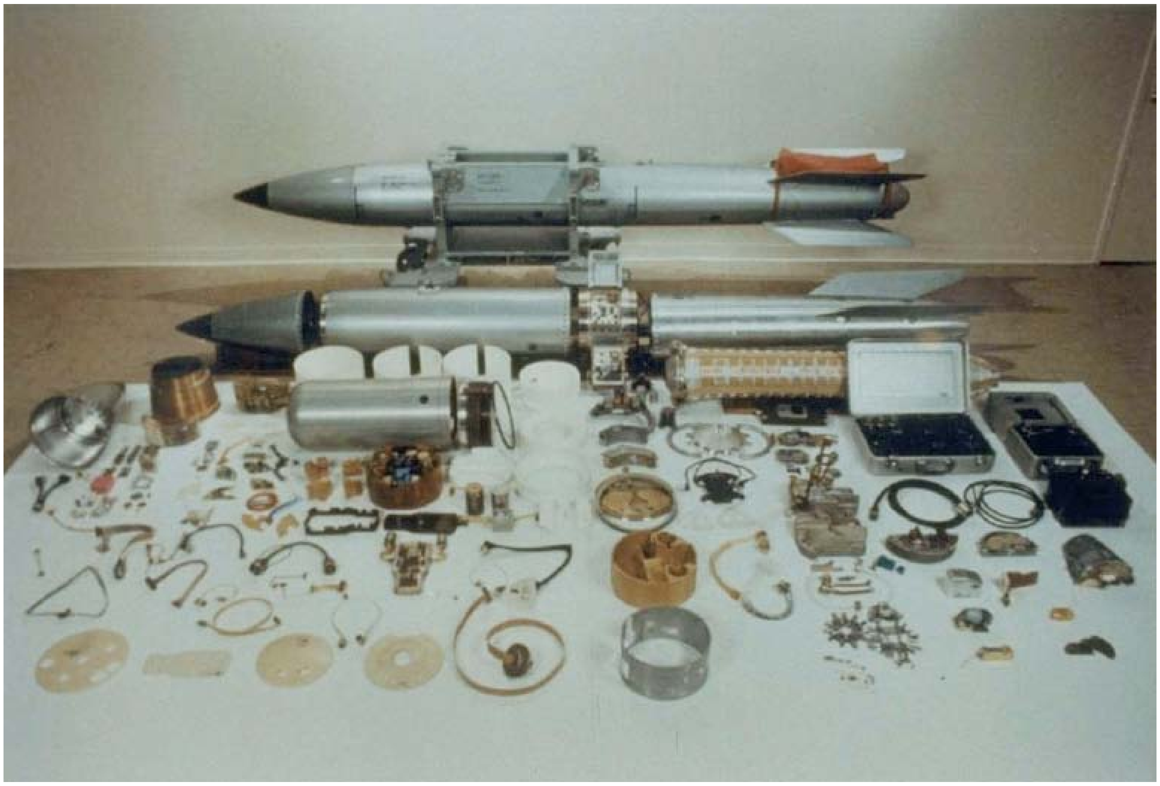
Nuclear fission is the disintegration of a susceptible (fissile) atom's nucleus into two different, smaller elements and other particles including neutrons. Approximately 2.4 neutrons are released per fission, which may cause additional fissions if enough fissionable material is present.

The common types of nuclear fission include thermal fission, which is fission caused by the absorption of a relatively slow thermal neutron with kinetic energy approximately 0.025 eV. Fast fission is fission caused by the absorption of a more energetic neutron, with kinetic energy on the order of MeV. Also, in especially heavy nuclei, spontaneous fission may occur. Nuclei that are fissionable by neutrons typically carry at least a very small chance of spontaneous fission occurring.

Generally, thermal fission is used in commercial reactors, though Fast Breeder Reactors have been developed to harness fast fission.

The United States gets about 20% of its electricity from nuclear power. Nuclear engineers in this field generally work, directly or indirectly, in the nuclear power industry or for national laboratories. Current research in the industry is directed at producing economical, proliferation-resistant reactor designs with passive safety features. Although government labs research the same areas as industry, they also study a myriad of other issues such as nuclear fuels and nuclear fuel cycles, advanced reactor designs, and nuclear weapon design and maintenance. A principal pipeline for trained personnel for US reactor facilities is the Navy Nuclear Power Program.

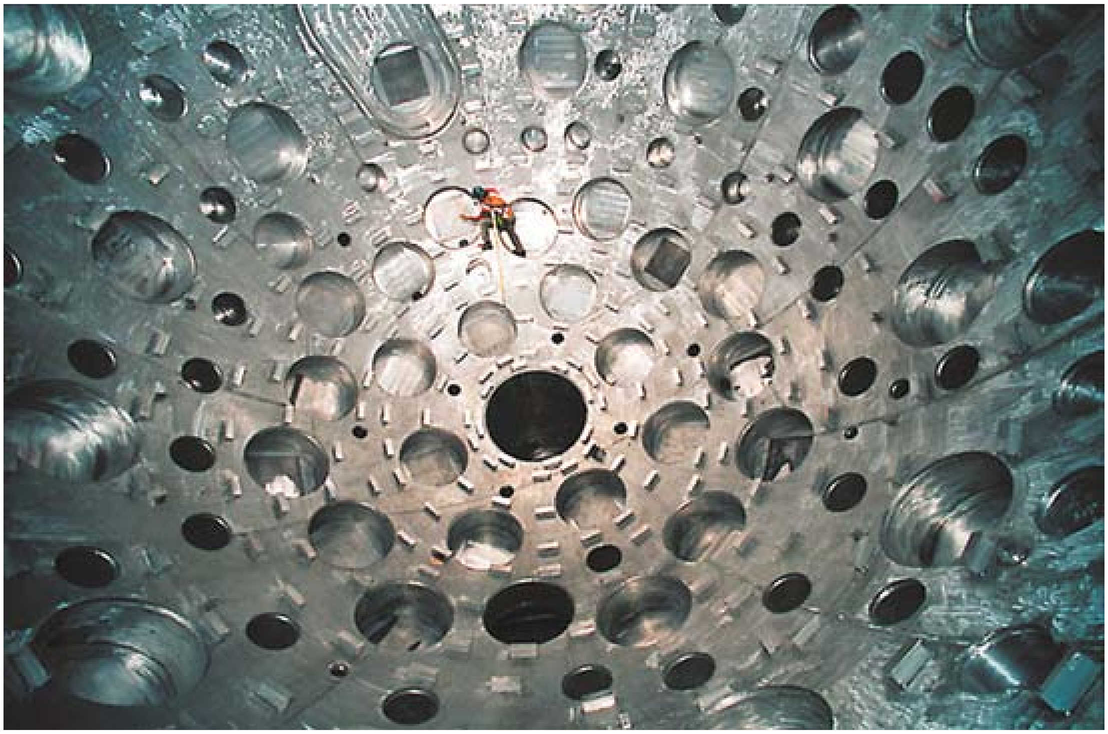
Nuclear Powerplant



B-61 thermonuclear weapon

Nuclear fusion and plasma physics

Research areas in nuclear fusion and plasma physics include high-temperature, plasma dynamics, and radiation-resistant materials. Internationally, research is currently directed at building a prototype tokamak called ITER. The research at ITER will primarily focus on instabilities and diverter design refinement. Researchers in the USA are also building an inertial confinement experiment called the National Ignition Facility or NIF. NIF will be used to refine neutron transport calculations for the US stockpile stewardship initiative.



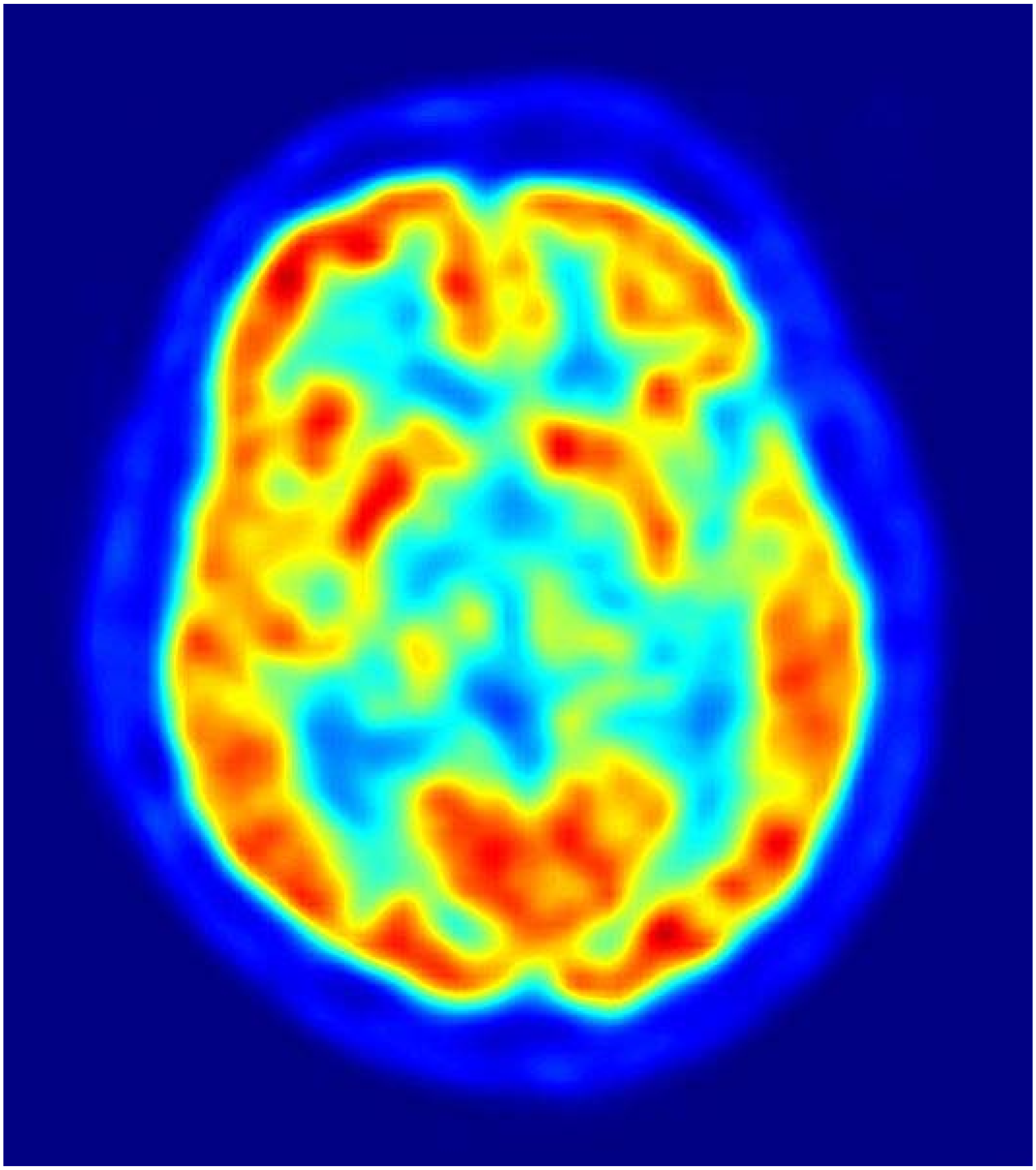
NIF (National Ignition Facility) target chamber

Nuclear medicine and medical physics

An important field is medical physics, and its subfields nuclear medicine, radiation therapy, health physics, and diagnostic imaging. From x-ray machines to MRI to PET, among many others, medical physics provides most of modern medicine's diagnostic capability along with providing many treatment options.

X-Ray Image of a male skull

Magnetic Resonance Imaging scan of a head

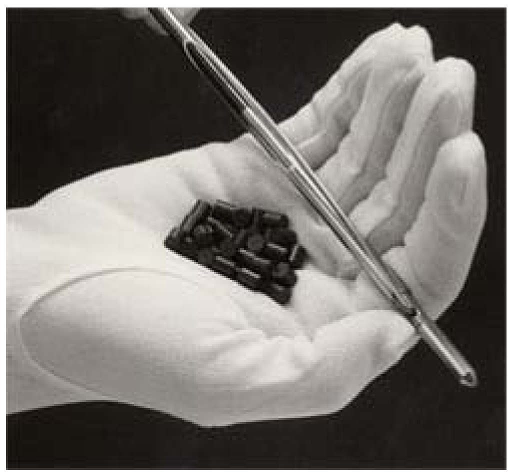


PET taken with an ECAT Exact HR+ PET Scanner

Nuclear materials and nuclear fuels

Nuclear materials research focuses on two main subject areas, nuclear fuels and irradiation-induced modification of materials. Improvement of nuclear fuels is crucial for obtaining increased efficiency from nuclear reactors. Irradiation effects studies have many purposes, from studying structural changes to reactor components to studying nano-modification of metals using ion-beams or particle accelerators.

Uranium ore, the principal raw material of nuclear fuel



Nuclear fuel pellets

A Focused ion beam

Radiation measurements and dosimetry

Nuclear engineers and radiological scientists are interested in the development of more advanced ionizing radiation measurement and detection systems, and using these to improve imaging technologies. This includes detector design, fabrication and analysis, measurements of fundamental atomic and nuclear parameters, and radiation imaging systems, among other things.

A modern Geiger counter

A neutron detector

Scintillation detector next to Uraninite

Chapter-7

Neutron Moderator

Currently operating thermal nuclear reactors (nuclear reactors with moderator)

Moderator	Reactors	Design	Country
graphite	30	AGR, Magnox, RBMK	United Kingdom, Russia
heavy water	42	CANDU	Canada, India, South Korea, others
light water	359	PWR, BWR	27 countries

In nuclear engineering, a **neutron moderator** is a medium that reduces the speed of fast neutrons, thereby turning them into thermal neutrons capable of sustaining a nuclear chain reaction involving uranium-235.

Commonly used moderators include regular (light) water (roughly 75% of the world's reactors), solid graphite (20% of reactors) and heavy water (5% of reactors). Beryllium has also been used in some experimental types, and hydrocarbons have been suggested as another possibility.

Moderation

Neutrons are normally bound into an atomic nucleus, and do not exist free for long in nature. The unbound neutron has a half-life of just under 15 minutes. The release of neutrons from the nucleus requires exceeding the binding energy of the neutron, which is typically 7-9 MeV for most isotopes. Neutron sources generate free neutrons by a variety of nuclear reactions, including nuclear fission and nuclear fusion. Whatever the source of neutrons, they are released with energies of several MeV.

Since the kinetic energy, *E*, can be related to temperature via:

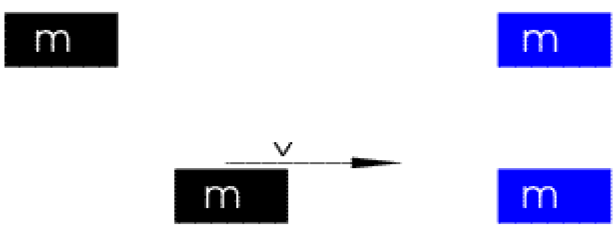
$$E = \frac{1}{2}mv^2 = \frac{3}{2}k_BT$$

the characteristic neutron temperature of a several-MeV neutron is several tens of millions of degrees Celsius.

Moderation is the process of the reduction of the initial high kinetic energy of the free neutron. Since energy is conserved, this reduction of the neutron kinetic energy takes place by transfer of energy to a material known as a moderator. It is also known as *neutron slowing down*, since along with the reduction of energy comes a reduction in speed.

The probability of scattering of a neutron from a nucleus is given by the scattering cross section. The first couple of collisions with the moderator may be of sufficiently high energy to excite the nucleus of the moderator. Such a collision is inelastic, since some of the kinetic energy is transformed to potential energy by exciting some of the internal degrees of freedom of the nucleus to form an excited state. As the energy of the neutron is lowered, the collisions become predominantly elastic, i.e., the total kinetic energy and momentum of the system (that of the neutron and the nucleus) is conserved.

Given the mathematics of elastic collisions, as neutrons are very light compared to most nuclei, the most efficient way of removing kinetic energy from the neutron is by choosing a moderating nucleus that has near identical mass.

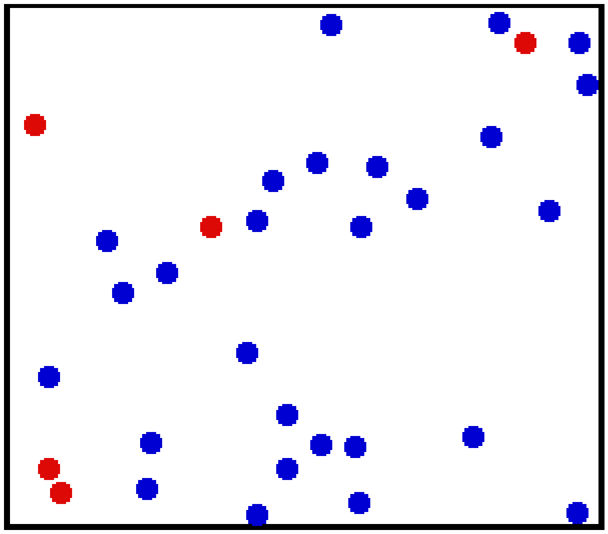


Elastic collision of equal masses

A collision of a neutron, which has mass of 1, with a ^{1}H nucleus (a proton) could result in the neutron losing virtually all of its energy in a single head-on collision. More generally, it is necessary to take into account both glancing and head-on collisions. The *mean logarithmic reduction of neutron energy per collision*, ξ, depends only on the atomic mass, *A*, of the nucleus and is given by:

$$\xi = \ln \frac{E_0}{E} = 1 + \frac{(A-1)^2}{2A} \ln\left(\frac{A-1}{A+1}\right).$$

This can be reasonably approximated to the very simple form $\xi \simeq \frac{2}{A+1}$. From this one can deduce *n*, the expected number of collisions of the neutron with nuclei of a given type that is required to reduce the kinetic energy of a neutron from E_0 to E: $n = \frac{1}{\xi}(\ln E_0 - \ln E)$.



In a system at thermal equilibrium, neutrons (red) are elastically scattered by a hypothetical moderator of free hydrogen nuclei (blue), undergoing thermally activated motion. Kinetic energy is transferred between particles. As the neutrons have essentially the same mass as protons and there is no absorption, the velocity distributions of both particles types would be well-described by a single Maxwell–Boltzmann distribution.

Choice of moderator materials

Some nuclei have larger absorption cross sections than others, which removes free neutrons from the flux. Therefore, a further criterion for an efficient moderator is one for which this parameter is small. The *moderating efficiency* gives the ratio of the macroscopic cross sections of scattering, Σ_s, weighted by ξ divided by that of absorption, Σ_a: i.e., $\frac{\xi \Sigma_s}{\Sigma_a}$. For a compound moderator composed of more than one element, such as light or heavy water, it is necessary to take into account the moderating and absorbing effect of both the hydrogen isotope and oxygen atom to calculate ξ. To bring a neutron from the fission energy of E_0 2 MeV to an E of 1 eV takes an expected n of 16 and 29 collisions for H_2O and D_2O, respectively. Therefore, neutrons are more rapidly moderated by light water, as H has a far higher Σ_s. However, it also has a far higher Σ_a, so that the moderating efficiency is nearly 80 times higher for heavy water than for light water.

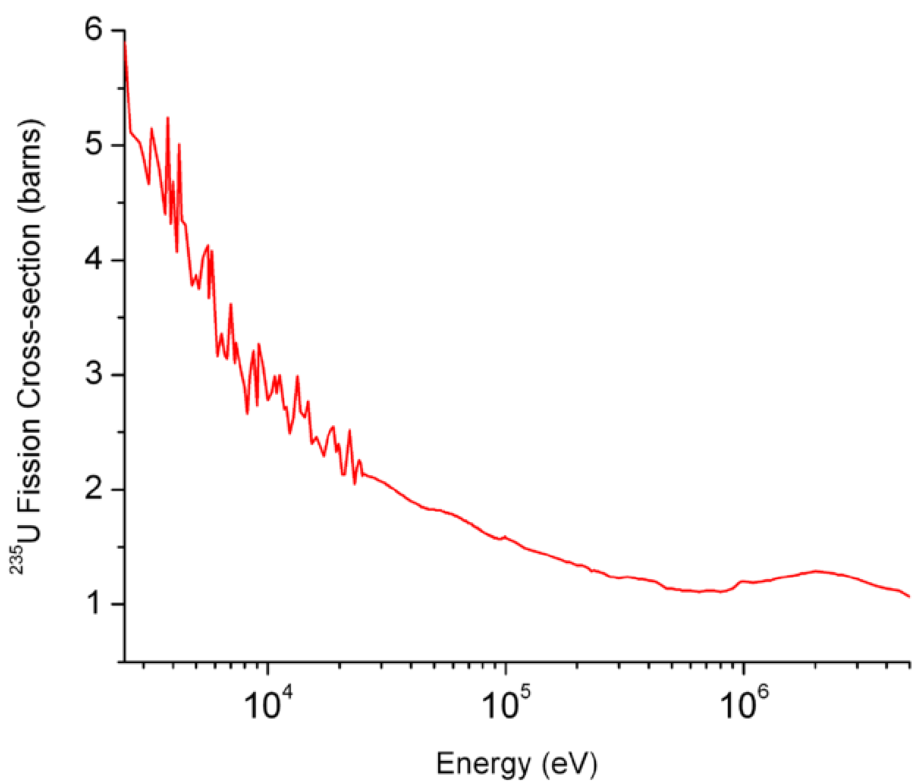
The ideal moderator is of low mass, high scattering cross section, and low absorption cross section.

Distribution of neutron velocities once moderated

After sufficient impacts, the speed of the neutron will be comparable to the speed of the nuclei given by thermal motion; this neutron is then called a thermal neutron, and the process may also be termed *thermalization*. Once at equilibrium at a given temperature the distribution of speeds (energies) expected of rigid spheres scattering elastically is given by the Maxwell–Boltzmann distribution. This is only slightly modified in a real moderator due to the speed (energy) dependence of the absorption cross-section of most materials, so that low-speed neutrons are preferentially absorbed, so that the true neutron velocity distribution in the core would be slightly hotter than predicted.

Reactor moderators

In a thermal nuclear reactor, the nucleus of a heavy fuel element such as uranium absorbs a slow-moving free neutron, becomes unstable, and then splits ("fissions") into two smaller atoms ("fission products"). The fission process for ^{235}U nuclei yields two fission products: two to three fast-moving free neutrons, plus an amount of energy primarily manifested in the kinetic energy of the recoiling fission products. The free neutrons are emitted with a kinetic energy of ~2 MeV each. Because more free neutrons are released from a uranium fission event than thermal neutrons are required to initiate the event, the reaction can become self sustaining — a chain reaction — under controlled conditions, thus liberating a tremendous amount of energy.



Fission cross section, measured in barns (a unit equal to 10^{-28} m^2), is a function of the energy of the neutron colliding with a ^{235}U nucleus. Fission probability decreases as neutron energy (and speed) increases. This explains why most reactors fueled with ^{235}U need a moderator to sustain a chain reaction and why removing a moderator can shut down a reactor.

The probability of further fission events is determined by the fission cross section, which is dependent upon the speed (energy) of the incident neutrons. For thermal reactors, high-energy neutrons in the MeV-range are much less likely to cause further fission. (Note: It is not *impossible* for fast neutrons to cause fission, just much less likely.) The newly-released fast neutrons, moving at roughly 10% of the speed of light, must be slowed down or "moderated," typically to speeds of a few kilometres per second, if they are to be likely to cause further fission in neighbouring ^{235}U nuclei and hence continue the chain reaction. This speed happens to be equivalent to temperatures in the few hundred celsius range.

In all moderated reactors, some neutrons of all energy levels will produce fission, including fast neutrons. Some reactors are more fully *thermalised* than others; for example, in a CANDU reactor nearly all fission reactions are produced by thermal neutrons, while in a pressurized water reactor (PWR) a considerable portion of the fissions are produced by higher-energy neutrons. In the proposed water-cooled supercritical water reactor (SCWR), the proportion of fast fissions may exceed 50%, making it technically a fast neutron reactor.

A fast reactor uses no moderator, but relies on fission produced by unmoderated fast neutrons to sustain the chain reaction. In some fast reactor designs, up to 20% of fissions can come from direct fast neutron fission of uranium-238, an isotope which is not fissile at all with thermal neutrons.

Moderators are also used in non-reactor neutron sources, such as plutonium-beryllium and spallation sources.

Form and location

The form and location of the moderator can greatly influence the cost and safety of a reactor. Classically, moderators were precision-machined blocks of high purity graphite with embedded ducting to carry away heat. They were in the hottest part of the reactor, and therefore subject to corrosion and ablation. In some materials, including graphite, the impact of the neutrons with the moderator can cause the moderator to accumulate dangerous amounts of Wigner energy. At Windscale, this problem led to the infamous Windscale fire.

Some pebble-bed reactors' moderators are not only simple, but also inexpensive: the nuclear fuel is embedded in spheres of reactor-grade pyrolytic carbon, roughly of the size of tennis balls. The spaces between the balls serve as ducting. The reactor is operated above the Wigner annealing temperature so that the graphite does not accumulate dangerous amounts of Wigner energy.

In CANDU and PWR reactors, the moderator is liquid water (heavy water for CANDU, light water for PWR). In the event of a loss-of-coolant accident in a PWR, the moderator is also lost and the reaction will stop. This negative void coefficient is an important safety feature of these reactors. In CANDU the moderator is located in a separate heavy-water circuit, surrounding the pressurized heavy-water coolant channels. This design gives CANDU reactors a positive void coefficient, although the slower neutron kinetics of heavy-water moderated systems compensates for this, leading to comparable safety with PWRs."

Moderator impurities

Good moderators are also free of neutron-absorbing impurities such as boron. In commercial nuclear power plants the moderator typically contains dissolved boron. The boron concentration of the reactor coolant can be changed by the operators by adding boric acid or by diluting with water to manipulate reactor power. The German World War II nuclear program suffered a substantial setback when its inexpensive graphite moderators failed to work. At that time, most graphites were deposited on boron electrodes, and the German commercial graphite contained too much boron. Since the war-time German program never discovered this problem, they were forced to use far more expensive heavy water moderators. In the U.S., Leo Szilard, a former chemical engineer, discovered the problem.

Non-graphite moderators

Some moderators are quite expensive, for example beryllium, and reactor-grade heavy water. Reactor-grade heavy water must be 99.75% pure to enable reactions with unenriched uranium. This is difficult to prepare because heavy water and regular water form the same chemical bonds in almost the same ways, at only slightly different speeds.

The much cheaper light water moderator (essentially very pure regular water) absorbs too many neutrons to be used with unenriched natural uranium, and therefore uranium enrichment or nuclear reprocessing becomes necessary to operate such reactors, increasing overall costs. Both enrichment and reprocessing are expensive and technologically challenging processes, and additionally both enrichment and several types of reprocessing can be used to create weapons-usable material, causing proliferation concerns. Reprocessing schemes that are more resistant to proliferation are currently under development.

The CANDU reactor's moderator doubles as a safety feature. A large tank of low-temperature, low-pressure heavy water moderates the neutrons and also acts as a heat sink in extreme loss-of-coolant accident conditions. It is separated from the fuel rods that actually generate the heat. Heavy water is very effective at slowing down (moderating) neutrons, giving CANDU reactors their important and defining characteristic of high "neutron economy."

Nuclear weapon design

Early speculation about nuclear weapons assumed that an "atom bomb" would be a large amount of fissile material, moderated by a neutron moderator, similar in structure to a nuclear reactor or "pile." Only the Manhattan project embraced the idea of a chain reaction of fast neutrons in pure metallic uranium or plutonium. Other moderated designs were also considered by the Americans; proposals included using uranium hydride as the fissile material. In 1943 Robert Oppenheimer and Niels Bohr considered the possibility of using a "pile" as a weapon. The motivation was that with a graphite moderator it would be possible to achieve the chain reaction without the use of any isotope separation. In August 1945, when information of the atomic bombing of Hiroshima was relayed to the scientists of the German nuclear program, interned at Farm Hall in England, chief scientist Werner Heisenberg hypothesized that the device must have been "something like a nuclear reactor, with the neutrons slowed by many collisions with a moderator."

After the success of the Manhattan project, all major nuclear weapons programs have relied on fast neutrons in their weapons designs. The notable exception is the *Ruth* and *Ray* test explosions of Operation Upshot-Knothole. The aim of the University of California Radiation Laboratory design was to produce an explosion powerful enough to ignite a thermonuclear weapon with the minimal amount of fissile material. The core consisted of uranium hydride, with hydrogen, or in the case of *Ray*, deuterium acting as the neutron moderator. The predicted yield was 1.5 to 3 kt for *Ruth* and 0.5-1 kt for *Ray*. The tests produced yields of 200 tons of TNT each; both tests were considered to be fizzles.

The main benefit of using a moderator in a nuclear explosive is that the amount of fissile material needed to reach criticality may be greatly reduced. Slowing of fast neutrons will increase the cross section for neutron absorption, reducing the critical mass. A side effect is however that as the chain reaction progresses, the moderator will be heated, thus losing its ability to cool the neutrons.

Another effect of moderation is that the time between subsequent neutron generations is increased, slowing down the reaction. This makes the containment of the explosion a problem; the inertia that is used to confine implosion type bombs will not be able to confine the reaction. The end result may be a fizzle instead of a bang.

The explosive power of a fully moderated explosion is thus limited, at worst it may be equal to a chemical explosive of similar mass. Again quoting Heisenberg: *"One can never make an explosive with slow neutrons, not even with the heavy water machine, as then the neutrons only go with thermal speed, with the result that the reaction is so slow that the thing explodes sooner, before the reaction is complete."*

While a nuclear bomb working on thermal neutrons may be impractical, modern weapons designs may still benefit from some level of moderation. A beryllium tamper used as a neutron reflector will also act as a moderator.

Materials used

- Hydrogen, as in ordinary "light water." Because protium also has a significant cross section for neutron capture only limited moderation is possible without losing too many neutrons. The less-moderated neutrons are relatively more likely to be captured by uranium-238 and less likely to fission uranium-235, so light water reactors require enriched uranium to operate.
  - There are also proposals to use the compound formed by the chemical reaction of metallic uranium and hydrogen (uranium hydride--UH_3) as a combination fuel and moderator in a new type of reactor.
  - Hydrogen is also used in the form of cryogenic liquid methane and sometimes liquid hydrogen as a cold neutron source in some research reactors: yielding a Maxwell–Boltzmann distribution for the neutrons whose maximum is shifted to much lower energies.
  - Hydrogen combined with carbon as in Paraffin was used in some early German experiments.
- Deuterium, in the form of heavy water, in heavy water reactors, e.g. CANDU. Reactors moderated with heavy water can use unenriched natural uranium.
- Carbon, in the form of reactor-grade graphite or pyrolytic carbon, used in e.g. RBMK and pebble-bed reactors, or in compounds, e.g. carbon dioxide . Lower-temperature reactors are susceptible to buildup of Wigner energy in the material. Like deuterium-moderated reactors, some of these reactors can use unenriched natural uranium.
  - Graphite is also deliberately allowed to be heated to around 2000 K or higher in some research reactors to produce a hot neutron source: giving a Maxwell–Boltzmann distribution whose maximum is spread out to generate higher energy neutrons.
- Beryllium, in the form of metal. Beryllium is expensive and toxic, so its use is limited.
- Lithium-7, in the form of a lithium fluoride salt, typically in conjunction with beryllium fluoride salt (FLiBe). This is the most common type of moderator in a Molten Salt Reactor.

Other light-nuclei materials are unsuitable for various reasons. Helium is a gas and it requires special design to achieve sufficient density; lithium-6 and boron-10 absorb neutrons.

Chapter-8

Nuclear Criticality Safety and Atomic Battery

Nuclear criticality safety

Nuclear criticality safety is a field of nuclear engineering dedicated to the prevention of an inadvertent, self-sustaining nuclear chain reaction. Additionally, nuclear criticality safety is concerned with mitigating the consequences of a nuclear criticality accident. A nuclear criticality accident occurs from operations that involve fissile material and results in a tremendous and potentially lethal release of radiation. Nuclear criticality safety practitioners attempt to minimize the probability of a nuclear criticality accident by analyzing normal and abnormal fissile material operations and providing controls on the processing of fissile materials. A common practice is to apply a double contingency analysis to the operation in which two or more independent, concurrent and unlikely changes in process conditions must occur before a nuclear criticality accident can occur. For example, the first change in conditions may be complete or partial flooding and the second change a rearrangement of the fissile material. Controls (requirements) on process parameters (e.g., fissile material mass, equipment) result from this analysis. These controls, either passive (physical), active (mechanical), or administrative (human), are implemented by inherently safe or fault-tolerant plant designs, or, if such designs are not practicable, by administrative controls such as operating procedures, job instructions and other means to minimize the potential for significant process changes that could lead to a nuclear criticality accident.

Principles

Seven factors influence a criticality system.

Geometry or shape of the fissile material: If neutrons escape (leak from) the fissile system they are not available to interact with the fissile material to cause a fission event. Therefore the shape of the fissile material affects the probability of occurrence of fission events. A large surface area such as a thin slab has lots of leakage and is safer than the same amount of fissile material in a small, compact shape such as a cube or a sphere.

Interaction of units: Neutrons leaking from one unit can enter another. Two units, which by themselves are sub-critical, could interact with each other to form a critical system. The distance separating the units and any material between them influences the effect.

Reflection: When neutrons collide with other atomic particles (primarily nuclei) and are not absorbed, they change direction. If the change in direction is large enough, the neutron may travel back into the system, increasing the likelihood of interaction (fission). This is called 'reflection'. Good reflectors include hydrogen, beryllium, carbon, lead, uranium, water, polyethylene, concrete, Tungsten carbide and steel.

Moderation: Neutrons resulting from fission are typically fast (high energy). These fast neutrons do not cause fission as readily as slower (less energetic) ones. Neutrons are slowed down (moderated) by collision with atomic nuclei. The most effective moderating nuclei are hydrogen, deuterium, beryllium and carbon. Hence hydrogenous materials including oil, polyethylene, water, wood, paraffin, and the human body are good moderators. Note that moderation comes from collisions; therefore most moderators are also good reflectors.

Absorption: Absorption removes neutrons from the system. Large amounts of absorbers are used to control or reduce the probability of a criticality. Good absorbers are boron, cadmium, gadolinium, silver, and indium.

Enrichment: The probability of a neutron reacting with a fissile nucleus is influenced by the relative numbers of fissile and non-fissile nuclei in a system. The process of increasing the relative number of fissile nuclei in a system is called enrichment. Typically, low enrichment means less likelihood of a criticality and high enrichment means a greater likelihood.

Mass: The probability of fission increases as the total number of fissile nuclei increases. The relationship is not linear. There is a threshold below which a criticality will not occur. This threshold is called the critical mass.

Calculations and analyses

To determine whether a system containing fissile material is safe, calculations are performed using computer programmes. The analyst describes the geometry of the system and the materials, usually with conservative or pessimistic assumptions. The density and size of any neutron absorbers is minimised while the amount of fissile material is maximised. As some moderators are also absorbers, the analyst must be careful when modelling these to be pessimistic. Computer programmes allow analysts to describe a three dimensional system with boundary conditions. These boundary conditions can represent real boundaries such as concrete walls or the surface of a pond, or can be used to represent an artificial infinite system using a periodic boundary condition. These are useful when representing a large system consisting of many repeated units.

Computer codes used for criticality safety analyses include MONK (UK), KENO (USA), MCNP (USA) and CRISTAL (France).

Burnup credit

Traditional criticality analyses assume that the fissile material is in its most reactive condition, which is usually at maximum enrichment, with no irradiation. For spent nuclear fuel storage and transport, burnup credit may be used to allow fuel to be more closely packed, reducing space and allowing more fuel to be handled safely. In order to implement burnup credit, fuel is modeled as irradiated using pessimistic conditions which produce an isotopic composition representative of all irradiated fuel. Fuel irradiation produces actinides consisting of both neutron absorbers and fissionable isotopes as well as fission products which absorb neutrons.

In fuel storage pools using burnup credit, separate regions are designed for storage of fresh and irradiating fuel. In order to store fuel in the irradiating fuel store it must satisfy a loading curve which is dependent on initial enrichment and irradiation.

Atomic battery

The terms **atomic battery**, **nuclear battery**, **tritium battery** and **radioisotope generator** are used to describe a device which uses the emissions from a radioactive isotope to generate electricity. Like nuclear reactors they generate electricity from atomic energy, but differ in that they do not use a chain reaction. Compared to other batteries they are very costly, but have extremely long life and high energy density, and so they are mainly used as power sources for equipment that must operate unattended for long periods of time, such as spacecraft and automated scientific stations in remote parts of the world.

Nuclear battery technology began in 1913, when Henry Moseley first demonstrated the beta cell. The field received considerable in depth research attention for applications requiring long-life power sources for space needs during the 50s and 60s. Over the years many types and methods have been developed. The scientific principles are well known, but modern nano-scale technology and new wide bandgap semiconductors have created new devices and interesting material properties not previously available.

Batteries using the energy of radioisotope decay to provide long-lived power (10–20 years) are being developed internationally. Conversion techniques can be grouped into two types: thermal and non-thermal. The thermal converters (whose output power is a function of a temperature differential) include thermoelectric and thermionic generators. The non-thermal converters (whose output power is not a function of a temperature difference) extract a fraction of the incident energy as it is being degraded into heat rather than using thermal energy to run electrons in a cycle. Atomic batteries usually have an efficiency of 0.1–5%. High efficiency betavoltaics have 6–8%.

Thermal converters

Thermionic converter

A thermionic converter consists of a hot electrode which thermionically emits electrons over a space charge barrier to a cooler electrode, producing a useful power output. Caesium vapor is used to optimize the electrode work functions and provide an ion supply (by surface contact ionization) to neutralize the electron space charge.

Radioisotope thermoelectric generator

A thermoelectric converter connects pairs of thermocouples in series. Each thermocouple is formed by the junction of two dissimilar materials. One of each pair is heated and the other cooled. Metal thermocouples have low thermal-to-electrical efficiency. However, the carrier density and charge can be adjusted in semiconductor materials such as bismuth telluride and silicon germanium to achieve much higher conversion efficiencies.

Thermophotovoltaic cells

Thermophotovoltaic cells work by the same principles as a photovoltaic cell, except that they convert infrared light (rather than visible light) emitted by a hot surface, into electricity. Thermophotovoltaic cells have an efficiency slightly higher than thermoelectric couples and can be overlaid on thermoelectric couples, potentially doubling efficiency. The University of Houston TPV Radioisotope Power Conversion Technology development effort is aiming at combining thermophotovoltaic cell concurrently with thermocouples to provide a 3 to 4-fold improvement in system efficiency over current thermoelectric radioisotope generators.

Alkali-metal thermal to electric converter

The alkali-metal thermal to electric converter (AMTEC) is an electrochemical system which is based on the electrolyte used in the sodium-sulfur battery, sodium beta-alumina. The device is a sodium concentration cell which uses a ceramic, polycrystalline β-alumina solid electrolyte (BASE), as a separator between a high pressure region containing sodium vapor at 900 - 1300 K and a low pressure region containing a condenser for liquid sodium at 400 - 700 K. Efficiency of AMTEC cells has reached 16% in the laboratory and is predicted to approach 20%.

Non-thermal converters

Non-thermal converters extract a fraction of the nuclear energy as it is being degraded into heat. Their outputs are not functions of temperature differences as are thermoelectric and thermionic converters. Non-thermal generators can be grouped into three classes.

Direct charging generators

In the first type, the primary generators consists of a capacitor which is charged by the current of charged particles from a radioactive layer deposited on one of the electrodes.

Spacing can be either vacuum or dielectric. Negatively charged beta particles or positively charged alpha particles, positrons or fission fragments may be utilized. Although this form of nuclear-electric generator dates back to 1913, few applications have been found in the past for the extremely low currents and inconveniently high voltages provided by direct charging generators. Oscillator/transformer systems are employed to reduce the voltages, then rectifiers are used to transform the AC power back to Direct Current.

English physicist H.G.J. Moseley constructed the first of these. Moseley's apparatus consisted of a glass globe silvered on the inside with a radium emitter mounted on the tip of a wire at the center. The charged particles from the radium created a flow of electricity as they moved quickly from the radium to the inside surface of the sphere. As late as 1945 the Moseley model guided other efforts to build experimental batteries generating electricity from the emissions of radioactive elements.

Betavoltaics

Betavoltaics are generators of electrical current, in effect a form of battery, which use energy from a radioactive source emitting beta particles (electrons). A common source used is the hydrogen isotope, tritium. Unlike most nuclear power sources, which use nuclear radiation to generate heat, which then generates electricity (thermoelectric and thermionic sources), betavoltaics use a non-thermal conversion process.

Betavoltaics are particularly well-suited to low-power electrical applications where long life of the energy source is needed, such as implantable medical devices or military and space applications.

Optoelectric

An optolectric nuclear battery has also been proposed by researchers of the Kurchatov Institute in Moscow. A beta-emitter (such as technetium-99) would stimulate an excimer mixture, and the light would power a photocell. The battery would consist of an excimer mixture of argon/xenon in a pressure vessel with an internal mirrored surface, finely-divided Tc-99, and an intermittent ultrasonic stirrer, illuminating a photocell with a bandgap tuned for the excimer. The advantage of this design is that precision electrode assemblies are not needed, and most beta particles escape the finely-divided bulk material to contribute to the battery's net power.

Reciprocating Electromechanical Atomic Batteries

Electromechanical atomic batteries use the build up of charge between two plates to pull one bendable plate towards the other, until the two plates touch, discharge, equalizing the electrostatic buildup, and spring back. The mechanical motion produced can be used to produce electricity through flexing of a piezoelectric material or through a linear generator. Milliwatts of power are produced in pulses depending on the charge rate, in some cases multiple times per second (35Hz).

Radioisotopes Used

Atomic batteries use radioisotopes that produce low energy beta particles or sometimes alpha particles of varying energies. Low energy beta particles are needed to prevent the production of high energy penetrating Bremsstrahlung radiation that would require heavy shielding. Radioisotopes such as tritium, nickel-63, promethium-147, and technetium-99 have been tested. Plutonium-238, curium-242, curium-244 and strontium-90 have been used.

Chapter-9

Nuclear Fuel Cycle

The **nuclear fuel cycle**, also called **nuclear fuel chain**, is the progression of nuclear fuel through a series of differing stages. It consists of steps in the *front end*, which are the preparation of the fuel, steps in the *service period* in which the fuel is used during reactor operation, and steps in the *back end*, which are necessary to safely manage, contain, and either reprocess or dispose of spent nuclear fuel. If spent fuel is not reprocessed, the fuel cycle is referred to as an *open fuel cycle* (or a *once-through fuel cycle*); if the spent fuel is reprocessed, it is referred to as a *closed fuel cycle*.

Basic concepts

Nuclear power relies on fissionable material that can sustain a chain reaction with neutrons. Examples of such materials include uranium and plutonium. Most nuclear reactors use a moderator to lower the kinetic energy of the neutrons and increase the probability that fission will occur. This allows reactors to use material with far lower concentration of fissile isotopes than nuclear weapons. Heavy water and graphite are the most effective moderators, because they slow the neutrons through collisions without absorbing them. Reactors using graphite or heavy water as the moderator can operate using natural uranium.

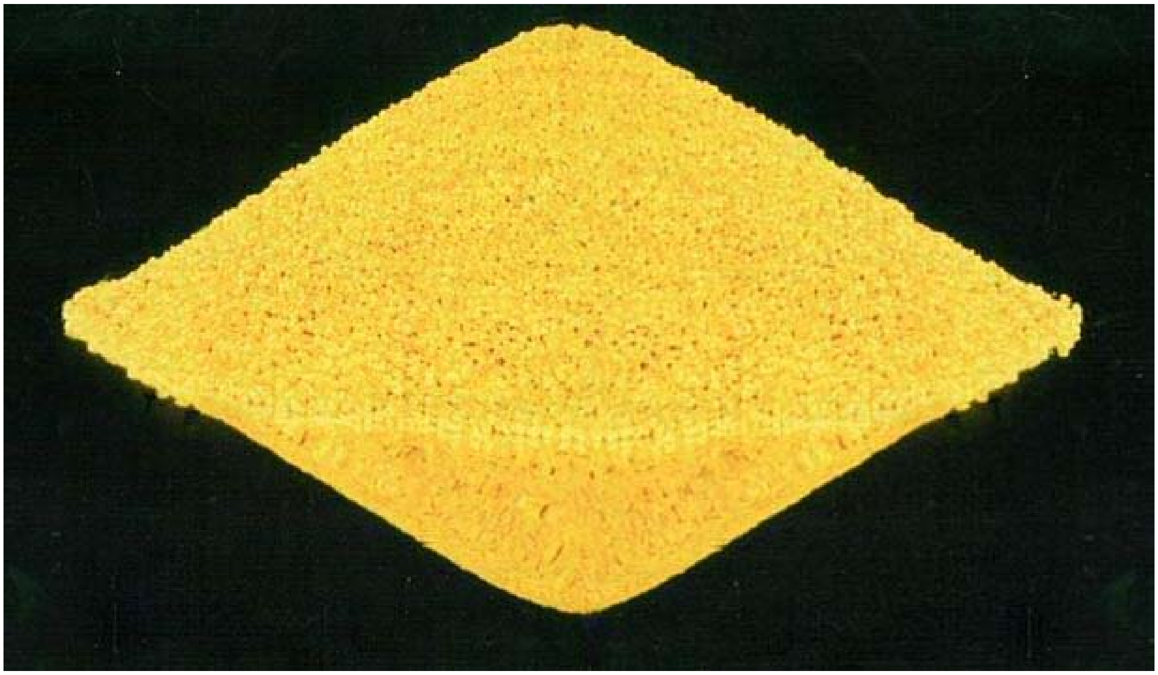
Reactors using light water (the form that occurs in nature) require fuel that is enriched in fissile isotopes, typically uranium enriched to 3-5% in the less common isotope U-235, the only fissile isotope that is found in significant quantity in nature. Two alternatives to this low-enriched uranium (LEU) fuel are Mixed Oxide fuels produced by blending either plutonium or the uranium isotope U-233. These are produced from the absorption of neutrons by irradiating fertile materials in a reactor, including the common uranium isotope U-238 and thorium, respectively, and can be separated from spent uranium and thorium fuels in reprocessing plants.

Some reactors do not use moderators to slow the neutrons. Like nuclear weapons, which also use unmoderated or "fast" neutrons, these Fast-neutron reactors require much higher concentrations of fissile isotopes in order to sustain a chain reaction. They are also capable of breeding fissile isotopes from fertile materials; a Breeder reactor is one that generates more fissile material in this way than it consumes.

During the nuclear reaction inside a reactor, the fissile isotopes in nuclear fuel are consumed, producing more and more fission products, most of which are considered radioactive waste. The buildup of fission products and consumption of fissile isotopes eventually stop the nuclear reaction, causing the fuel to become a spent nuclear fuel. When 3% enriched LEU fuel is used, the spent fuel typically consists of roughly 1% U-235, 95% U-238, 1% plutonium and 3% fission products. Spent fuel and other high-level radioactive waste is extremely hazardous, although nuclear reactors produce relatively small volumes of waste compared to other power plants because of the high energy density of nuclear fuel. Safe management of these byproducts of nuclear power, including their storage and disposal, is a difficult problem for any country using nuclear power.

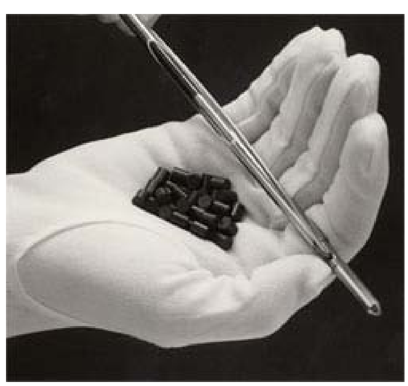
Front end

1 Uranium ore - the principal raw material of nuclear fuel



2 Yellowcake - the form in which uranium is transported to a conversion plant

3 UF_6 - used in enrichment



4 Nuclear fuel - a compact, inert, insoluble solid

Exploration

A deposit of uranium, such as uraninite, discovered by geophysical techniques, is evaluated and sampled to determine the amounts of uranium materials that are extractable at specified costs from the deposit. Uranium reserves are the amounts of ore that are estimated to be recoverable at stated costs. Uranium in nature consists primarily of two isotopes, U-238 and U-235. The numbers refer to the atomic mass number for each isotope, or the number of protons and neutrons in the atomic nucleus. Naturally occurring uranium consists of approximately 99.28% U-238 and 0.71% U-235. The atomic nucleus of U-235 will nearly always fission when struck by a free neutron, and the isotope is therefore said to be a "fissile" isotope. The nucleus of a U-238 atom on the other hand, rather than undergoing fission when struck by a free neutron, will nearly always absorb the neutron and yield an atom of the isotope U-239. This isotope then undergoes natural radioactive decay to yield Pu-239, which, like U-235, is a fissile isotope. The atoms of U-238 are said to be fertile, because, through neutron irradiation in the core, some eventually yield atoms of fissile Pu-239.

Mining

Uranium ore can be extracted through conventional mining in open pit and underground methods similar to those used for mining other metals. In-situ leach mining methods also are used to mine uranium in the United States. In this technology, uranium is leached from the in-place ore through an array of regularly spaced wells and is then recovered from the leach solution at a surface plant. Uranium ores in the United States typically range from about 0.05 to 0.3% uranium oxide (U_3O_8). Some uranium deposits developed in other countries are of higher grade and are also larger than deposits mined in the United States. Uranium is also present in very low-grade amounts (50 to 200 parts per million) in some domestic phosphate-bearing deposits of marine origin. Because very large quantities of phosphate-bearing rock are mined for the production of wet-process phosphoric acid used in high analysis fertilizers and other phosphate chemicals, at some phosphate processing plants the uranium, although present in very low concentrations, can be economically recovered from the process stream.

Milling

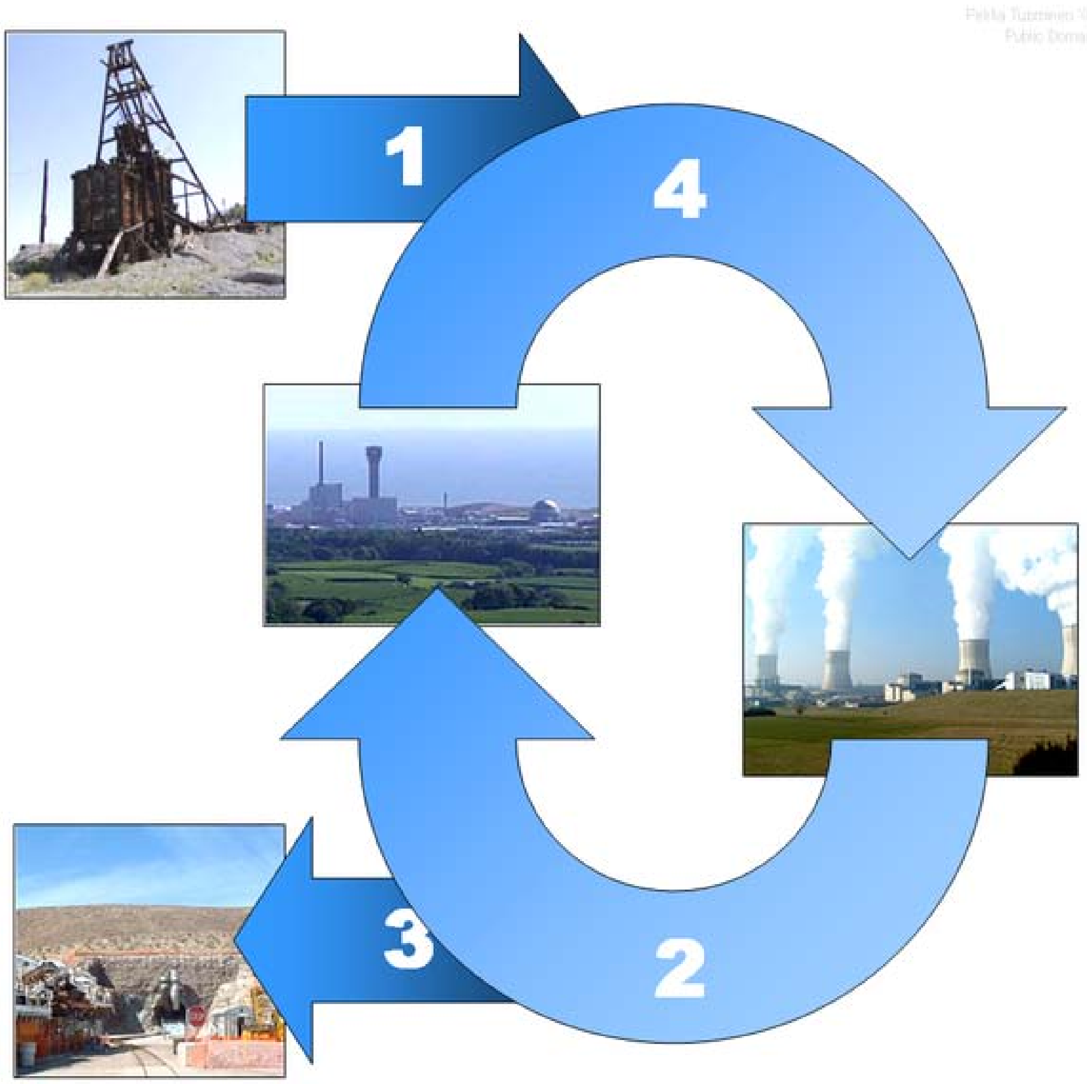
Mined uranium ores normally are processed by grinding the ore materials to a uniform particle size and then treating the ore to extract the uranium by chemical leaching. The milling process commonly yields dry powder-form material consisting of natural uranium, "yellowcake", which is sold on the uranium market as U_3O_8.

Uranium conversion

Milled uranium oxide, U_3O_8, must be converted to uranium hexafluoride, UF_6, which is the form required by most commercial uranium enrichment facilities currently in use. A solid at room temperature, uranium hexafluoride can be changed to a gaseous form at moderately higher temperature of 57 °C (134 °F). The uranium hexafluoride conversion product contains only natural, not enriched, uranium.

Triuranium octaoxide (U_3O_8) is also converted directly to ceramic grade uranium dioxide (UO_2) for use in reactors not requiring enriched fuel, such as CANDU. The volumes of material converted directly to UO_2 are typically quite small compared to the amounts converted to UF_6.

Enrichment



Nuclear fuel cycle begins when uranium is mined, enriched and manufactured to 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 (if fuel is recycled) (2) or to a final repository (if no recycling is done) (3) for geological disposition. In reprocessing 95% of spent fuel can be recycled to be returned to usage in a nuclear power plant (4).

The concentration of the fissionable isotope, U-235 (0.71% in natural uranium) is less than that required to sustain a nuclear chain reaction in light water reactor cores. Natural UF_6 thus must be enriched in the fissionable isotope for it to be used as nuclear fuel. The different levels of enrichment required for a particular nuclear fuel application are specified by the customer: light-water reactor fuel normally is enriched to 3.5% U-235, but uranium enriched to lower concentrations is also required. Enrichment is accomplished using one or more methods of isotope separation. Gaseous diffusion and gas centrifuge are the commonly used uranium enrichment technologies, but new enrichment technologies are currently being developed.

The bulk (96%) of the byproduct from enrichment is depleted uranium (DU), which can be used for armor, kinetic energy penetrators, radiation shielding and ballast. Still, there are vast quantities of depleted uranium in storage. The United States Department of Energy alone has 470,000 tonnes. About 95% of depleted uranium is stored as uranium hexafluoride (UF_6).

Fabrication

For use as nuclear fuel, enriched uranium hexafluoride is converted into uranium dioxide (UO_2) powder that is then processed into pellet form. The pellets are then fired in a high temperature sintering furnace to create hard, ceramic pellets of enriched uranium. The cylindrical pellets then undergo a grinding process to achieve a uniform pellet size. The pellets are stacked, according to each nuclear reactor core's design specifications, into tubes of corrosion-resistant metal alloy. The tubes are sealed to contain the fuel pellets: these tubes are called fuel rods. The finished fuel rods are grouped in special fuel assemblies that are then used to build up the nuclear fuel core of a power reactor.

The metal used for the tubes depends on the design of the reactor. Stainless steel was used in the past, but most reactors now use zirconium. For the most common types of reactors, boiling water reactors (BWR) and pressurized water reactors (PWR), the tubes are assembled into bundles with the tubes spaced precise distances apart. These bundles are then given a unique identification number, which enables them to be tracked from manufacture through use and into disposal.

Service period

Transport of radioactive materials

Transport is an integral part of the nuclear fuel cycle. There are nuclear power reactors in operation in several countries but uranium mining is viable in only a few areas. Also, in the course of over forty years of operation by the nuclear industry, a number of specialized facilities have been developed in various locations around the world to provide fuel cycle services and there is a need to transport nuclear materials to and from these facilities. Most transports of nuclear fuel material occur between different stages of the cycle, but occasionally a material may be transported between similar facilities. With some exceptions, nuclear fuel cycle materials are transported in solid form, the exception being uranium hexafluoride (UF_6) which is considered a gas. Most of the material used in nuclear fuel is transported several times during the cycle. Transports are frequently international, and are often over large distances. Nuclear materials are generally transported by specialized transport companies.

Since nuclear materials are radioactive, it is important to ensure that radiation exposure of both those involved in the transport of such materials and the general public along transport routes is limited. Packaging for nuclear materials includes, where appropriate, shielding to reduce potential radiation exposures. In the case of some materials, such as fresh uranium fuel assemblies, the radiation levels are negligible and no shielding is required. Other materials, such as spent fuel and high-level waste, are highly radioactive and require special handling. To limit the risk in transporting highly radioactive materials, containers known as spent nuclear fuel shipping casks are used which are designed to maintain integrity under normal transportation conditions and during hypothetical accident conditions.

In-core fuel management

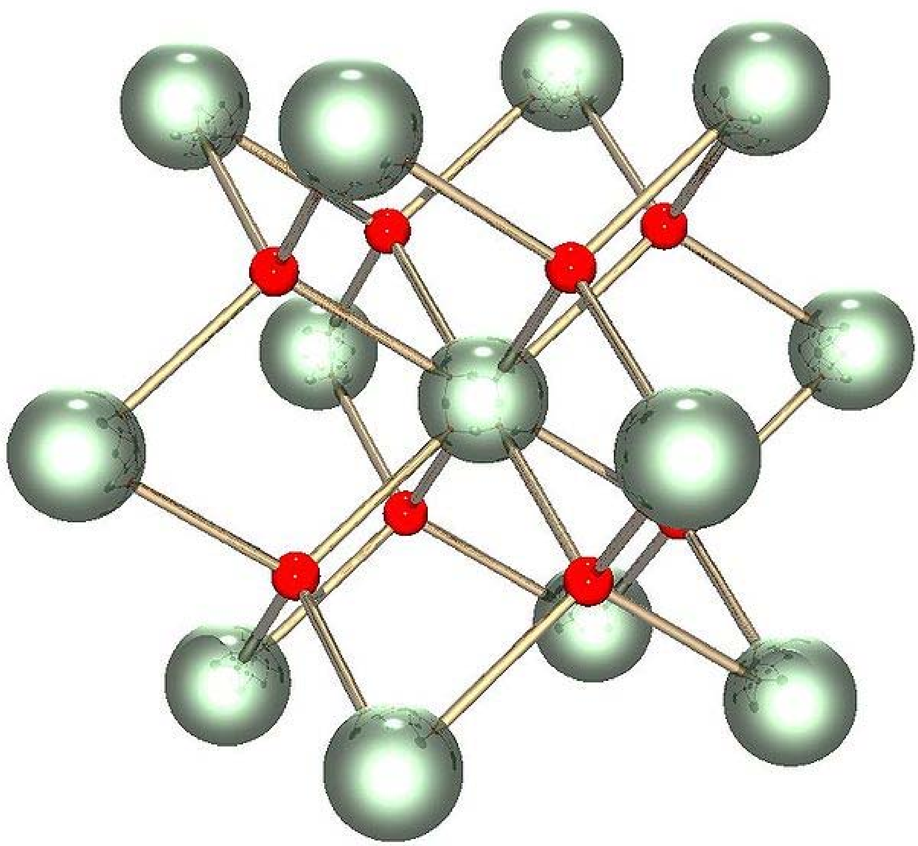
A nuclear reactor core is composed of a few hundred "assemblies", arranged in a regular array of cells, each cell being formed by a fuel or control rod surrounded, in most designs, by a moderator and coolant, which is water in most reactors.

Because of the fission process that consumes the fuels, the old fuel rods must be changed periodically to fresh ones (this period is called a cycle). However, only a part of the assemblies (typically one-third) are removed since the fuel depletion is not spatially uniform. Furthermore, it is not a good policy, for efficiency reasons, to put the new assemblies exactly at the location of the removed ones. Even bundles of the same age may have different burn-up levels, which depends on their previous positions in the core. Thus the available bundles must be arranged in such a way that the yield is maximized, while safety limitations and operational constraints are satisfied. Consequently reactor operators are faced with the so-called **optimal fuel reloading problem**, which consists in optimizing the rearrangement of all the assemblies, the old and fresh ones, while still maximizing the reactivity of the reactor core so as to maximise fuel burn-up and minimise fuel-cycle costs.

This is a discrete optimization problem, and computationally infeasible by current combinatorial methods, due to the huge number of permutations and the complexity of each computation. Many numerical methods have been proposed for solving it and many commercial software packages have been written to support fuel management. This is an on-going issue in reactor operations as no definitive solution to this problem has been found and operators use a combination of computational and empirical techniques to manage this problem.

The study of used fuel

Used nuclear fuel is studied in Post irradiation examination, where used fuel is examined to know more about the processes that occur in fuel during use, and how these might alter the outcome of an accident. For example, during normal use, the fuel expands due to thermal expansion, which can cause cracking. Most nuclear fuel is uranium dioxide, which is a cubic solid with a structure similar to that of calcium fluoride. In used fuel the solid state structure of most of the solid remains the same as that of pure cubic uranium dioxide. SIMFUEL is the name given to the simulated spent fuel which is made by mixing finely ground metal oxides, grinding as a slurry, spray drying it before heating in hydrogen/argon to 1700 ^{o}C. In SIMFUEL, 4.1% of the volume of the solid was in the form of metal nanoparticles which are made of molybdenum, ruthenium, rhodium and palladium. Most of these metal particles are of the ε phase (hexagonal) of Mo-Ru-Rh-Pd alloy, while smaller amounts of the α (cubic) and σ (tetragonal) phases of these metals were found in the SIMFUEL. Also present within the SIMFUEL was a cubic perovskite phase which is a barium strontium zirconate ($Ba_xSr_{1-x}ZrO_3$).



The solid state structure of uranium dioxide, the oxygen atoms are in green and the uranium atoms in red

Uranium dioxide is very insoluble in water, but after oxidation it can be converted to uranium trioxide or another uranium(VI) compound which is much more soluble. Uranium dioxide (UO_2) can be oxidised to an oxygen rich hyperstoichiometric oxide (UO_{2+x}) which can be further oxidised to U_4O_9, U_3O_7, U_3O_8 and $UO_3.2H_2O$.

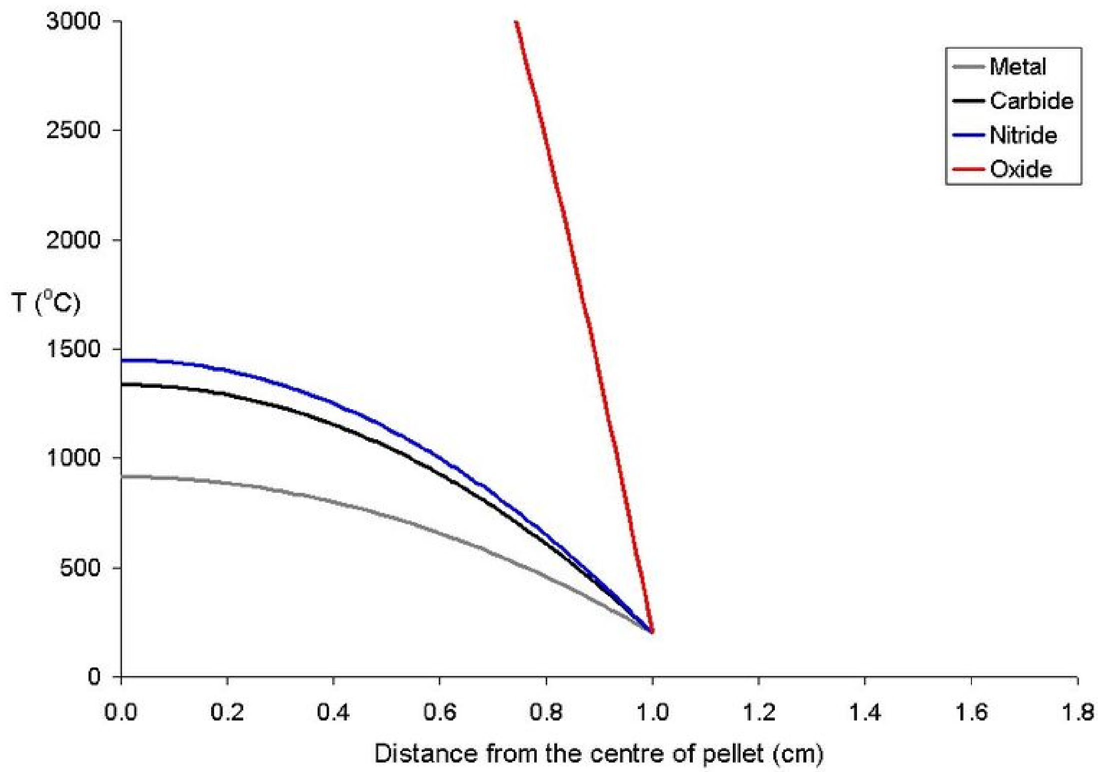
Because used fuel contains alpha emitters (plutonium and the minor actinides), the effect of adding an alpha emitter (^{238}Pu) to uranium dioxide on the leaching rate of the oxide has been investigated. For the crushed oxide, adding ^{238}Pu tended to increase the rate of leaching, but the difference in the leaching rate between 0.1 and 10% ^{238}Pu was very small.

The concentration of carbonate in the water which is in contact with the used fuel has a considerable effect on the rate of corrosion, because uranium(VI) forms soluble anionic carbonate complexes such as $[UO_2(CO_3)_2]^{2-}$ and $[UO_2(CO_3)_3]^{4-}$. When carbonate ions are absent, and the water is not strongly acidic, the hexavalent uranium compounds which form on oxidation of uranium dioxide often form insoluble hydrated uranium trioxide phases.

By 'sputtering', using uranium metal and an argon/oxygen gas mixture, thin films of uranium dioxide can be deposited upon gold surfaces. These gold surfaces modified with uranium dioxide have been used for both cyclic voltammetry and AC impedance experiments, and these offer an insight into the likely leaching behaviour of uranium dioxide.

Fuel cladding interactions

The study of the nuclear fuel cycle includes the study of the behaviour of nuclear materials both under normal conditions and under accident conditions. For example, there has been much work on how uranium dioxide based fuel interacts with the zirconium alloy tubing used to cover it. During use, the fuel swells due to thermal expansion and then starts to react with the surface of the zirconium alloy, forming a new layer which contains both fuel and zirconium (from the cladding). Then, on the fuel side of this mixed layer, there is a layer of fuel which has a higher caesium to uranium ratio than most of the fuel. This is because xenon isotopes are formed as fission products that diffuse out of the lattice of the fuel into voids such as the narrow gap between the fuel and the cladding. After diffusing into these voids, it decays to caesium isotopes. Because of the thermal gradient which exists in the fuel during use, the volatile fission products tend to be driven from the centre of the pellet to the rim area. Below is a graph of the temperature of uranium metal, uranium nitride and uranium dioxide as a function of distance from the centre of a 20 mm diameter pellet with a rim temperature of 200 ^{o}C. The uranium dioxide (because of its poor thermal conductivity) will overheat at the centre of the pellet, while the other more thermally conductive forms of uranium remain below their melting points.



Temperature profile for a 20 mm diameter fuel pellet with a power density of 1000 W per cubic meter. The fuels other than uranium dioxide are not compromised.

Normal and abnormal conditions

The nuclear chemistry associated with the nuclear fuel cycle can be divided into two main areas, one area is concerned with operation under the intended conditions while the other area is concerned with maloperation conditions where some alteration from the normal operating conditions has occurred or (*more rarely*) an accident is occurring.

The releases of radioactivity from normal operations are the small planned releases from uranium ore processing, enrichment, power reactors, reprocessing plants and waste stores. These can be in a different chemical/physical form to the releases which could occur under accident conditions. In addition the isotope signature of a hypothetical accident may be very different to that of a planned normal operational discharge of radioactivity to the environment.

Just because a radioisotope is released it does not mean it will enter a human and then cause harm. For instance the migration of radioactivity can be altered by the binding of the radioisotope to the surfaces of soil particles. For example caesium binds tightly to clay minerals such as illite and montmorillonite hence it remains in the upper layers of soil where it can be accessed by plants with shallow roots (such as grass). Hence grass and mushrooms can carry a considerable amount of ^{137}Cs which can be transferred to humans through the food chain. But ^{137}Cs is not able to migrate quickly through most soils and thus is unlikely to contaminate well water. Colloids of soil minerals can migrate through soil so simple binding of a metal to the surfaces of soil particles does not fix the metal totally.

According to Jiří Hála's text book the distribution coefficient K_d is the ratio of the soil's radioactivity (Bq g^{-1}) to that of the soil water (Bq ml^{-1}). If the radioisotope is tightly bound to the minerals in the soil then less radioactivity can be absorbed by crops and grass growing on the soil.

- Cs-137 K_d = 1000
- Pu-239 K_d = 10000 to 100000
- Sr-90 K_d = 80 to 150
- I-131 K_d = 0.007 to 50

One of the best countermeasures in dairy farming against ^{137}Cs is to mix up the soil by deeply ploughing the soil. This has the effect of putting the ^{137}Cs out of reach of the shallow roots of the grass, hence the level of radioactivity in the grass will be lowered. Also after a nuclear war or serious accident the removal of top few cm of soil and its burial in a shallow trench will reduce the long term gamma dose to humans due to ^{137}Cs as the gamma photons will be attenuated by their passage through the soil.

Even after the radioactive element arrives at the roots of the plant, the metal may be rejected by the biochemistry of the plant. The details of the uptake of ^{90}Sr and ^{137}Cs into sunflowers grown under hydroponic conditions has been reported. The caesium was found in the leaf veins, in the stem and in the apical leaves. It was found that 12% of the caesium entered the plant, and 20% of the strontium. This paper also reports details of the effect of potassium, ammonium and calcium ions on the uptake of the radioisotopes.

In livestock farming an important countermeasure against ^{137}Cs is to feed animals a small amount of prussian blue. This iron potassium cyanide compound acts as a ion-exchanger. The cyanide is so tightly bonded to the iron that it is safe for a human to eat several grams of prussian blue per day. The prussian blue reduces the biological half life (different from the nuclear half life) of the caesium. The physical or nuclear half life of ^{137}Cs is about 30 years. This is a constant which can not be changed but the biological half life is not a constant. It will change according to the nature and habits of the organism for which it is expressed. Caesium in humans normally has a biological half life of between one and four months. An added advantage of the prussian blue is that the caesium which is stripped from the animal in the droppings is in a form which is not available to plants. Hence it prevents the caesium from being recycled. The form of prussian blue required for the treatment of humans or animals is a special grade. Attempts to use the pigment grade used in paints have not been successful. Note that a good source of data on the subject of caesium in Chernobyl fallout exists at (*Ukrainian Research Institute for Agricultural Radiology*).

Release of radioactivity from fuel during normal use and accidents

The IAEA assume that under normal operation the coolant of a water cooled reactor will contain some radioactivity but during a reactor accident the coolant radioactivity level may rise. The IAEA state that under a series of different conditions different amounts of the core inventory can be released from the fuel, the four conditions the IAEA consider are *normal operation*, a spike in coolant activity due to a sudden shutdown/loss of pressure (core remains covered with water), a cladding failure resulting in the release of the activity in the fuel/cladding gap (this could be due to the fuel being uncovered by the loss of water for 15–30 minutes where the cladding reached a temperature of 650-1250 ^{o}C) or a melting of the core (the fuel will have to be uncovered for at least 30 minutes, and the cladding would reach a temperature in excess of 1650 ^{o}C).

Based upon the assumption that a PWR contains 300 tons of water, and that the activity of the fuel of a 1 GWe reactor is as the IAEA predict, then the coolant activity after an accident such as the three mile island accident (where a core is uncovered and then recovered with water) can be predicted.

Releases from reprocessing under normal conditions

It is normal to allow used fuel to stand after the irradiation to allow the short-lived and radiotoxic iodine isotopes to decay away. In one experiment in the USA fresh fuel which had not been allowed to decay was reprocessed (the Green run) to investigate the effects of a large iodine release from the reprocessing of short cooled fuel. It is normal in reprocessing plants to scrub the off gases from the dissolver to prevent the emission of iodine. In addition to the emission of iodine the noble gases and tritium are released from the fuel when it is dissolved. It has been proposed that by voloxidation (heating the fuel in a furnace under oxidizing conditions) the majority of the tritium can be recovered from the fuel.

A paper was written on the radioactivity in oysters found in the Irish Sea. These were found by gamma spectroscopy to contain ^{141}Ce, ^{144}Ce, ^{103}Ru, ^{106}Ru, ^{137}Cs, ^{95}Zr and ^{95}Nb. Additionally, a zinc activation product (^{65}Zn) was found, which is thought to be due to the corrosion of magnox fuel cladding in cooling ponds. It is likely that the modern releases of all these isotopes from Windscale is smaller.

On-load reactors

Some reactor designs, such as RBMKs or CANDU reactors, can be refueled without being shut down. This is achieved through the use of many small pressure tubes to contain the fuel and coolant, as opposed to one large pressure vessel as in pressurized water reactor (PWR) or boiling water reactor (BWR) designs. Each tube can be individually isolated and refueled by an operator-controlled fueling machine, typically at a rate of up to 8 channels per day out of roughly 400 in CANDU reactors. On-load refueling allows for the problem of **optimal fuel reloading problem** to be dealt with continuously, leading to more efficient use of fuel. This increase in efficiency is partially offset by the added complexity of having hundreds of pressure tubes and the fueling machines to service them.

Back end

Interim storage

After its operating cycle, the reactor is shut down for refueling. The fuel discharged at that time (spent fuel) is stored either at the reactor site (commonly in a spent fuel pool) or potentially in a common facility away from reactor sites. If on-site pool storage capacity is exceeded, it may be desirable to store the now cooled aged fuel in modular dry storage facilities known as Independent Spent Fuel Storage Installations (ISFSI) at the reactor site or at a facility away from the site. The spent fuel rods are usually stored in water or boric acid, which provides both cooling (the spent fuel continues to generate decay heat as a result of residual radioactive decay) and shielding to protect the environment from residual ionizing radiation, although after at least a year of cooling they may be moved to dry cask storage.

Reprocessing

The Sellafield reprocessing plant

Spent fuel discharged from reactors contains appreciable quantities of fissile (U-235 and Pu-239), fertile (U-238), and other radioactive materials, including reaction poisons, which is why the fuel had to be removed. These fissile and fertile materials can be chemically separated and recovered from the spent fuel. The recovered uranium and plutonium can, if economic and institutional conditions permit, be recycled for use as nuclear fuel. This is currently not done for civilian spent nuclear fuel in the United States.

Mixed oxide, or MOX fuel, is a blend of reprocessed uranium and plutonium and depleted uranium which behaves similarly, although not identically, to the enriched uranium feed for which most nuclear reactors were designed. MOX fuel is an alternative to low-enriched uranium (LEU) fuel used in the light water reactors which predominate nuclear power generation.

Currently, plants in Europe are reprocessing spent fuel from utilities in Europe and Japan. Reprocessing of spent commercial-reactor nuclear fuel is currently not permitted in the United States due to the perceived danger of nuclear proliferation. However the recently announced Global Nuclear Energy Partnership would see the U.S. form an international partnership to see spent nuclear fuel reprocessed in a way that renders the plutonium in it usable for nuclear fuel but not for nuclear weapons.

Partitioning and transmutation

As an alternative to the disposal of the PUREX raffinate in glass or Synroc, the most radiotoxic elements can be removed through advanced reprocessing. After separation the minor actinides and some long lived fission products can be converted to short-lived isotopes by either neutron or photon irradiation. This is called transmutation.

Waste disposal

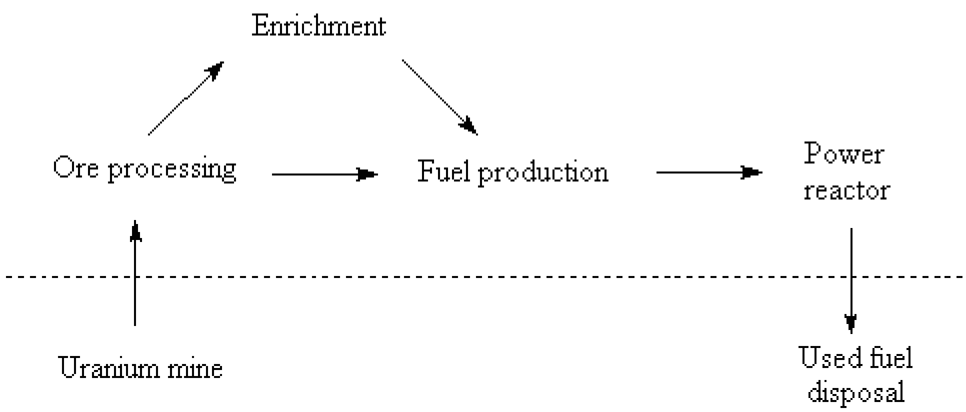
A current concern in the nuclear power field is the safe disposal and isolation of either spent fuel from reactors or, if the reprocessing option is used, wastes from reprocessing plants. These materials must be isolated from the biosphere until the radioactivity contained in them has diminished to a safe level. In the U.S., under the Nuclear Waste Policy Act of 1982 as amended, the Department of Energy has responsibility for the development of the waste disposal system for spent nuclear fuel and high-level radioactive waste. Current plans call for the ultimate disposal of the wastes in solid form in a licensed deep, stable geologic structure called a deep geological repository. The Department of Energy chose Yucca Mountain as the location for the repository. However, its opening has been repeatedly delayed.

It is worth noting that some non-PLWR reactor designs, and in particular the ones using liquid thorium fuel in molten salt reactors, would produce virtually no long-lasting nuclear waste. It is also possible to burn rather than bury nuclear waste, for instance in Integral Fast Reactors or in variations of molten salt reactors.

A proposed type of nuclear reactor called a traveling wave reactor is claimed, if it were to be built, to be able to be fueled by nuclear waste, and to be able to operate for 200 years without needing any refueling.

Fuel cycles

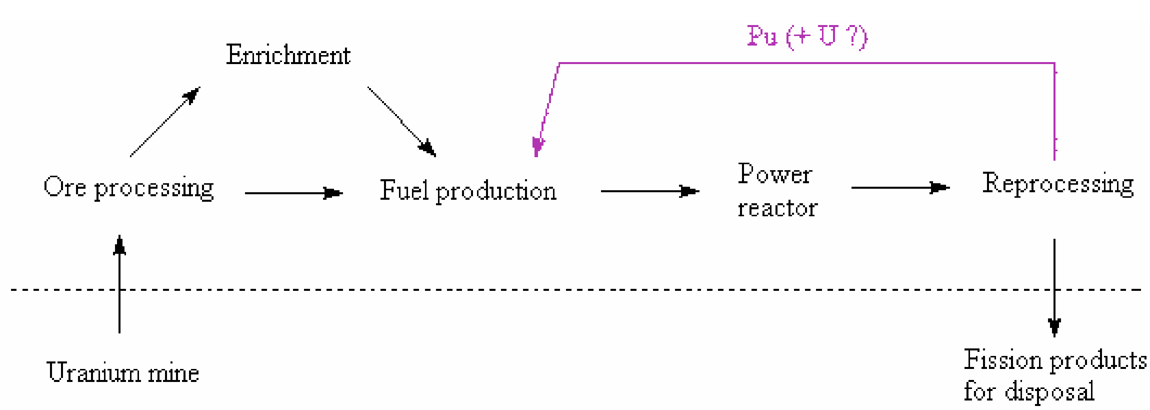
Once-through nuclear fuel cycle



A once through (or open) fuel cycle

Not a cycle *per se*, fuel is used once and then sent to storage without further processing save additional packaging to provide for better isolation from the biosphere. This method is favored by six countries: the United States, Canada, Sweden, Finland, Spain and South Africa. Some countries, notably Sweden and Canada, have designed repositories to permit future recovery of the material should the need arise, while others plan for permanent sequestration in a geological repository like the Yucca Mountain nuclear waste repository in the United States.

Plutonium cycle



A fuel cycle in which plutonium is used for fuel

Several countries, including Japan, Switzerland, and previously Spain and Germany, are using or have used the reprocessing services offered by BNFL and COGEMA. Here, the fission products, minor actinides, activation products, and reprocessed uranium are separated from the reactor-grade plutonium, which can then be fabricated into MOX fuel. Because the proportion of the non-fissile even-mass isotopes of plutonium rises with each pass through the cycle, there are currently no plans to reuse plutonium from used MOX fuel for a third pass in a thermal reactor. However, if fast reactors become available, they may be able to burn these, or almost any other actinide isotopes.

Minor actinides recycling

It has been proposed that in addition to the use of plutonium, the minor actinides could be used in a critical power reactor. Tests are already being conducted in which americium is being used as a fuel.

A number of reactor designs, like the Integral Fast Reactor, have been designed for this rather different fuel cycle. In principle, it should be possible to derive energy from the fission of any actinide nucleus. With a careful reactor design, all the actinides in the fuel can be consumed, leaving only lighter elements with short half-lives. Whereas this has been done in prototype plants, no such reactor has ever been operated on a large scale, and the first plants with full actinide recovery are expected to be ready for commercial deployment in 2015 at the earliest.

However, such schemes would most likely require advanced remote reprocessing methods due to the neutron emitting compounds formed. For instance if curium is irradiated with neutrons it will form the very heavy actinides californium and fermium which undergo spontaneous fission. As a result, the neutron emission from a used fuel element which had included curium will be much higher, potentially posing a risk to workers at the back end of the cycle unless all reprocessing is done remotely. This could be seen as a disadvantage, but on the other hand it also makes the nuclear material difficult to steal or divert, making it more resistant to nuclear proliferation

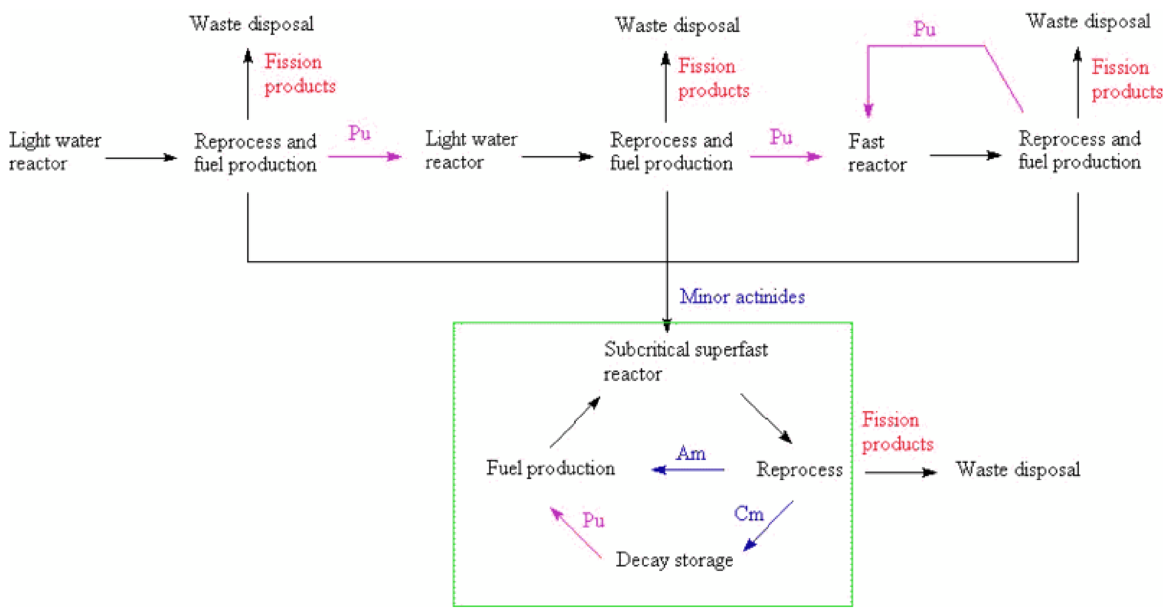
It so happens that the neutron cross-section of many actinides decreases with increasing neutron energy, but the ratio of fission to simple activation (neutron capture) changes in favour of fission as the neutron energy increases. Thus with a sufficiently high neutron energy, it should be possible to destroy even curium without the generation of the transcurium metals. This could be very desirable as it would make it significantly easier to reprocess and handle the actinide fuel.

One promising alternative from this perspective is an accelerator driven subcritical reactor. Here a beam of either protons (United States and European designs) or electrons (Japanese design) is directed into a target. In the case of protons, very fast neutrons will spall off the target, while in the case of the electrons, very high energy photons will be generated. These high-energy neutrons and photons will then be able to cause the fission of the heavy actinides.

Such reactors compare very well to other neutron sources in terms of neutron energy:

- Thermal 0 to 100 eV
- Epithermal 100 eV to 100 KeV
- Fast (from nuclear fission) 100 KeV to 3 MeV
- DD fusion 2.5 MeV
- DT fusion 14 MeV
- Accelerator driven core 200 MeV (lead driven by 1.6 GeV protons)
- Muon-catalyzed fusion 7 GeV.

As an alternative, the curium-244, with a half life of 18 years, could be left to decay into plutonium-240 before being used in fuel in a fast reactor.



A pair of fuel cycles in which uranium and plutonium are kept separate from the minor actinides. The minor actinide cycle is kept within the green box.

Fuel or targets for this actinide transmutation

To date the nature of the fuel (targets) for actinide transformation has not been chosen.

If actinides are transmuted in a Subcritical reactor it is likely that the fuel will have to be able to tolerate more thermal cycles than conventional fuel. An accelerator driven sub critical reactor is unlikely to be able to maintain a constant operation period for equally long times as a critical reactor, and each time the accelerator stops then the fuel will cool down.

On the other hand, if actinides are destroyed using a fast reactor, such as an Integral Fast Reactor, then the fuel will most likely not be exposed to many more thermal cycles than in a normal power station.

Depending on the matrix the process can generate more transuranics from the matrix. This could either be viewed as good (generate more fuel) or can be viewed as bad (generation of more *radiotoxic* transuranic elements). A series of different matrices exists which can control this production of heavy actinides.

Fissile nuclei, like Uranium-235, Plutonium-239 and Uranium-233 respond well to delayed neutrons and are thus important to keep a critical reactor stable, and this limits the amount of minor actinides that can be destroyed in a critical reactor. As a consequence it is important that the chosen matrix allows the reactor to keep the ratio of fissile to non-fissile nuclei high, as this enables it to destroy the long lived actinides safely. In contrast, the power output of a sub-critical reactor is limited by the intensity of the driving particle accelerator, and thus it need not contain any uranium or plutonium at all. In such a system it may be preferable to have an inert matrix that doesn't produce additional long-lived isotopes.

Actinides in an inert matrix

The actinides will be mixed with a metal which will not form more actinides, for instance an alloy of actinides in a solid such as zirconia could be used.

Actinides in a thorium matrix

Thorium will on neutron bombardment form uranium-233. U-233 is fissile, and has a larger fission cross section than both U-235 and U-238, and thus it is likely to produce very little additional actinides through neutron capture.

Actinides in a uranium matrix

If the actinides are incorporated into a uranium-metal or uranium-oxide matrix, then the neutron capture of U-238 is likely to generate new plutonium-239. An advantage of mixing the actinides with uranium and plutonium is that the large fission cross sections of U-235 and Pu-239 for the less energetic delayed-neutrons could make the reaction stable enough to be carried out in a critical fast reactor, which is likely to be both cheaper and simpler than an accelerator driven system.

Mixed matrix

It is also possible to create a matrix made from a mix of the above mentioned materials. This is most commonly done in fast reactors where one may wish to keep the breeding ratio of new fuel high enough to keep powering the reactor, but still low enough that the generated actinides can be safely destroyed without transporting them to another site.

One way to do this is to use fuel where actinides and uranium is mixed with inert zirconium, producing fuel elements with the desired properties.

Thorium cycle

In the thorium fuel cycle thorium-232 absorbs a neutron in either a fast or thermal reactor. The thorium-233 beta decays to protactinium-233 and then to uranium-233, which in turn is used as fuel. Hence, like uranium-238, thorium-232 is a fertile material.

After starting the reactor with existing U-233 or some other fissile material such as U-235 or Pu-239, a breeding cycle similar to but more efficient than that with U-238 and plutonium can be created. The Th-232 absorbs a neutron to become Th-233 which quickly decays to protactinium-233. Protactinium-233 in turn decays with a half-life of 27 days to U-233. In some molten salt reactor designs, the Pa-233 is extracted and protected from neutrons (which could transform it to Pa-234 and then to U-234), until it has decayed to U-233. This is done in order to improve the breeding ratio which is low compared to fast reactors.

Thorium is at least 4-5 times more abundant in nature than all of uranium isotopes combined; thorium is fairly evenly spread around Earth with a lot of countries having huge supplies of it; preparation of thorium fuel does not require difficult and expensive enrichment processes; the thorium fuel cycle creates mainly Uranium-233 contaminated with Uranium-232 which makes it harder to use in a normal, pre-assembled nuclear weapon which is stable over long periods of time (unfortunately drawbacks are much lower for immediate use weapons or where final assembly occurs just prior to usage time); elimination of at least the transuranic portion of the nuclear waste problem is possible in MSR and other breeder reactor designs.

One of the earliest efforts to use a thorium fuel cycle took place at Oak Ridge National Laboratory in the 1960s. An experimental reactor was built based on molten salt reactor technology to study the feasibility of such an approach, using thorium fluoride salt kept hot enough to be liquid, thus eliminating the need for fabricating fuel elements. This effort culminated in the Molten-Salt Reactor Experiment that used ^{232}Th as the fertile material and ^{233}U as the fissile fuel. Due to a lack of funding, the MSR program was discontinued in 1976.

Current industrial activity

Currently the only isotopes used as nuclear fuel are uranium-235 (U-235), uranium-238 (U-238) and plutonium-239, although the proposed thorium fuel cycle has advantages. Some modern reactors, with minor modifications, can use thorium. Thorium is approximately three times more abundant in the Earth's crust than uranium (and 550 times more abundant than uranium-235). However, there has been little exploration for thorium resources, and thus the proved resource is small. Thorium is more plentiful than uranium in some countries, notably India.

Heavy water reactors and graphite-moderated reactors can use natural uranium, but the vast majority of the world's reactors require enriched uranium, in which the ratio of U-235 to U-238 is increased. In civilian reactors the enrichment is increased to as much as 5% U-235 and 95% U-238, but in naval reactors there is as much as 93% U-235.

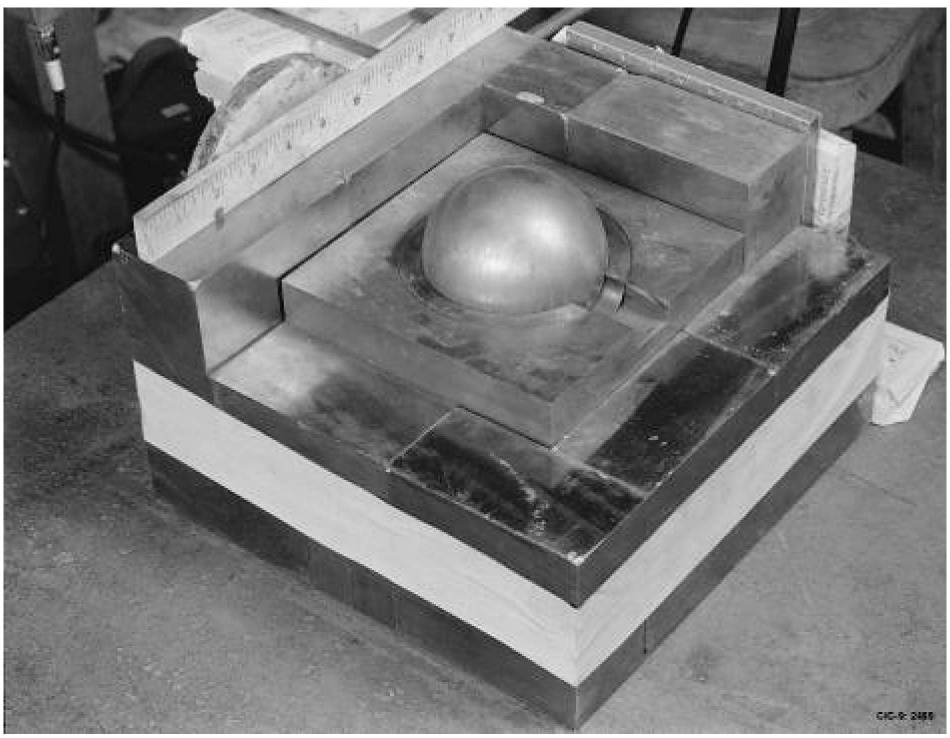
The term *nuclear fuel* is not normally used in respect to fusion power, which fuses isotopes of hydrogen into helium to release energy.

Integrated Nuclear Fuel Cycle Information System

Integrated nuclear fuel cycle information system (iNFCIS) is a set of databases related to the nuclear fuel cycle maintained by the International Atomic Energy Agency (IAEA). iNFCIS provides information on various aspects of nuclear fuel cycles. Presently iNFCIS includes UDEPO - World distribution of uranium deposits; NFCIS - Nuclear fuel cycle information system, a database of civilian nuclear fuel cycle facilities; PIEDB - Post irradiation examination facilities database; MABD - Minor actinide property database and NFCSS - Nuclear fuel cycle simulation system, a tool for modeling material flow and actinide accumulations in the nuclear fuel cycle. iNFCIS requires free registration for on-line access.

Chapter-10

Critical Mass



As part of a re-creation of a 1945 criticality accident, a plutonium pit is surrounded by blocks of neutron-reflective tungsten carbide. The original experiment was designed to measure the radiation produced when an extra block was added. Instead, the mass went supercritical.

A **critical mass** is the smallest amount of fissile material needed for a sustained nuclear chain reaction. The critical mass of a fissionable material depends upon its nuclear properties (e.g. the nuclear fission cross-section), its density, its shape, its enrichment, its purity, its temperature and its surroundings.

Explanation of criticality

When a nuclear chain reaction in a mass of fissile material is self-sustaining, the mass is said to be in a *critical* state in which there is no increase or decrease in power, temperature or neutron population.

A numerical measure of a critical mass is dependent on the effective neutron multiplication factor k, the average number of neutrons released per fission event that go on to cause another fission event rather than being absorbed or leaving the material. When $k = 1$, the mass is critical, and the chain reaction is barely self-sustaining.

A *subcritical* mass is a mass of fissile material that does not have the ability to sustain a fission reaction. A population of neutrons introduced to a subcritical assembly will exponentially decrease. In this case, $k < 1$. A steady rate of spontaneous fissions causes a proportionally steady level of neutron activity. The constant of proportionality increases as k increases.

A *supercritical* mass is one where there is an increasing rate of fission. The material may settle into equilibrium (*i.e.* become critical again) at an elevated temperature/power level or destroy itself, by which equilibrium is reached. In the case of supercriticality, $k > 1$.

Changing the point of criticality

The point and therefore the mass where criticality occurs may be changed by modifying certain attributes such as fuel, shape, temperature, density and the installation of a neutron-reflective substance. These attributes have complex interactions and interdependencies. Here we, explains only the simplest ideal cases.

- **Varying the amount of fuel**

It is possible for a fuel assembly to be critical at near zero power. If the perfect quantity of fuel were added to a slightly subcritical mass to create an "exactly critical mass", fission would be self-sustaining for one neutron generation (fuel consumption makes the assembly subcritical).

If the perfect quantity of fuel were added to a slightly subcritical mass, to create a barely supercritical mass, the temperature of the assembly would increase to an initial maximum (for example: 1 K above the ambient temperature) and then decrease back to room temperature after a period of time, because fuel consumed during fission brings the assembly back to subcriticality once again.

- **Changing the shape**

A mass may be exactly critical without being a perfect homogeneous sphere. More closely refining the shape toward a perfect sphere will make the mass supercritical.

Conversely changing the shape to a less perfect sphere will decrease its reactivity and make it subcritical.

- **Changing the temperature**

A mass may be exactly critical at a particular temperature. Fission and absorption cross-sections increase as the relative neutron velocity decreases. As fuel temperature increases, neutrons of a given energy appear faster and thus fission/absorption is less likely. This is not unrelated to doppler broadening of the U238 resonances but is common to all fuels/absorbers/configurations. Neglecting the very important resonances, the total neutron cross section of every material exhibits an inverse relationship with relative neutron velocity. Hot fuel is always less reactive than cold fuel (over/under moderation in LWR is a different topic). Thermal expansion associated with temperature increase also contributes a negative coefficient of reactivity since fuel atoms are moving farther apart. A mass that is exactly critical at room temperature would be sub-critical in an environment anywhere above room temperature due to thermal expansion alone.

- **Varying the density of the mass**

The higher the density, the lower the critical mass. The density of a material at a constant temperature can be changed by varying the pressure or tension or by changing crystal structure. An ideal mass will become subcritical if allowed to expand or conversely the same mass will become supercritical if compressed. Changing the temperature may also change the density; however, the effect on critical mass is then complicated by temperature effects and by whether the material expands or contracts with increased temperature. Assuming the material expands with temperature (enriched Uranium 235 at room temperature for example), at an exactly critical state, it will become subcritical if warmed to lower density or become supercritical if cooled to higher density. Such a material is said to have a negative temperature coefficient of reactivity to indicate that its reactivity decreases when its temperature increases. Using such a material as fuel means fission decreases as the fuel temperature increases.

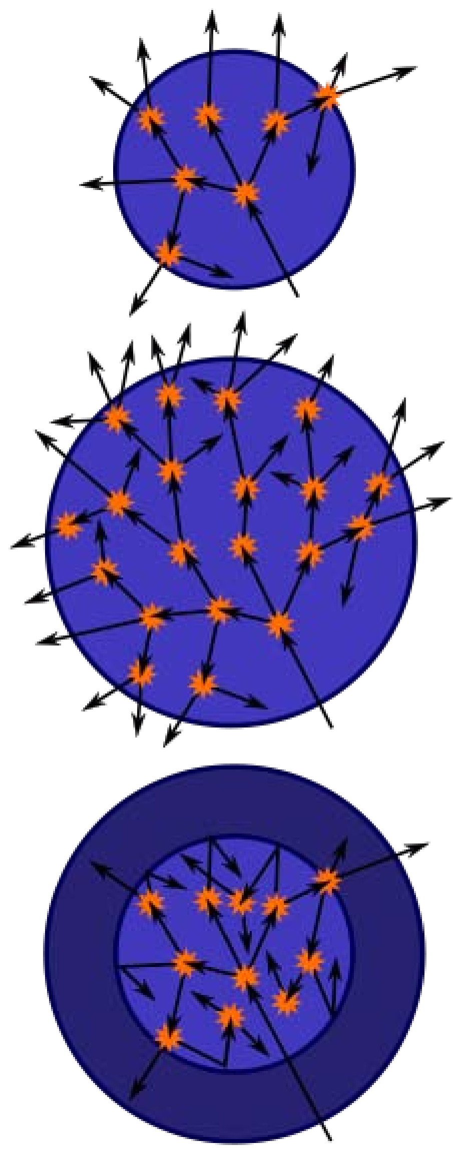
- **Use of a neutron reflector**

Surrounding a spherical critical mass with a neutron reflector further reduces the mass needed for criticality. A common material for a neutron reflector is beryllium metal. This reduces the number of neutrons which escape the fissile material, resulting in increased reactivity.

- **Use of a tamper**

In a bomb, a dense shell of material surrounding the fissile core will contain, via inertia, the expanding fissioning material. This increases the efficiency. Because a bomb relies on fast neutrons (not ones moderated by reflection with light elements, as in a reactor) the tamper in a bomb is not functioning as a neutron reflector. Also, if the tamper is (e.g. depleted) uranium, it can fission due to the high energy neutrons generated by the primary explosion. This can greatly increase yield, especially if even more neutrons are generated by fusing hydrogen isotopes, in a so-called boosted configuration.

Critical mass of a bare sphere



Top: A sphere of fissile material is too small to allow the chain reaction to become self-sustaining as neutrons generated by fissions can too easily escape.

Middle: By increasing the mass of the sphere to a critical mass, the reaction can become self-sustaining.

Bottom: Surrounding the original sphere with a neutron reflector increases the efficiency of the reactions and also allows the reaction to become self-sustaining.

The shape with minimal critical mass and the smallest physical dimensions is a sphere. Bare-sphere critical masses at normal density of some actinides are listed in the following table.

Nuclide	Critical Mass (kg)	Diameter (cm)
protactinium-231	750±180?	45±3?
uranium-233	15	11
uranium-235	52	17
neptunium-236	7	8.7
neptunium-237	60	18
plutonium-238	9.04–10.07	9.5-9.9
plutonium-239	10	9.9
plutonium-240	40	15
plutonium-241	12	10.5
plutonium-242	75–100	19-21
americium-241	55–77	20-23
americium-242	9–14	11-13
americium-243	180–280	30-35
curium-243	7.34–10	10-11
curium-244	(13.5)–30	(12.4)–16
curium-245	9.41–12.3	11-12
curium-246	39–70.1	18-21
curium-247	6.94–7.06	9.9
californium-249	6	9
californium-251	5	8.5

The critical mass for lower-grade uranium depends strongly on the grade: with 20% U-235 it is over 400 kg; with 15% U-235, it is well over 600 kg.

The critical mass is inversely proportional to the square of the density. If the density is 1% more and the mass 2% less, then the volume is 3% less and the diameter 1% less. The probability for a neutron per cm travelled to hit a nucleus is proportional to the density. It follows that 1% greater density means that the distance travelled before leaving the system is 1% less. This is something that must be taken into consideration when attempting more precise estimates of critical masses of plutonium isotopes than the approximate values given above, because plutonium metal has a large number of different crystal phases which can have widely varying densities.

Note that not all neutrons contribute to the chain reaction. Some escape and others undergo radiative capture.

Let *q* denote the probability that a given neutron induces fission in a nucleus. Let us consider only prompt neutrons, and let ν denote the number of prompt neutrons generated in a nuclear fission. For example, ν ≈ 2.5 for uranium-235. Then, criticality occurs when $\nu \cdot q = 1$. The dependence of this upon geometry, mass, and density appears through the factor *q*.

Given a total interaction cross section σ (typically measured in barns), the mean free path of a prompt neutron is $\ell^{-1} = n\sigma$ where *n* is the nuclear number density. Most interactions are scattering events, so that a given neutron obeys a random walk until it either escapes from the medium or causes a fission reaction. So long as other loss mechanisms are not significant, then, the radius of a spherical critical mass is rather roughly given by the product of the mean free path ℓ and the square root of one plus the number of scattering events per fission event (call this *s*), since the net distance travelled in a random walk is proportional to the square root of the number of steps:

$$R_c \simeq \ell\sqrt{s} \simeq \frac{\sqrt{s}}{n\sigma}$$

Note again, however, that this is only a rough estimate.

In terms of the total mass *M*, the nuclear mass *m*, the density ρ, and a fudge factor *f* which takes into account geometrical and other effects, criticality corresponds to

$$1 = \frac{f\sigma}{m\sqrt{s}}\rho^{2/3}M^{1/3}$$

which clearly recovers the aforementioned result that critical mass depends inversely on the square of the density.

Alternatively, one may restate this more succinctly in terms of the areal density of mass, Σ:

$$1 = \frac{f'\sigma}{m\sqrt{s}}\Sigma$$

where the factor *f* has been rewritten as *f'* to account for the fact that the two values may differ depending upon geometrical effects and how one defines Σ. For example, for a bare solid sphere of Pu-239 criticality is at 320 kg/m^2, regardless of density, and for U-235 at 550 kg/m^2. In any case, criticality then depends upon a typical neutron "seeing" an amount of nuclei around it such that the areal density of nuclei exceeds a certain threshold.

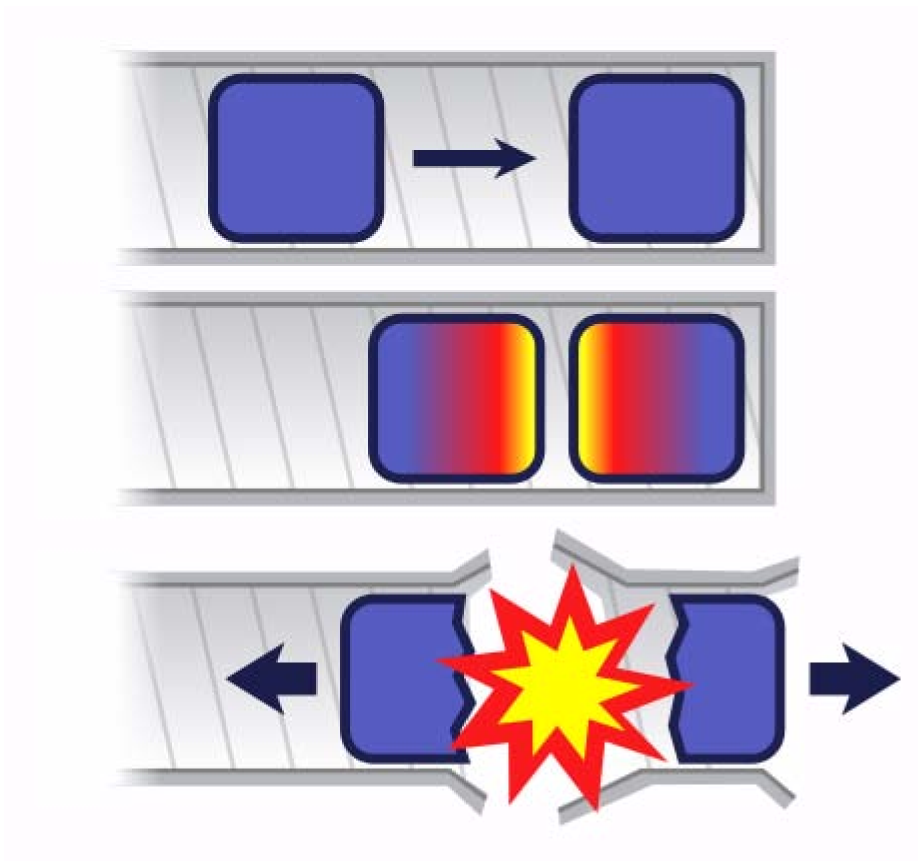
This is applied in implosion-type nuclear weapons where a spherical mass of fissile material that is substantially less than a critical mass is made supercritical by very rapidly increasing ρ (and thus Σ as well). Indeed, sophisticated nuclear weapons programs can make a functional device from less material than more primitive weapons programs require.

Aside from the math, there is a simple physical analog that helps explain this result. Consider diesel fumes belched from an exhaust pipe. Initially the fumes appear black, then gradually you are able to see through them without any trouble. This is not because the total scattering cross section of all the soot particles has changed, but because the soot has dispersed. If we consider a transparent cube of length L on a side, filled with soot, then the optical depth of this medium is inversely proportional to the square of L, and therefore proportional to the areal density of soot particles: we can make it easier to see through the imaginary cube just by making the cube larger.

Several uncertainties contribute to the determination of a precise value for critical masses, including (1) detailed knowledge of cross sections, (2) calculation of geometric effects. This latter problem provided significant motivation for the development of the Monte Carlo method in computational physics by Nicholas Metropolis and Stanislaw Ulam. In fact, even for a homogeneous solid sphere, the exact calculation is by no means trivial. Finally note that the calculation can also be performed by assuming a continuum approximation for the neutron transport. This reduces it to a diffusion problem. However, as the typical linear dimensions are not significantly larger than the mean free path, such an approximation is only marginally applicable.

Finally, note that for some idealized geometries, the critical mass might formally be infinite, and other parameters are used to describe criticality. For example, consider an infinite sheet of fissionable material. For any finite thickness, this corresponds to an infinite mass. However, criticality is only achieved once the thickness of this slab exceeds a critical value.

Criticality in nuclear weapon design



If two pieces of subcritical material are not brought together fast enough, nuclear predetonation (fizzle) can occur, whereby a very small explosion will blow the bulk of the material apart.

Until detonation is desired, a nuclear weapon must be kept subcritical. In the case of a uranium bomb, this can be achieved by keeping the fuel in a number of separate pieces, each below the critical size either because they are too small or unfavorably shaped. To produce detonation, the uranium is brought together rapidly. In Little Boy, this was achieved by firing a piece of uranium (a 'doughnut'), down a gun barrel onto another piece, (a 'spike'), a design referred to as a *gun-type fission weapon*.

A theoretical 100% pure Pu-239 weapon could also be constructed as a gun-type weapon, like the Manhattan Project's proposed Thin Man design. In reality, this is impractical because even "weapons grade" Pu-239 is contaminated with a small amount of Pu-240, which has a strong propensity toward spontaneous fission. Because of this, a reasonably-sized gun-type weapon would suffer nuclear reaction before the masses of plutonium would be in a position for a full-fledged explosion to occur.

Instead, the plutonium is present as a subcritical sphere (or other shape), which may or may not be hollow. Detonation is produced by exploding a shaped charge surrounding the sphere, increasing the density (and collapsing the cavity, if present) to produce a prompt critical configuration. This is known as an *implosion type weapon*.

Chapter-11

Neutron Poison and Neutron Source

Neutron poison

A **neutron poison** (also called a 'neutron absorber' or a 'nuclear poison') is a substance with a large neutron absorption cross-section in applications, such as nuclear reactors. In such applications, absorbing neutrons is normally an undesirable effect. However neutron-absorbing materials, also called poisons, are intentionally inserted into some types of reactors in order to lower the high reactivity of their initial fresh fuel load. Some of these poisons deplete as they absorb neutrons during reactor operation, while others remain relatively constant.

The capture of neutrons by short half-life fission products is known as **reactor poisoning**; neutron capture by long-lived or stable fission products is called **reactor slagging**.

Transient fission product poisons

Some of the fission products generated during a nuclear reaction have a high neutron absorption capacity, such as xenon-135 (2,000,000 barns) and samarium-149 (74,500 σ). Because these two fission product poisons remove neutrons from the reactor, they will have an impact on the thermal utilization factor and thus the reactivity. The poisoning of a reactor core by these fission products may become so serious that the chain reaction comes to a standstill.

Xenon-135 in particular has a tremendous impact on the operation of a nuclear reactor. The inability of a reactor to be started due to the effects of xenon-135 is sometimes referred to as *xenon precluded start-up*. The period of time in which the reactor is unable to override the effects of xenon-135 is called the *xenon dead time* or *poison outage*. During periods of steady state operation, at a constant neutron flux level, the xenon-135 concentration builds up to its equilibrium value for that reactor power in about 40 to 50 hours. When the reactor power is increased, xenon-135 concentration initially decreases because the burn up is increased at the new higher power level. Because 95% of the xenon-135 production is from iodine-135 decay, which has a 6 to 7 hour half-life, the production of xenon-135 remains constant; at this point, the xenon-135 concentration reaches a minimum. The concentration then increases to the equilibrium for the new power level in the same time, roughly 40 to 50 hours. The magnitude and the rate of change of concentration during the initial 4 to 6 hour period following the power change is dependent upon the initial power level and on the amount of change in power level; the xenon-135 concentration change is greater for a larger change in power level. When reactor power is decreased, the process is reversed.

Because samarium-149 is not radioactive and is not removed by decay, it presents problems somewhat different from those encountered with xenon-135. The equilibrium concentration and (thus the poisoning effect) builds to an equilibrium value during reactor operation in about 500 hours (about three weeks), and since samarium-149 is stable, the concentration remains essentially constant during reactor operation. Another problematic isotope that is building up is gadolinium-157, with cross-section of 200,000 σ.

Accumulating fission product poisons

There are numerous other fission products that, as a result of their concentration and thermal neutron absorption cross section, have a poisoning effect on reactor operation. Individually, they are of little consequence, but taken together they have a significant impact. These are often characterized as *lumped fission product poisons* and accumulate at an average rate of 50 barns per fission event in the reactor. The buildup of fission product poisons in the fuel eventually leads to loss of efficiency, and in some cases to instability. 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: solid spent nuclear fuel contains about 97% of the original fissionable material present in newly manufactured nuclear fuel. Chemical separation of the fission products restores the fuel so that it can be used again.

Other potential approaches to fission product removal include solid but porous fuel which allows escape of fission products and liquid or gaseous fuel (Molten salt reactor, Aqueous homogeneous reactor). These ease the problem of fission product accumulation in the fuel, but pose the additional problem of safely removing and storing the fission products.

Other fission products with relatively high absorption cross sections include ^{83}Kr, ^{95}Mo, ^{143}Nd, ^{147}Pm. Above this mass, even many even-mass number isotopes have large absorption cross sections, allowing one nucleus to serially absorb multiple neutrons. Fission of heavier actinides produces more of the heavier fission products in the lanthanide range, so the total neutron absorption cross section of fission products is higher.

In a fast reactor the fission product poison situation may differ significantly because neutron absorption cross sections can differ for thermal neutrons and fast neutrons. In the

RBEC-M Lead-Bismuth Cooled Fast Reactor, the fission products with neutron capture more than 5% of total fission products capture are, in order, ^{133}Cs, ^{101}Ru, ^{103}Rh, ^{99}Tc, ^{105}Pd and ^{107}Pd in the core, with ^{149}Sm replacing ^{107}Pd for 6th place in the breeding blanket.

Decay poisons

In addition to fission product poisons, other materials in the reactor decay to materials that act as neutron poisons. An example of this is the decay of tritium to helium-3. Since tritium has a half-life of 12.3 years, normally this decay does not significantly affect reactor operations because the rate of decay of tritium is so slow. However, if tritium is produced in a reactor and then allowed to remain in the reactor during a prolonged shutdown of several months, a sufficient amount of tritium may decay to helium-3 to add a significant amount of negative reactivity. Any helium-3 produced in the reactor during a shutdown period will be removed during subsequent operation by a neutron-proton reaction.

Control poisons

During operation of a reactor the amount of fuel contained in the core decreases monotonically. If the reactor is to operate for a long period of time, fuel in excess of that needed for exact criticality must be added when the reactor is fueled. The positive reactivity due to the excess fuel must be balanced with negative reactivity from neutron-absorbing material. Movable control rods containing neutron-absorbing material is one method, but control rods alone to balance the excess reactivity may be impractical for a particular core design as there may be insufficient room for the rods or their mechanisms.

Burnable poisons

To control large amounts of excess fuel reactivity without control rods, burnable poisons are loaded into the core. Burnable poisons are materials that have a high neutron absorption cross section that are converted into materials of relatively low absorption cross section as the result of neutron absorption. Due to the burn-up of the poison material, the negative reactivity of the burnable poison decreases over core life. Ideally, these poisons should decrease their negative reactivity at the same rate that the fuel's excess positive reactivity is depleted. Fixed burnable poisons are generally used in the form of compounds of boron or gadolinium that are shaped into separate lattice pins or plates, or introduced as additives to the fuel. Since they can usually be distributed more uniformly than control rods, these poisons are less disruptive to the core's power distribution. Fixed burnable poisons may also be discretely loaded in specific locations in the core in order to shape or control flux profiles to prevent excessive flux and power peaking near certain regions of the reactor. Current practice however is to use fixed non-burnable poisons in this service.

Non-burnable poison

A non-burnable poison is one that maintains a constant negative reactivity worth over the life of the core. While no neutron poison is strictly non-burnable, certain materials can be treated as non-burnable poisons under certain conditions. One example is hafnium. The removal (by absorption of neutrons) of one isotope of hafnium leads to the production of another neutron absorber, and continues through a chain of five absorbers. This absorption chain results in a long-lived burnable poison which approximates non-burnable characteristics.

Soluble poisons

Soluble poisons, also called chemical shim, produce a spatially uniform neutron absorption when dissolved in the water coolant. The most common soluble poison in commercial pressurized water reactors (PWR) is boric acid, which is often referred to as soluble boron, or simply *solbor*. The boric acid in the coolant decreases the thermal utilization factor, causing a decrease in reactivity. By varying the concentration of boric acid in the coolant, a process referred to as boration and dilution, the reactivity of the core can be easily varied. If the boron concentration is increased, the coolant/moderator absorbs more neutrons, adding negative reactivity. If the boron concentration is reduced (dilution), positive reactivity is added. The changing of boron concentration in a PWR is a slow process and is used primarily to compensate for fuel burnout or poison buildup. The variation in boron concentration allows control rod use to be minimized, which results in a flatter flux profile over the core than can be produced by rod insertion. The flatter flux profile occurs because there are no regions of depressed flux like those that would be produced in the vicinity of inserted control rods. This system is not in widespread use because the chemicals make the moderator temperature reactivity coefficient less negative.

Soluble poisons are also used in emergency shutdown systems. During SCRAM the operators can inject solutions containing neutron poisons directly into the reactor coolant. Various solutions, including sodium polyborate and gadolinium nitrate ($Gd(NO_3)_3 \cdot xH_2O$), are used.

On 16 March 2011, South Korea said they will send 1 kg sample of their Boric Acid stock to Japan. If the sample works on the reactors in Japan, South Korea will ship over 50 tons of Boric Acid to Japan. This was requested by the Japanese government in an attempt to further prevent meltdown at the Fukushima Nuclear Power Plant.

Neutron source

Neutron source is a general term referring to a variety of devices that emit neutrons, irrespective of the mechanism used to produce the neutrons. Depending upon variables including the energy of the neutrons emitted by the source, the rate of neutrons emitted by the source, the size of the source, the cost of owning and maintaining the source, and government regulations related to the source, these devices find use in a diverse array of applications in areas of physics, engineering, medicine, nuclear weapons, petroleum exploration, biology, chemistry, nuclear power and other industries.

There are several kinds of neutron sources:

Small-sized devices

Radioisotopes which undergo spontaneous fission

Certain isotopes undergo spontaneous fission with emission of neutrons. The most commonly used spontaneous fission source is the radioactive isotope californium-252. Cf-252 and all other spontaneous fission neutron sources are produced by irradiating uranium or another transuranic element in a nuclear reactor, where neutrons are absorbed in the starting material and its subsequent reaction products, transmuting the starting material into the SF isotope. Cf-252 neutron sources are typically 1/4" to 1/2" in diameter and 1" to 2" in length. When purchased new a typical Cf-252 neutron sources emit between 1×10^7 to 1×10^9 neutrons per second but, with a half life of 2.6 years, this neutron output rate drops to half of this original value in 2.6 years. The price of a typical Cf-252 neutron source is from $15,000 to $20,000.

Radioisotopes which decay with alpha particles packed in a low-Z elemental matrix

Neutrons are produced when alpha particles impinge upon any of several low atomic weight isotopes including isotopes of lithium, beryllium, carbon and oxygen. This nuclear reaction can be used to construct a neutron source by intermixing a radioisotope that emits alpha particles such as radium or polonium with a low atomic weight isotope, usually in the form of a mixture of powders of the two materials. Typical emission rates for alpha reaction neutron sources range from 1×10^6 to 1×10^8 neutrons per second. As an example, a representative alpha-beryllium neutron source can be expected to produce approximately 30 neutrons for every one million alpha particles. The useful lifetime for these types of sources is highly variable, depending upon the half-life of the radioisotope that emits the alpha particles. The size and cost of these neutron sources are also comparable to spontaneous fission sources. Usual combinations of materials are plutonium-beryllium (PuBe), americium-beryllium (AmBe), or americium-lithium (AmLi). The neutron initiators of early nuclear weapons used a polonium-beryllium layers separated by nickel and gold until a neutron pulse was desired.

Radioisotopes which decay with high energy photons co-located with beryllium or deuterium

Gamma radiation with an energy exceeding the neutron binding energy of a nucleus can eject a neutron. Two examples and their decay products:

- ^{9}Be + >1.7 Mev photon → 1 neutron + 2 ^{4}He
- ^{2}H (deuterium) + >2.26 MeV photon → 1 neutron + ^{1}H

Sealed tube neutron generators

Some particle accelerator-based neutron generators exist that work by inducing nuclear fusion between beams of deuterium and/or tritium ions and metal hydride targets which also contain these isotopes.

Medium-sized devices

Plasma focus and plasma pinch devices

The plasma focus neutron source produces controlled nuclear fusion by creating a dense plasma within which ionized deuterium and/or tritium gas is heated to temperatures sufficient for creating fusion.

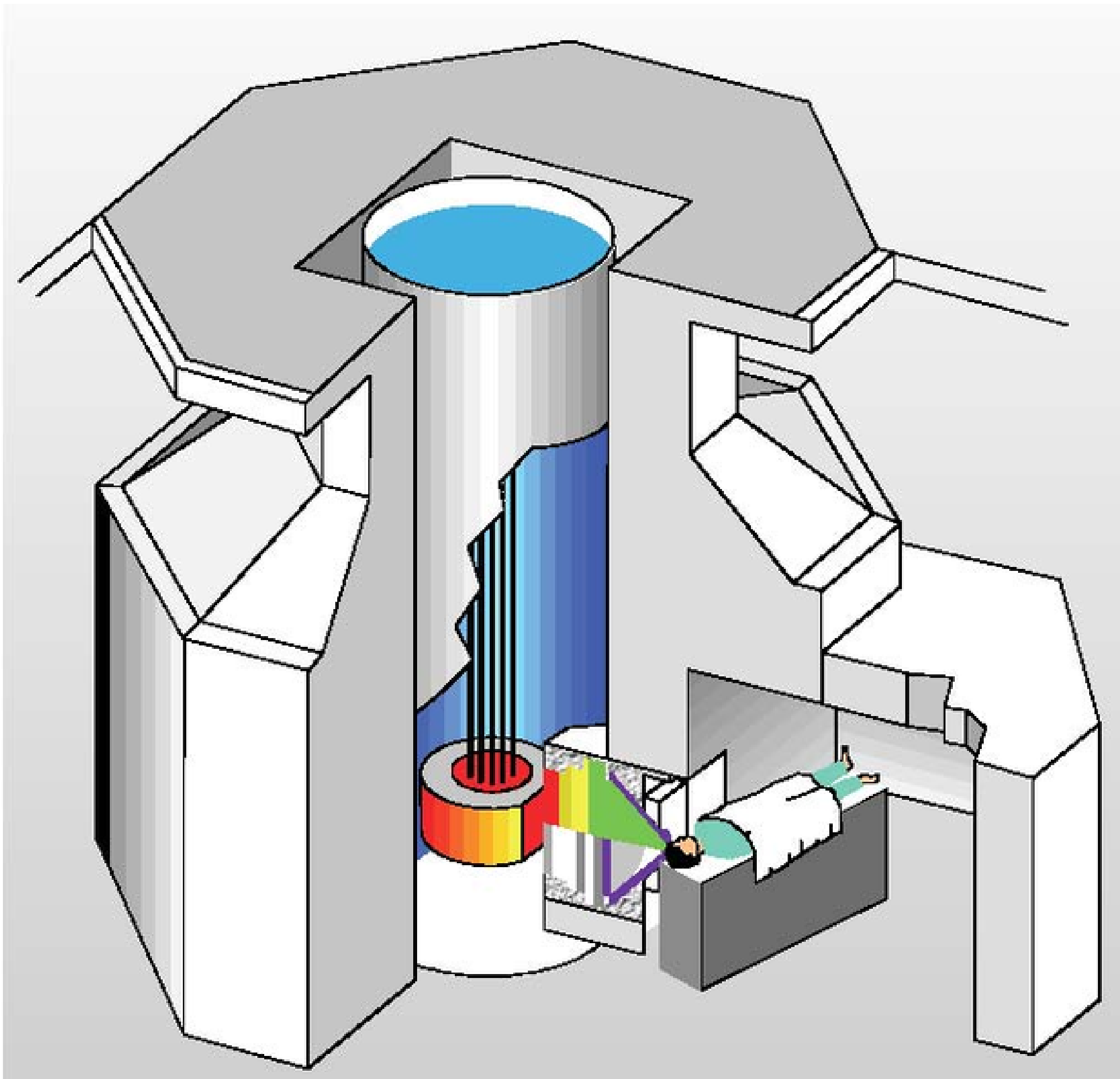
Light ion accelerators

Traditional particle accelerators with hydrogen (H), deuterium (D), or tritium (T) ion sources may be used to produce neutrons using targets of deuterium, tritium, lithium, beryllium, and other low-Z materials. Typically these accelerators operate with voltages in the > 1 MeV range,

High energy photoneutron/photofission systems

Neutrons (so-called photoneutrons) are produced when photons above the nuclear binding energy of a substance are incident on that substance, causing it to undergo giant dipole resonance after which it either emits a neutron (photodisintegration) or undergoes fission (photofission). The number of neutrons released by each fission event is dependent on the substance. Typically photons begin to produce neutrons on interaction with normal matter at energies of about 7 to 40 MeV, which means that megavoltage photon radiotherapy facilities may produce neutron radiation as well, and require special shielding for it. In addition, electrons of energy over about 50 MeV may induce giant dipole resonance in nuclides by a mechanism which is the inverse of internal conversion, and thus produce neutrons by a mechanism similar to that of photoneutrons.

Large-sized devices



Schematic drawing of the TRIGA reactor at the Aalto University campus refitted to be used as a stable neutron source for BNCT treatments.

Nuclear fission reactors

Nuclear fission which takes place within in a nuclear reactor produces very large quantities of neutrons and can be used for a variety of purposes including power generation and experiments. Subcritical reactors can be also used.

Nuclear fusion systems

Nuclear fusion, the combining of the heavy isotopes of hydrogen, also has the potential to produce large quantities of neutrons. Small scale fusion systems exist for research purposes at many universities and laboratories around the world. A small number of large scale nuclear fusion systems also exist including the

National Ignition Facility in the USA, JET in the UK, and soon the recently started ITER experiment in France.

High energy particle accelerators

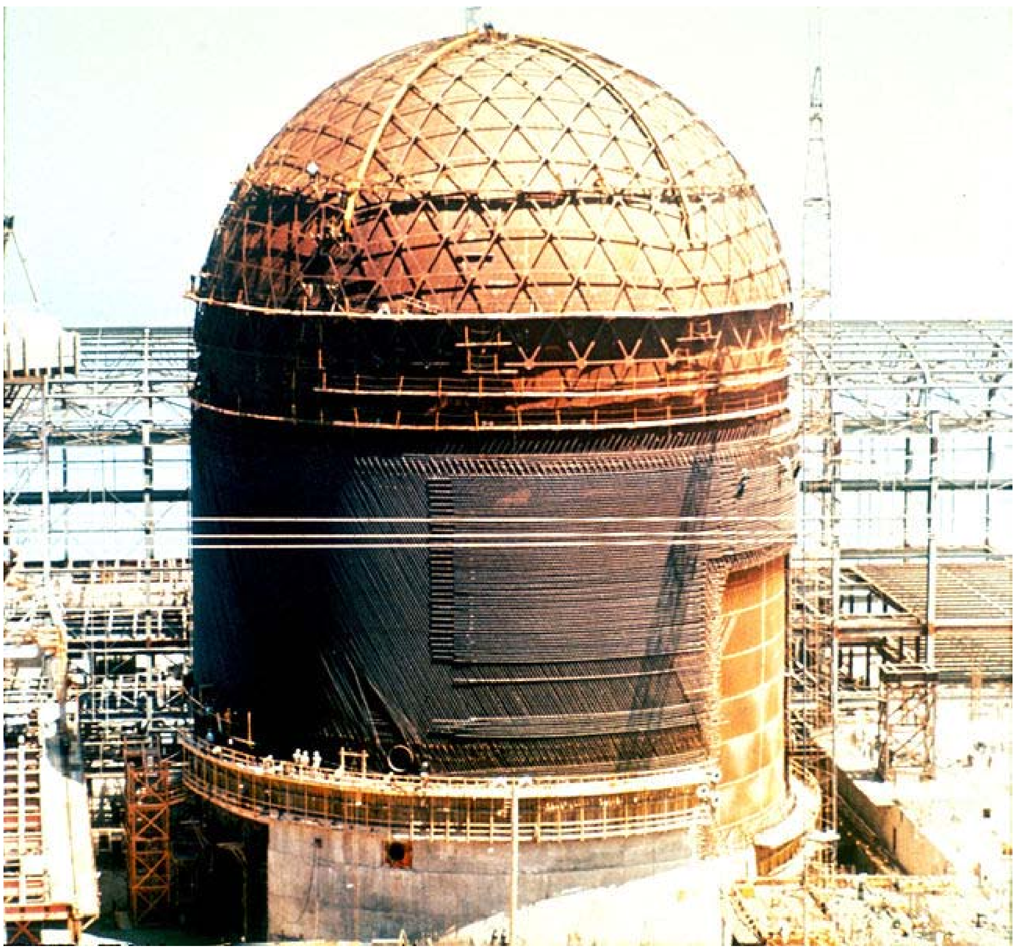
A spallation source is a high-flux source in which protons that have been accelerated to high energies hit a target material, prompting the emission of neutrons.

Neutron flux density

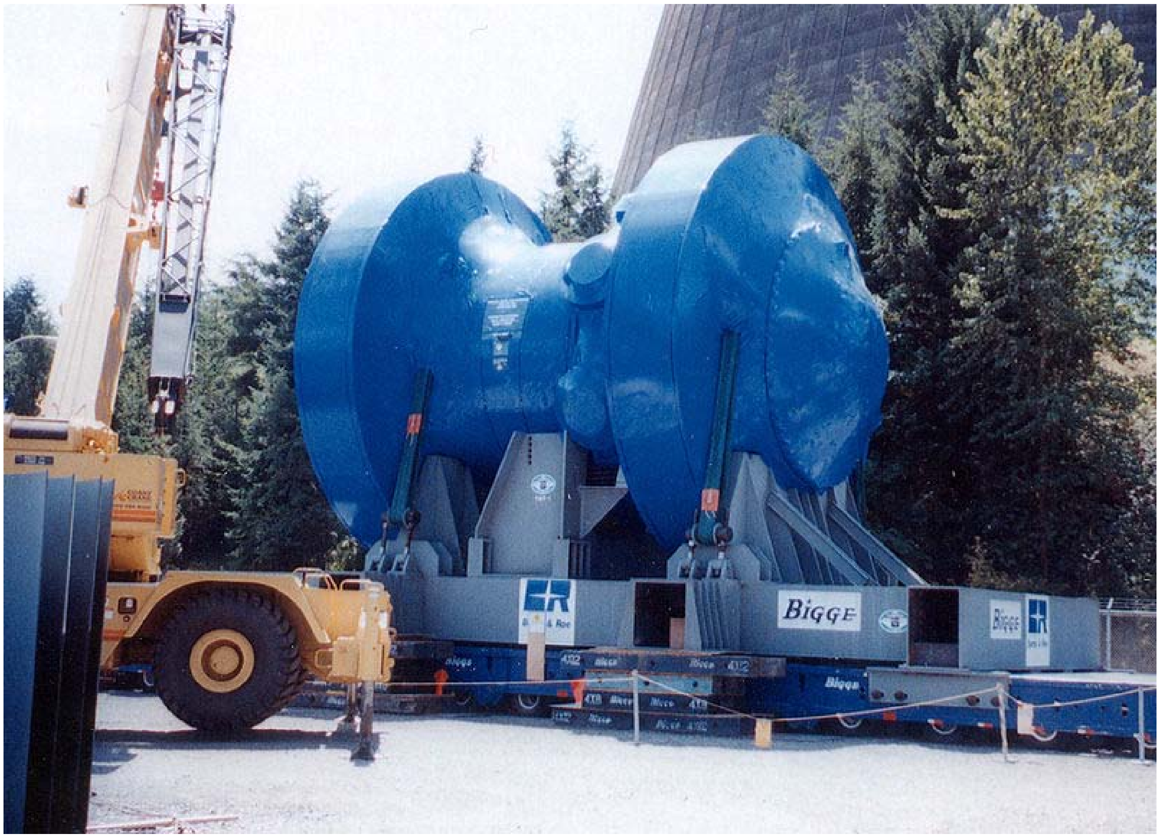
For most applications, a higher neutron flux is always better (since it reduces the time required to conduct the experiment, acquire the image, etc.). Amateur fusion devices, like the fusor, generate only about 300 000 neutrons per second. Commercial fusor devices can generate on the order of 10^9 neutrons per second, which corresponds to a usable flux of less than 10^5 n/(cm² s). Large neutron beamlines around the world achieve much greater flux. Reactor-based sources now produce 10^{15} n/(cm² s), and spallation sources generate greater than 10^{17} n/(cm² s).

Chapter-12

Nuclear Decommissioning



Example of decommissioning work underway.



The reactor pressure vessel being transported away from the site, which will be buried. Images courtesy of the NRC.

Nuclear decommissioning is the dismantling of a nuclear power plant and decontamination of the site to a state no longer requiring protection from radiation for the general public. The main difference from the dismantling of other power plants is the presence of radioactive material that requires special precautions.

Generally speaking, nuclear plants were designed for a life of about 30 years. Newer plants are designed for a 40 to 60-year operating life.

Decommissioning involves many administrative and technical actions. It includes all clean-up of radioactivity and progressive demolition of the plant. Once a facility is decommissioned, there should no longer be any danger of a radioactive accident or to any persons visiting it. After a facility has been completely decommissioned it is released from regulatory control, and the licensee of the plant no longer has responsibility for its nuclear safety.

Decommissioning options

The International Atomic Energy Agency has defined three options for decommissioning, the definitions of which have been internationally adopted:

- *Immediate Dismantling* (or Early Site Release/Decon in the US): This option allows for the facility to be removed from regulatory control relatively soon after shutdown or termination of regulated activities. Usually, the final dismantling or decontamination activities begin within a few months or years, depending on the facility. Following removal from regulatory control, the site is then available for re-use.
- *Safe Enclosure* (or Safestor(e) SAFSTOR): This option postpones the final removal of controls for a longer period, usually in the order of 40 to 60 years. The facility is placed into a safe storage configuration until the eventual dismantling and decontamination activities occur.
- *Entombment*: This option entails placing the facility into a condition that will allow the remaining on-site radioactive material to remain on-site without the requirement of ever removing it totally. This option usually involves reducing the size of the area where the radioactive material is located and then encasing the facility in a long-lived structure such as concrete, that will last for a period of time to ensure the remaining radioactivity is no longer of concern.

Experience

A wide range of nuclear facilities has been decommissioned so far. This includes nuclear power plants (NPPs), research reactors, isotope production plants, particle accelerators, and uranium mines. The number of decommissioned power plants is small. There are companies specialized in nuclear decommissioning; the practice of decommissioning has turned into a profitable business. Decommissionning is very expensive. The current estimate by the United Kingdom's Nuclear Decommissioning Authority is that it will cost at least £70 billion to decommission the 19 existing United Kingdom nuclear sites; this takes no account of what will happen in the future. Also, due to the radioactivity in the reactor structure, decommissioning is a slow process which takes place in stages. The plans of the Nuclear Decommissioning Authority for decommissioning reactors have an average 50 year time frame. The long time frame makes reliable cost estimates extremely difficult. Excessive cost overruns are not uncommon even for projects done in a much shorter time frame.

Nuclear Decommissioning in North America

The Pickering Nuclear Generating Station, viewed from the west. All eight reactors are visible; two units have been shut down

Several nuclear reactors dismantled in America, type, power and decommissioning cost (often is mentioned only the probable cost per kilowatt of power:

Country:	Location:	Reactor type:	Operative life:	Decommissioning phase:	Dismantling costs:
Canada (Québec)	Gentilly-1	CANDU-BWR 250 MWe	180 days (between 1966 and 1973)	"Static state" since 1986	stage two: US $ 25 Million
Canada (Ontario)	Pickering NGS Units A2 and A3	CANDU-PWR 8 x 542 MWe	30 years (from 1974 to 2004)	Two units currently in "cold standby" Decommissioning in 2012?	(calculated: $ 270–430/kWe ?)]
USA	Fort St. Vrain	HTGR (helium-graphite) 380 MWe	12 years (1977–1989)	Immediate Decon	$ 195 Million
USA	Rancho Seco	Multiunit: PWR 913 MWe	12 years (Closed after a referedum nel 1989)	SAFSTOR: 5–10 years completion 2018	($ 200–500/kWe)
USA	Three Mile Island 2	Multiunit: 913 MWe PWR	INCIDENT: core fusion (in 1979)	Post-Defuelling Phase 2 (1979)	$ 805 Million (estimated)
USA	Shippingport	(The first BWR) 60 MWe	25 years (closed in 1989)	Decon completed dismantled in 5 years (first small experimental reactor)	$ 98.4 Million
USA	Trojan	PWR 1.180 MWe	16 years (Closed in 1993 because nearby to	SAFSTOR: (cooling tower demolished in 2006)	

			seismic fault)		
USA	Yankee Rowe	PWR 185 MWe	31 years (1960–1991)	DECON COMPLETED - Demolished (greenfield open to visitors)	$608 million with $8 million per year upkeep
USA	Maine Yankee	PWR 860 MWe	24 years (closed in 1996)	DECON COMPLETED - Demolished in 2004 (greenfield open to visitors)	$ 635 Million
USA	Connecticut Yankee	PWR 590 MWe	28 years (closed in 1996)	Decon - demolished in 2007 (greenfield open to visitors)	$ 820 Million
USA	Exelon - Zion 1 & 2	PWR - Westinghouse 2 x 1040 MWe	25 years (1973–1998) (Incident in proceedings, abandoned because of the excessive cost of vaporizers substitution)	Safstor- EnergySolutions (opening of the site to visitors for 2018)	$ 900–1,100 Million (2007 dollars)

Nuclear Decommissioning in Asia

Several nuclear reactors dismantled in Asia, type, power and decommissioning cost per kilowatt of electric power (source: World Nuclear Association article).

Country:	Location:	Reactor type:	Operative Life:	Decommissioning Phase:	Dismantling Cost:
China	Beijing (CIAE)	HWWR 10 MWe (multipurpose) (Heavy Water Experimental Reactor for the production	49 years (1958–2007)	Safestore & Decon in 20 years (until 2027)	proposed: $ 6 Million for dismantling $ 5 Million for fuel remotion

		of plutonium and tritium)			
North Korea	Yongbyon	Magnox-type (reactor for the production of nuclear weapons through PUREX treatment)	20 years (1985–2005) Deactivated after a treaty	SAFESTORE: Cooling tower dismantled	
Japan	Tokai-1	Magnox (GCR) 160 MWe	32 years (1966–1988)	Safestore: 10 years then DECON until 2018	estimanted cost: Yen 93 Billion (Euro 660 Million of 2003)
India ,	Tarapur-1,2 (Maharashtra)	2x BWR 160 MWe	40 years ? (1969–2009?)	NOT deactivated	
India	Rawatbhata Atomic Power Station-1,2 (Rajasthan)	1x PHWR 100 MWe 1x PHWR 200 MWe (similar to CANDU)	40 years ? (1970–2011?)	NOT deactivated	
Iraq	Osiraq/Tammuz-1	BWR 40 MWe Nuclear reactor with weapons-grade plutonium production capability	(Destroyed by Israeli Air Force in 1981)	Not radioactive: Never refurbished with uranium	

Nuclear decommissioning in Western Europe

Several nuclear reactors dismantled in Western Europe, type, power and decommissioning cost per kilowatt of power: European Union Website about Nuclear Decommissioning, World Nuclear Association (reactor building companies), United Kingdom.

Country:	Location:	Reactor type:	Operative Life:	Decommiss-oning phase:	Dismantling cost:
Austria (Nuclear Free Country)	Zwentendorf NPP Google Maps	PWR 723 MWe	NEVER activated , after referendum in 1978		
Belgium	Mol	PWR (BR-3)	25 years (1962–1987)	DECON COMPLETED - pilot project (underwater cutting and remote operated tools)	
France	Brennilis	HWGCR 70 MWe	12 years (1967–1979)	Phase 3	Euro 480 Million (20 times the forecasted amount)
France	Bugey-1	UNGG Gas cooled, graphite moderator	1972-1994	postponed	
France	Chinon 1,2,3	Gas-graphite	(1973–1990)	postponed	
France	Saint-Laurent Nuclear Power Plant	Gas-graphite	1969-1992	postponed	
France	Superphénix at Creys-Malville	Fast breeder nuclear reactor (sodium-cooled)	11 years (1985–1996)	postponed	estimated for the future: $ 4000/kWe ?
United Kingdom	Berkeley	Magnox (2 x 138 MWe)	27 years (1962–1989)	Safestore: 30 years (internal demolition)	$ 2600/kWe
United Kingdom	Sellafield-Windscale (Note: Windscale:	Windscale Advanced Gas Reactor WAGR	18 years (1963–1981) Fire of graphite in moderation	Remotion of reactor in 2009 - pilot project	Bigger than $2600/kWe (WNI estimates)

	Britain's Biggest Nuclear Disaster)	(32 MWe)	bars inside the reactor partial meltdown of fuel	(cutting with remote controlled robots, UV lasers) ,	Until now E. 117 Million
West Germany	Gundremmingen-A	BWR 250 MWe	11 years	Immediate dismantling - pilot project (underwater cutting)	(~ $ 300–550/kWe)
Italy	Caorso NPP	BWR 840 MWe	3 years (1978 - Closed in 1987 after referendum in 1986)	Safstore: 30 years (demolizione interna)	$/kWe
Italy	Garigliano NPP (Caserta)	BWR 150 MWe	? years (Closed on March 1, 1982)	Safstore: 30 years (internal demolition)	$/kWe
Italy	Latina NPP (Foce Verde)	Magnox 210 MWe Gas-graphite	24 years (1962 - Closed in 1986 after referendum)	Safstore: 30 years (internal demolition)	$/kWe
Italy	Trino Vercellese NPP	PWR Westinghouse, 270 MWe	? years (Closed in 1986 after referendum)	Safstore: 30 years (internal demolition)	$/kWe
Nederlands	Dodewaard NPP	BWR Westinghouse, 58 MWe	28 years (1969–1997)	Defuelling completed - Safstore for 40 years	$/kWe
Slovenia (former-Yugoslavia)	Krsko NPP	PWR (Westinghouse) 696 MWe	40? years (1981–2021?)	Will be deactivated in 2022	
Spain	Vandellós NPP-1	UNGG 480 MWe (gas-graphite)	18 years Incident: fire in a turbogenerator (1989)	Safestore: 30 years (internal demolition)	Phases 1 and 2: Euro 93 Million
Switzerland	DIORIT	MWe Gas-graphite (experimental)	()	Safestore: ? years (internal demolition)	

Switzerland	LUCENS	8,3 MWe CO_2-heavy water (experimental)	(1962–1969) Incident: fire in 1969	Entombment for ? years Safestore & Decon: 24 years (internal demolition)	
Switzerland	SAPHIR	0,01-0,1 MWe (Light water pool)	39 years (1955–1994) (Experimental demonstrator)	(In public display since inauguration open to visitors: "Cherenkov's light")	

- Repository for radioactive waste Morsleben: 2.2 billion euro.

Nuclear Decommissioning in Eastern Europe and former Soviet Union

Several nuclear reactors dismantled in the nations born from the former Soviet Union: (Belarus, Russia, Ukraine and others) and rectors dismantled in countries formerly belonging to "Warsaw Pact" and/or to "Comecon", type, electric power and decommissioning cost per kilowatt of power: World Nuclear Association, OSTI (Russia & USA).

Country:	Location:	Reactor typr:	Operative life:	Decommissioning phase:	Dismantling cost:
Bulgaria	Kozloduy NPP-1,2,3,4	PWR VVER-440 (4 x 408 MWe)	Reactors 1,2 closed in 2003, reactors 3,4 closed in 2006 (Closing forced by European Union)	De-fuelling	
East Germany	Greifswald NPP-1, 2,3,4,5	VVER-440 5 x 408 MWe		Immediate dismantling (underwater cutting)	(~ $ 330/kWe)
East Germany	Rheinsberg NPP-1	VVER-210 70–80 MWe	24 years (1966–1990)	In dismantling since 1996 Safstor (underwater cutting)	(~ $ 330/kWe)

East Germany	Stendal NPP-1,2,3,4	VVER-1000 (4 x 1000 MWe)	Never activated (1st reactor 85% completed)	NOT radioactive (Cooling towers demolished with explosives)	(?) (Structure in exhibition inside an industrial park)
Russia	Mayak (Chelyabinsk-65)	PUREX plant for uranium enrichment	Several severe incidents (1946–1956)		
Russia	Seversk (Tomsk-7)	Three plutonium reactors Plant for uranium enrichment	Two fast-breeder reactors closed (of three), after disarmaments agreements with USA in 2003 .		
Slovakia	Mochovce NPP-1,2 (180 km east from Vienna)	VVER 440 2 X 440 MWe	(1998–2028?)		
Ukraine	Chernobyl NPP-4 (110 km from Kiev)	RBMK-1000 1000 MWe	? years WORST NUCLEAR ACCIDENT IN ALL HISTORY: hydrogen explosion, then graphite fire (1986)	ENTOMBMENT (armed concrete "sarcophagus")	Past: ? Future: riding sarcophagus in steel

Legal aspects

The decommission of a nuclear reactor can only take place after the appropriate licence has been granted pursuant to the relevant legislation. As part of the licensing procedure various documents, reports and expert opinions have to be written and delivered to the competent authority, e.g. safety report, technical documents, environmental impact study (EIS).

In the European Union these documents are the basis for the environmental impact assessment (EIA) according to Council Directive 85/337/EEC. A precondition for granting such a licence is an opinion by the European Commission according to Article 37 of the Euratom Treaty. Article 37 obliges every Member State of the European Union to communicate certain data relating to the release of radioactive substances to the Commission. This information must reveal whether and if so what radiological impacts decommissioning – planned disposal and accidental release – will have on the environment, i.e. water, soil or airspace, of the EU Member States. On the basis of these general data, the Commission must be in a position to assess the exposure of reference groups of the population in the nearest neighbouring states.

Cost of decommissioning

In USA many utilities estimates now average $325 million per reactor all-up (1998 $).

In France, decommissioning of Brennilis Nuclear Power Plant, a fairly small 70 MW power plant, already cost 480 million euros (20x the estimate costs) and is still pending after 20 years. Despite the huge investments in securing the dismantlement, radioactive elements such as Plutonium, Cesium-137 and Cobalt-60 leaked out into the surrounding lake.

In the UK, decommissioning of Windscale Advanced Cooled Reactor (WAGR), a 32 MW power plant, cost 117 million euros.

In Germany, decommissioning of Niederaichbach nuclear power plant, a 100 MW power plant, amounted to more than 143 million euros.

Decommissioning Funds

In Europe there is considerable concern on the funds necessary to finance final decommissioning. In many countries either the funds do not appear sufficient to pay the financial decommissioning, and in other countries the (substantial) funds are being used (too) freely for activities other than decommissioning, putting the funds at risk, and distorting competition with parties who do not have nuclear decommissioning funds available.

Currently (2008) the European Commission is looking into this issue.

Similar concerns exist in the United States, where the U.S. Nuclear Regulatory Commission has located apparent decommissioning funding assurance shortfalls and requested 18 nuclear power plants to address that issue.

Chapter-13

Long-lived Fission Product and Nuclear Fusion-Fission Hybrid

Long-lived fission product

Long-lived fission products are radioactive materials with a long half-life (more than 200,000 years) produced by nuclear fission.

Evolution of radioactivity in nuclear waste

Nuclear fission produces fission products, as well as actinides from nuclear fuel nuclei that capture neutrons but fail to fission, and activation products from neutron activation of reactor or environmental materials.

Short-term

The high short-term radioactivity of spent nuclear fuel is primarily from fission products with short half-life. The radioactivity in the fission product mixture is mostly short lived isotopes such as I-131 and ^{140}Ba, after about four months ^{141}Ce, ^{95}Zr/^{95}Nb and ^{89}Sr take the largest share, while after about two or three years the largest share is taken by ^{144}Ce/^{144}Pr, ^{106}Ru/^{106}Rh and ^{147}Pm. Note that in the case of a release of radioactivity from a power reactor or used fuel, only some elements are released. As a result the isotopic signature of the radioactivity is very different from an open air nuclear detonation where all the fission products are dispersed.

Medium-lived fission products

Medium-lived fission products				
Prop:	**t½**	**Yield**	**Q ***	**βγ**
Unit:	**a**	**%**	**KeV**	*****
^{155}Eu	4.76	.0803	252	βγ

^{85}Kr	10.76	.2180	687 βγ
^{113m}Cd	14.1	.0008	316 β
^{90}Sr	28.9	4.505	2826 **β**
^{137}Cs	30.23	6.337	1176 β**γ**
^{121m}Sn	43.9	.00005	390 βγ
^{151}Sm	90	.5314	77 β

After several years of cooling, most radioactivity is from the fission products caesium-137 and strontium-90, which are each produced in about 6% of fissions, and have half-lives of about 30 years. Other fission products with similar half-lives have much lower fission product yields, lower decay energy, and several (^{151}Sm, ^{155}Eu, ^{113m}Cd) are also quickly destroyed by neutron capture while still in the reactor, so are not responsible for more than a tiny fraction of the radiation production at any time. Therefore, in the period from several years to several hundred years after use, radioactivity of spent fuel can be modeled simply as exponential decay of the ^{137}Cs and ^{90}Sr. These are sometimes known as medium-lived fission products.

Krypton-85, the 3rd most active MLFP, is a noble gas which escapes during current nuclear reprocessing; however, its inertness means that it does not concentrate in the environment, but diffuses to a uniform low concentration in the atmosphere. Spent fuel in the US and some other countries is not likely to be reprocessed until decades after use, and by that time most of the Kr-85 will have decayed.

Actinides

Actinides				**Half-life**	**Fission products**			
^{244}Cm	^{241}**Pu** f	^{250}Cf	^{243}**Cm** f	**10–30 y**	^{137}Cs	^{90}Sr	^{85}Kr	
^{232}**U** f		^{238}Pu	**f** is for fissile	**69–90 y**			^{151}Sm nc→	
4n	^{249}**Cf** f	^{242}**Am** f		**141–351**	No fission product has half-life 10^2 to 2×10^5 years			
	^{241}Am		^{251}**Cf** f	**431–898**				
^{240}Pu	^{229}Th	^{246}Cm	^{243}Am	**5–7 ky**				
	^{245}**Cm** f	^{250}Cm	^{239}**Pu** f	**8–24 ky**				
4n	^{233}**U** f	^{230}Th	^{231}Pa	**32–160**				
	4n+1	^{234}U	**4n+3**	**211–290**	^{99}Tc		^{126}Sn	^{79}Se
^{248}Cm		^{242}Pu		**340–373**	**Long-lived fission products**			
	^{237}Np	**4n+2**		**1–2 my**	^{93}Zr	^{135}Cs nc→		
^{236}U			^{247}**Cm** f	**6–23 my**		^{107}Pd	^{129}I	
^{244}Pu	**4n+1**			**80 my**	>7%	>5%	>1%	>.1%
^{232}Th		^{238}U	^{235}**U** f	**0.7–12by**	fission product yield			

After Cs-137 and Sr-90 have decayed to low levels, the bulk of radioactivity from spent fuel is from not fission products but actinides, notably plutonium-239, plutonium-240, americium-241, americium-243, curium-245, and curium-246. These can be recovered by nuclear reprocessing (either before or after most Cs-137 and Sr-90 decay) and fissioned, offering the possibility of greatly reducing waste radioactivity in the time scale of about 10^3 to 10^5 years. Pu-239 is usable as fuel in existing thermal reactors, but some minor actinides like Am-241, as well as the non-fissile and less-fertile isotope plutonium-242, are better destroyed in fast reactors, accelerator-driven subcritical reactors, or fusion reactors.

Long-lived fission products

On scales greater than 10^5 years, fission products, chiefly ^{99}Tc, again represent a significant proportion of the remaining, though lower, radioactivity, along with longer-lived actinides like neptunium-237 and plutonium-242, if those have not been destroyed.

The most abundant long-lived fission products have total decay energy around 100-300 KeV, only part of which appears in the beta particle; the rest is lost to a neutrino that has no effect. In contrast, actinides undergo multiple alpha decays, each with decay energy around 4-5 MeV.

Only seven fission products have long half-lives, and these are much longer than 30 years, in the range of 200,000 to 16 million years. These are known as long-lived fission products (LLFP). Two or three have relatively high yields of about 6%, while the rest appear at much lower yields. (This list of seven excludes isotopes with very slow decay and halflives longer than the age of the universe, which are effectively stable and already found in nature; as well as a few nuclides like technetium-98 and samarium-146 that are "shadowed" from beta decay and can only occur as direct fission products, not as beta decay products of more neutron-rich initial fission products. The shadowed fission products have yields on the order of one millionth as much as iodine-129.)

The 7 long-lived fission products

Long-lived fission products				
Prop:	**$t^{½}$**	**Yield**	**Q ***	**βγ**
Unit:	**Ma**	**%**	**KeV**	*****
^{99}Tc	0.211	6.1385	294	β
^{126}Sn	0.230	0.1084	4050	βγ
^{79}Se	0.327	0.0447	151	β
^{93}Zr	1.53	5.4575	91	βγ
^{135}Cs	2.3	6.9110	269	β
^{107}Pd	6.5	1.2499	33	β
^{129}I	15.7	0.8410	194	βγ

The first three have comparable halflives, between 200 thousand and 300 thousand years; the last four have longer halflives, in the low millions of years.

1. Technetium-99 produces the largest amount of LLFP radioactivity. It emits beta particles of low to medium energy but no gamma rays, so has little hazard on external exposure, but only if ingested. However, technetium's chemistry allows it to form anions (pertechnate, TcO_4^-) that are relatively mobile in the environment.
2. Tin-126 has a large decay energy (due to a following short-halflife decay) and is the only LLFP that emits energetic gamma radiation, which is an external exposure hazard. However, this isotope is produced in very small quantities in fission by thermal neutrons, so the energy per unit time from ^{126}Sn is only about 5% as much as from ^{99}Tc for U-235 fission, or 20% as much for 65% U-235+35% Pu-239. Fast fission may produce higher yields. Tin is an inert metal with little mobility in the environment, helping limit health risks from its radiation.
3. Selenium-79 is produced at low yields and has weak radiation. Its decay energy per unit time should be only about 0.2% that of Tc-99.
4. Zirconium-93 is produced at a relatively high yield of about 6%, but its decay is 7.5 times slower than Tc-99, and its decay energy is only 30% as great; therefore its energy production is initially only 4% as great as Tc-99, though this fraction will increase as the Tc-99 decays. ^{93}Zr does produce gamma radiation, but of a very low energy, and zirconium is relatively inert in the environment.
5. Caesium-135's predecessor xenon-135 is produced at a high rate of over 6% of fissions, but is an extremely potent absorber of thermal neutrons (neutron poison), so that most of it is transmuted to nonradioactive xenon-136 before it can decay to caesium-135. If 90% of ^{135}Xe is destroyed, then the remaining ^{135}Cs's decay energy per unit time is initially only about 1% as great as that of the ^{99}Tc. In a fast reactor, less of the Xe-135 may be destroyed.
   ^{135}Cs is the only alkaline or electropositive LLFP; in contrast, the main medium-lived fission products and the minor actinides other than neptunium are all alkaline and tend to stay together during reprocessing; with many reprocessing techniques such as salt solution or salt volatilization, ^{135}Cs will also stay with this group, although some techniques such as high-temperature volatilization can separate it. Often the alkaline wastes are vitrified to form high level waste, which will include the ^{135}Cs.
   Fission caesium contains not only ^{135}Cs but also stable but neutron-absorbing ^{133}Cs (which wastes neutrons and forms ^{134}Cs which is radioactive with a halflife of 2 years) as well as the common fission product ^{137}Cs which does not absorb neutrons but is highly radioactive making handling more hazardous and complicated; for all these reasons, transmutation disposal of ^{135}Cs would be more difficult.
6. Palladium-107 has a very long halflife, a low yield (though the yield for plutonium fission is higher than the yield from uranium-235 fission), and very weak radiation. Its initial contribution to LLFP radiation should be only about one part in 10000 for U-235 fission, or 2000 for 65% U-235+35% Pu-239. Palladium is a noble metal and extremely inert.
7. Iodine-129 has the longest halflife, 15.7 million years. Initially it has only about 1% as intense radioactivity as Tc-99. However, radioactive iodine is a disproportionate biohazard because the thyroid gland concentrates iodine. I-129 has a halflife nearly a billion times as long as its sister isotope iodine-131 which is

a hazard from nuclear explosions, and a smaller decay energy, so is only about a billionth as radioactive per unit mass.

LLFP radioactivity compared

In total, the other six LLFPs, in thermal reactor spent fuel, initially release only a bit more than 10% as much energy per unit time as Tc-99 for U-235 fission, or 25% as much for 65% U-235+35% Pu-239. About 1000 years after fuel use, radioactivity from the medium-lived fission products Cs-137 and Sr-90 drops below the level of radioactivity from Tc-99 or LLFPs in general. (Actinides, if not removed, will be emitting more radioactivity than either at this point.) By about 1 million years, Tc-99 radioactivity will have declined below that of Zr-93, though immobility of the latter means it is probably still a lesser hazard. By about 3 million years, Zr-93 decay energy will have declined below that of I-129.

Nuclear transmutation is under consideration as a disposal method, primarily for Tc-99 and I-129 as these both represent the greatest biohazards and have the greatest neutron capture cross sections, although transmutation is still slow compared to fission of actinides in a reactor. Transmutation has also been considered for Cs-135, but is almost certainly not worthwhile for the other LLFPs.

Nuclear fusion-fission hybrid

Hybrid nuclear fusion-fission (**hybrid nuclear power**) is a proposed means of generating power by use of a combination of nuclear fusion and fission processes. The concept dates to the 1950s, and was briefly advocated by Hans Bethe during the 1970s, but largely remained unexplored until a revival of interest in 2009, due to the indefinite delays in the realization of pure fusion.

In the LIFE project at the Lawrence Livermore National Laboratory LLNL, using technology developed at the National Ignition Facility, the goal is to use fuel pellets of deuterium and tritium surrounded by a fissionable (or fertile) blanket to produce energy sufficiently greater than the input (laser) energy for electrical power generation. The principle involved is to induce inertial confinement fusion (ICF) in the fuel pellet which acts as a highly concentrated point source of neutrons which in turn converts and fissions the outer fissionable blanket. In parallel with the ICF approach, the University of Texas at Austin is developing a system based on the tokamak fusion reactor, optimising for nuclear waste disposal versus power generation. The principles behind using either ICF or tokamak reactors as a neutron source are essentially the same.

Rationale

The fusion process alone currently does not achieve sufficient gain (power output over power input) to be viable as a power source. By using the excess neutrons from the fusion reaction to in turn cause a high-yield fission reaction (close to 100%) in the surrounding subcritical fissionable blanket, the net yield from the hybrid fusion-fission process can provide a targeted gain of 100 to 300 times the input energy (an increase by a factor of three or four over fusion alone). Even allowing for high inefficiencies on the input side (i.e. low laser efficiency), this can still yield sufficient heat output for economical electric power generation. This can be seen as a shortcut to viable fusion power until more efficient pure fusion technologies can be developed, or as an end in itself to generate power, and also consume existing stockpiles of nuclear fissionables and waste products.

Unlike a conventional fission reactor, the fusion hybrid can consume almost all of the uranium fuel without enrichment or reprocessing. This has advantages for non-proliferation, as enrichment and reprocessing technologies are also associated with nuclear weapons production. The low fuel consumption, lack of need for enrichment, and small waste volumes also significantly reduce fuel cycle costs. However, the fusion equipment required will increase the construction cost of the reactor.

Use to dispose of nuclear waste

The surrounding blanket can be a fissile material (enriched uranium or plutonium) or a fertile material (capable of conversion to a fissionable material by neutron bombardment) such as thorium, depleted uranium or spent nuclear fuel. This offers currently the only means of active disposal (versus storage) of spent nuclear fuel without reprocessing. Fission by-products produced by the operation of commercial light water nuclear reactors LWRs are long-lived and highly radioactive, but they can be consumed using the excess neutrons in the fusion reaction along with the fissionable components in the blanket, essentially destroying them and producing a waste product which is far safer and less of a risk for nuclear proliferation. The waste would contain significantly reduced concentrations of long-lived, weapons-usable actinides per gigawatt-year of electric energy produced compared to the waste from a LWR. In addition, there would be about 20 times less waste per unit of electricity produced. This offers the potential to efficiently use the very large stockpiles of enriched fissile materials, depleted uranium, and spent nuclear fuel.

Safety

In contrast to current commercial fission reactors, hybrid reactors potentially demonstrate what is considered inherently safe behavior because they remain deeply subcritical under all conditions and decay heat removal is possible via passive mechanisms. The fission is driven by neutrons provided by fusion ignition events, and is consequently not self-sustaining. If the laser pulses are deliberately shut off or the process is disrupted by a mechanical failure, the fission damps out and stops instantly. This is in contrast to the forced damping in a conventional reactor by means of control rods which absorb neutrons to reduce the neutron flux below the critical, self-sustaining, level. The inherent danger of a conventional fission reactor is any situation leading to a positive feedback, runaway, chain reaction such as occurred during the Chernobyl disaster. In a hybrid configuration the fission and fusion reactions are decoupled, i.e. the fusion neutron output drives the fission, while the fission output has no effect whatsoever on the fusion reaction, completely eliminating any chance of a positive feedback loop.

Fuel cycle

There are three main components to the hybrid fusion fuel cycle: deuterium, tritium, and fissionable elements. Deuterium can be derived by separation of hydrogen isotopes in sea water. Tritium may be generated in the hybrid process itself by absorption of neutrons in lithium bearing compounds. This would entail an additional lithium bearing blanket and a means of collection. The third component is externally derived fissionable materials from demilitarized supplies of fissionables, or commercial nuclear fuel and waste streams. Fusion driven fission also offers the possibility of using Thorium as a fuel, which would greatly increase the potential amount of fissionables available. The extremely energetic nature of the fast neutrons emitted during the fusion events (up to 0.17 the speed of light) can allow normally non-fissioning U-238 to undergo fission directly (without conversion first to Pu-239), enabling refined natural Uranium to be used with very low enrichment, while still maintaining a deeply subcritical regime.

Chapter-14

Prompt Neutron and Prompt Critical

Prompt neutron

In nuclear engineering, a **prompt neutron** is a neutron immediately emitted by a nuclear fission event, as opposed to a delayed neutron decay which can occur within the same context, emitted by one of the fission products anytime from a few milliseconds to a few minutes later.

Principle

Using U-235 as an example, this nucleus absorbs thermal neutrons, and the immediate mass products of a fission event are two large fission fragments, which are remnants of the formed U-236 nucleus. These fragments emit, on average, two or three free neutrons (in average 2.47), called "prompt" neutrons. A subsequent fission fragment occasionally undergoes a stage of radioactive decay that yields an additional neutron, called a "delayed" neutron. These neutron-emitting fission fragments are called delayed neutron precursor atoms.

Delayed neutrons are associated with the beta decay of the fission products. After prompt fission neutron emission the residual fragments are still neutron rich and undergo a beta decay chain. The more neutron rich the fragment, the more energetic and faster the beta decay. In some cases the available energy in the beta decay is high enough to leave the residual nucleus in such a highly excited state that neutron emission instead of gamma emission occurs.

Delayed Neutron Data for Thermal Fission in U-235

Group	Half-Life (s)	Decay Constant (s^{-1})	Energy (keV)	Yield, Neutrons per Fission	Fraction
1	55.72	0.0124	250	0.00052	0.000215
2	22.72	0.0305	560	0.00546	0.001424
3	6.22	0.111	405	0.00310	0.001274

4	2.30	0.301	450	0.00624	0.002568
5	0.614	1.14	-	0.00182	0.000748
6	0.230	3.01	-	0.00066	0.000273

Importance in nuclear fission basic research

The standard deviation of the final kinetic energy distribution as a function of mass of final fragments from low energy fission of uranium 234 and uranium 236, presents a peak around light fragment masses region and another on heavy fragment masses region. Simulation by Monte Carlo method of these experiments suggests that that those peaks are produced by prompt neutron emission . This effect of prompt neutron emission does not permit to obtain primary primary mass and kinetic distribution which is important to study fission dynamics from saddle to scission point.

Importance in nuclear reactors

If a nuclear reactor happened to be prompt critical - even very slightly - the number of neutrons would increase exponentially at a high rate, and very quickly the reactor would become uncontrollable by means of cybernetics. The control of the power rise would then be left to its intrinsic physical stability factors, like the thermal dilatation of the core, or the increased resonance absorptions of neutrons, that usually tend to decrease the reactor's reactivity when temperature rises; but the reactor would run the risk of being damaged or destroyed by heat.

However, thanks to the delayed neutrons, it is possible to leave the reactor in a subcritical state as far as only prompt neutrons are concerned: the delayed neutrons come a moment later, just in time to sustain the chain reaction when it is going to die out. In that regime, neutron production overall still grows exponentially, but on a time scale that is governed by the delayed neutron production, which is slow enough to be controlled (just as an otherwise unstable bicycle can be balanced because human reflexes are quick enough on the time scale of its instability). Thus, by widening the margins of non-operation and supercriticality and allowing more time to regulate the reactor, the delayed neutrons are essential to inherent reactor safety and even in reactors requiring active control.

Fraction definitions

The factor β is defined as:

$$\beta = \frac{\text{precursor atoms}}{\text{prompt neutrons} + \text{precursor atoms}}.$$

and it is equal to 0.0064 for U-235.

The delayed neutron fraction (DNF) is defined as:

$$DNF = \frac{\text{delayed neutrons}}{\text{prompt neutrons} + \text{delayed neutrons}}.$$

These two factors, β and *DNF*, are not the same thing in case of a rapid change in the number of neutrons in the reactor.

Another concept, is the *effective fraction of delayed neutrons*, which is the fraction of delayed neutrons weighted (over space, energy, and angle) on the adjoint neutron flux. This concept arises because delayed neutrons are emitted with an energy spectrum more thermalized relative to prompt neutrons. For low enriched uranium fuel working on a thermal neutron spectrum, the difference between the average and effective delayed neutron fractions can reach 50 pcm (1 pcm = 1e-5).

Prompt critical

In nuclear engineering, an assembly is **prompt critical** if for each nuclear fission event, one or more of the immediate or prompt neutrons released causes an additional fission event. This causes a rapid, exponential increase in the number of fission events. Prompt criticality is a special case of supercriticality.

Criticality

An assembly is critical if each fission event causes, on average, exactly one other. This causes a self-sustaining fission chain reaction. When a uranium-235 (U-235) atom undergoes nuclear fission, it typically releases 2 or 3 neutrons (with the average being about 2.4). In this situation, an assembly is critical if every released neutron has a 1/2.4 = 0.42 = 42% probability of causing another fission event before it is absorbed by a non-fissile atom or lost to the chain-reaction by other routes. This can be achieved either through enrichment which increases the fraction of fissile U-235 atoms in the uranium fuel, or by slowing down the neutrons by letting them scatter off lighter nuclei called moderators (slow neutrons are more likely to fission U-235 than fast neutrons).

The average number of neutrons that cause new fission events is called the *criticality* or effective neutron multiplication factor, denoted by the letter *k*. When *k* is equal to 1, the assembly is called critical, if *k* is less than 1 the assembly is said to be subcritical, and if *k* is greater than 1 the assembly is called supercritical.

Critical versus prompt-critical

In a supercritical assembly the number of fissions per unit time, *N*, along with the power production, increases exponentially with time. How fast it grows depends on the average time it takes, *T*, for the neutrons released in a fission event to cause another fission. The growth rate of the reaction is given by:

$$N(t) = N_0 e^{kt/T}$$

Most of the neutrons released by a fission event are the ones released in the fission itself. These are called prompt neutrons, and strike other nuclei and cause additional fissions within microseconds. However a small additional source of neutrons is the fission products. Some of the nuclei resulting from the fission are radioactive isotopes with short half-lives, and nuclear reactions among them release additional neutrons after a long delay of up to several minutes after the initial fission event. These neutrons, which on average account for only a few percent of the total neutrons released in a fission, are called delayed neutrons.

A supercritical assembly is said to be prompt-critical if it is supercritical even without the contribution of the delayed neutrons. In this case the time between successive generations of the reaction, *T*, is only limited by the lifetime of the prompt neutrons, and the increase in the reaction will be extremely rapid, causing a rapid release of energy and a potential explosion within a few milliseconds. With the exception of specially designed research experiments, prompt-critical assemblies are only used in nuclear weapons. Their inadvertent creation is the cause of many criticality accidents.

In contrast, in a supercritical assembly that is not prompt-critical, called delayed-critical, the delayed neutrons are needed to make *k* greater than one. So the time between successive generations of the reaction, *T*, is dominated by the time it takes for the delayed neutrons to be released, on the order of seconds or minutes. Therefore the reaction will increase slowly, with a time constant of seconds or minutes. This is slow enough to allow the reaction to be controlled with electromechanical control systems such as control rods, and as such all nuclear reactors are designed to operate in the delayed-criticality regime.

When differentiating between a prompt neutron versus a delayed neutron, the difference between the two has to do with the source from which the neutron has been released into the reactor. The neutrons, once released, have no difference except the energy or speed which have been imparted to them. The relative proportion of delayed neutrons to the total (delayed and prompt) neutrons causing fissions is known as the delayed neutron fraction, DNF. The DNF value will trend higher as a reactor approaches critical. It will trend very low in a supercritical reactor on the verge of prompt criticality.

As the DNF goes lower, the proportion of fast fissions in the nuclear reactor will increase. Fast fissions occur when a high-energy neutron causes fission. In contrast, a thermal (relatively low energy) neutron causes thermal fission of the target nucleus. A nuclear weapon relies heavily on fast fission (to produce a high peak power in a fraction of a second), whereas most nuclear reactors rely heavily on thermal fissions to produce controllable power levels for months or years.

Nuclear reactors

In order to start up a self-sustaining controllable fission reaction, the assembly must not be subcritical, critical, nor prompt-critical. In other words, *k* must be greater than 1 (supercritical) without crossing the prompt-critical threshold. In nuclear reactors this is possible due to delayed neutrons. Because it takes some time before these neutrons are emitted following a fission event, it is possible to control the nuclear reaction using control rods.

A steady-state (constant power) reactor is operated so that it is critical due to the delayed neutrons, but not without their contribution. During a gradual and deliberate increase in reactor power level, the reactor is delayed-supercritical. The exponential increase of reactor activity is slow enough to make it possible to control the criticality factor, *k*, by inserting or withdrawing rods of neutron absorbing material. Using careful control rod movements, it is thus possible to achieve a supercritical reactor core without reaching an unsafe prompt-critical state.

Once a reactor plant is operating at its target or design power level, prudent operation can maintain it at critical for long periods of time with only minor corrections.

Prompt critical accidents

Large-scale (production) nuclear reactors are susceptible to prompt criticality accidents when a large amount of reactivity is added to a core, such as during the movement of control rods. Alternate mechanisms include the loss of negative reactivity, such as when hot, borated coolant water is replaced with cold, pure water in the reactor core. Historically, all such accidents have been caused by control rod movements. The rapid uncontrollable increase in reactor activity in prompt critical conditions may irreparably damage the primary containment of the reactor, namely the fuel cladding. A breach in the primary containment may be further exacerbated by a failure of the secondary, tertiary, and subsequent containment, which in a typical reactor plant might include the reactor vessel, reactor plant piping, various shielding materials that surround the reactor, and finally the reactor building. Nuclear reactors are designed to make prompt criticality as unlikely as possible, while utilizing multiple layers of containment as a precaution against the release of radioactive fission products should a breach occur as a result of a reactor accident.

With the exception of research and experimental reactors, only three reactor accidents are suspected of having achieved prompt criticality, those of Chernobyl #4, the U.S. Army's SL-1, and Soviet submarine K-431. In some cases there is doubt that prompt criticality occurred, although the uncontrolled surge in power was sufficient to cause an explosion that destroyed each reactor and caused a release of radioactive fission products into the atmosphere.

At Chernobyl in 1986, an unusual test was performed while generating power that resulted in an overheated reactor core. The emergency shutdown performed by the operators precipitated the accident due to the poor design of the control rods which accelerated the nuclear power excursion. This led to the rupturing of the fuel plates and water pipes, vaporization of water, a steam explosion, and a graphite fire. Since the reactor was not designed with a containment building capable of containing this catastrophic explosion, the accident released large amounts of radioactive material into the environment. The catastrophic fire in the graphite neutron moderator compounded the problem, sending massive amounts of radioactive debris into the atmosphere.

In the other two incidents, the reactor plants failed due to errors during a maintenance shutdown that was caused by the rapid and uncontrolled removal of at least one control rod. The SL-1 was a prototype reactor intended for use by the US Army in remote polar locations. At the SL-1 plant in 1961, the reactor was brought from shutdown to prompt critical state by manually extracting the central control rod too far. As the water in the core quickly converted to steam and expanded, the 26,000-pound (12,000 kg) reactor vessel jumped 9 feet 1 inch (2.77 m), leaving impressions in the ceiling above. All three men performing the maintenance procedure died from injuries. 1,100 curies of fission products were released as parts of the core were expelled. It took 2 years to investigate the accident and clean up the site. The excess prompt reactivity of the SL-1 core was calculated in a 1962 report:

The delayed neutron fraction of the SL-1 is 0.70%... Conclusive evidence revealed that the SL-1 excursion was caused by the partial withdrawal of the central control rod. The reactivity associated with the 20 inch withdrawal of this one rod has been estimated to be 2.4% δk/k which was sufficient to induce prompt criticality and place the reactor on a 4 millisecond period.

In the K-431 reactor accident, 10 were killed during a refueling operation. In these two catastrophes, the reactor plants went from complete shutdown to extremely high power levels in a fraction of a second, damaging the reactor plants beyond repair.

Many reactor designs succeed in making prompt criticality practically impossible. Some pressurized water reactors, for example, do not contain enough fuel of high enough enrichment to make a prompt critical assembly with the materials in the core. Such reactors can still overheat and even melt if the ability to cool them is lost (a loss-of-coolant accident), but they are unlikely to explode.

List of prompt critical excursions

A number of research reactors and tests have purposely examined the operation of a prompt critical reactor plant. CRAC, KEWB, SPERT-I, Godiva device, and BORAX experiments contributed to this research.

The following list of prompt critical power excursions is adapted from a report submitted in 2000 by a team of American and Russian nuclear scientists who studied criticality accidents, published by the Los Alamos Scientific Laboratory, the location of many of the excursions. A typical power excursion is about 1 x 10^17 fissions. The prompt critical excursions listed below occurred primarily during research and processing of nuclear fuel. SL-1 is the notable exception.

- Los Alamos Scientific Laboratory, 11 February 1945
- Los Alamos Scientific Laboratory, December 1949
- Los Alamos Scientific Laboratory, 1 February 1951
- Los Alamos Scientific Laboratory, 18 April 1952
- Argonne National Laboratory, 2 June 1952
- Oak Ridge National Laboratory, 26 May 1954
- Oak Ridge National Laboratory, 1 February 1956
- Los Alamos Scientific Laboratory, 3 July 1956
- Los Alamos Scientific Laboratory, 12 February 1957
- Mayak Production Association, 2 January 1958
- Oak Ridge Y-12 Plant, 16 June 1958 (possible)
- Los Alamos Scientific Laboratory, 30 December 1958
- SL-1, 3 January 1961
- Idaho Chemical Processing Plant, 25 January 1961
- Los Alamos Scientific Laboratory, 11 December 1962
- Sarov (Arzamas-16), 11 March 1963
- White Sands Missile Range, 28 May 1965
- Oak Ridge National Laboratory, 30 January 1968
- Chelyabinsk-70, 5 April 1968
- Aberdeen Proving Ground, 6 September 1968
- Mayak Production Association, 10 December 1968 (2 prompt critical excursions)
- Kurchatov Institute, 15 February 1971
- Idaho Chemical Processing Plant, 17 October 1978 (very nearly prompt critical)
- Sarov (Arzamas-16), 17 June 1997
- JCO Fuel Fabrication Plant, 30 September 1999

Nuclear weapons

In the design of nuclear weapons, on the other hand, achieving prompt criticality is essential. Indeed, one of the design problems to overcome in constructing a plutonium-fueled bomb is to contract the fissile materials and achieve prompt criticality before the chain reaction has a chance to force the core to expand. A good bomb design must therefore win the race to a dense, prompt critical core before a less-powerful chain reaction (known as a fizzle) disassembles the core without allowing a significant amount of fuel to fission. This generally means that nuclear bombs need special attention paid to the way the core is compressed, such as the novel implosion method hypothesized by Richard C. Tolman, Robert Serber, and other scientists at the University of California, Berkeley in 1942.

This is also the reason that highly enriched (weapons-grade) plutonium is used: lower grades (such as the plutonium produced by most nuclear power stations) make the timely assembly of a prompt critical configuration even more difficult because of the spontaneous fission of certain isotopes of plutonium, namely Pu-240. If the neutrons released by spontaneous fission over-run the creation of a prompt critical mass, then the reaction is spoiled and the bomb's yield will be rather weak.