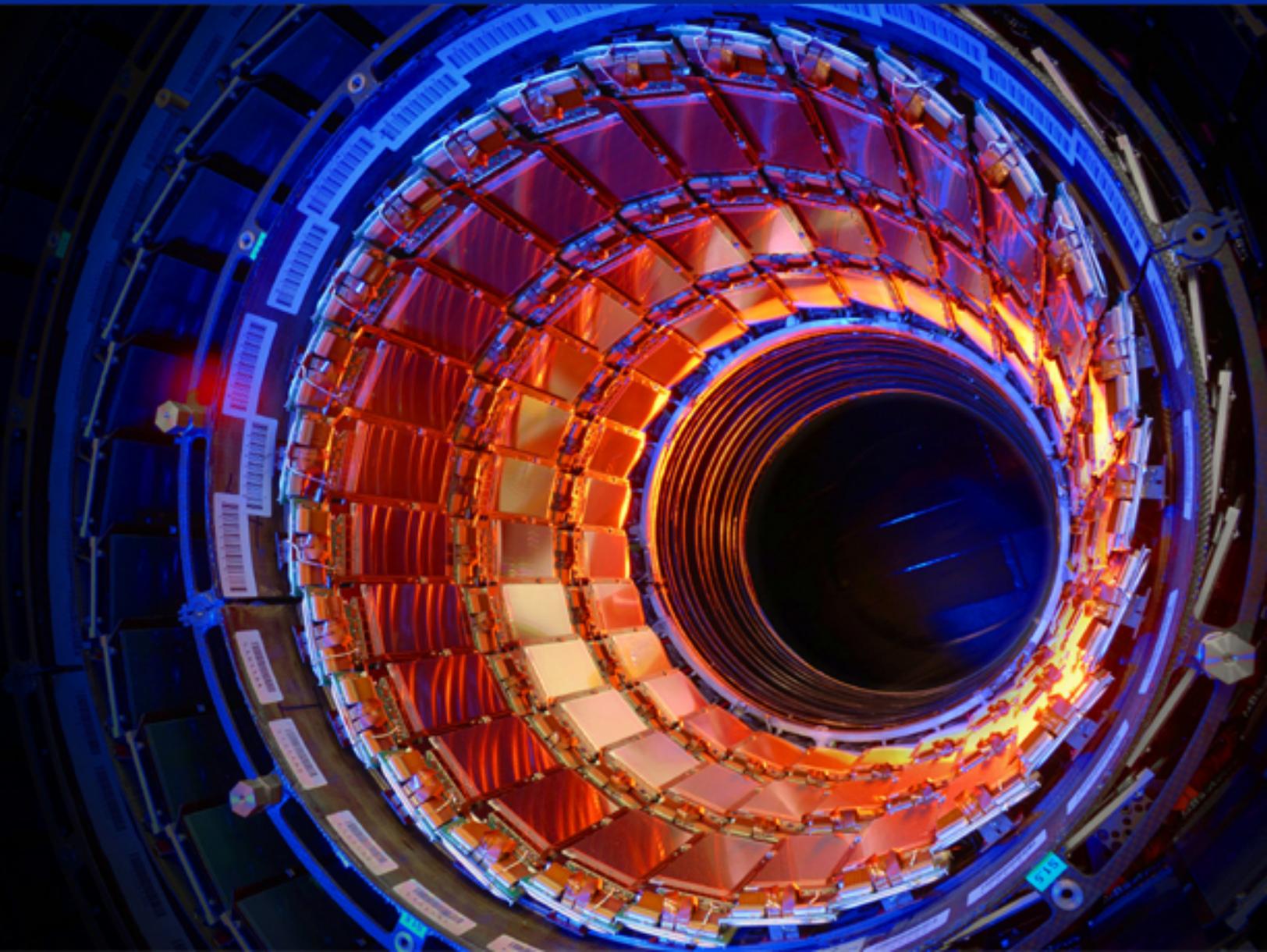


Advanced Nuclear Physics

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Introduction

Nuclear physics is the field of physics that studies the building blocks and interactions of atomic nuclei. The most commonly known applications of nuclear physics are nuclear power and nuclear weapons, but the research has provided wider applications, including those in medicine (nuclear medicine, magnetic resonance imaging), materials engineering (ion implantation) and archaeology (radiocarbon dating).

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

History

The history of nuclear physics as a discipline distinct from atomic physics starts with the discovery of radioactivity by Henri Becquerel in 1896, while investigating phosphorescence in uranium salts. The discovery of the electron by J. J. Thomson a year later was an indication that the atom had internal structure. At the turn of the 20th century the accepted model of the atom was J. J. Thomson's "plum pudding" model in which the atom was a large positively charged ball with small negatively charged electrons embedded inside of it. By the turn of the century physicists had also discovered three types of radiation coming from atoms, which they named alpha, beta, and gamma radiation. Experiments in 1911 by Lise Meitner and Otto Hahn, and by James Chadwick in 1914 discovered that the beta decay spectrum was continuous rather than discrete. That is, electrons were ejected from the atom with a range of energies, rather than the discrete amounts of energies that were observed in gamma and alpha decays. This was a problem for nuclear physics at the time, because it indicated that energy was not conserved in these decays.

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

Rutherford's team discovers the nucleus

In 1907 Ernest Rutherford published "Radiation of the α Particle from Radium in passing through Matter". Geiger expanded on this work in a communication to the Royal Society with experiments he and Rutherford had done passing α particles through air, aluminum foil and gold leaf. More work was published in 1909 by Geiger and Marsden and further

greatly expanded work was published in 1910 by Geiger, In 1911-2 Rutherford went before the Royal Society to explain the experiments and propound the new theory of the atomic nucleus as we now understand it.

The key experiment behind this announcement happened in 1910 at the University of Manchester, as Ernest Rutherford's team performed a remarkable experiment in which Hans Geiger and Ernest Marsden under his supervision fired alpha particles (helium nuclei) at a thin film of gold foil. The plum pudding model predicted that the alpha particles should come out of the foil with their trajectories being at most slightly bent. Rutherford had the idea to instruct his team to look for something that shocked him to actually observe: a few particles were scattered through large angles, even completely backwards, in some cases. He likened it to firing a bullet at tissue paper and having it bounce off. The discovery, beginning with Rutherford's analysis of the data in 1911, eventually led to the Rutherford model of the atom, in which the atom has a very small, very dense nucleus containing most of its mass, and consisting of heavy positively charged particles with embedded electrons in order to balance out the charge (since the neutron was unknown). As an example, in this model (which is not the modern one) nitrogen-14 consisted of a nucleus with 14 protons and 7 electrons (21 total particles), and the nucleus was surrounded by 7 more orbiting electrons.

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

James Chadwick discovers the neutron

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

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

Yukawa's meson postulated to bind nuclei

In 1935 Hideki Yukawa proposed the first significant theory of the strong force to explain how the nucleus holds together. In the Yukawa interaction a virtual particle, later called a meson, mediated a force between all nucleons, including protons and neutrons. This force explained why nuclei did not disintegrate under the influence of proton repulsion, and it also gave an explanation of why the attractive strong force had a more limited range than the electromagnetic repulsion between protons. Later, the discovery of the pi meson showed it to have the properties of Yukawa's particle.

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

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

Modern nuclear physics

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

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

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

Much of current research in nuclear physics relates to the study of nuclei under extreme conditions such as high spin and excitation energy. Nuclei may also have extreme shapes (similar to that of Rugby balls) or extreme neutron-to-proton ratios. Experimenters can create such nuclei using artificially induced fusion or nucleon transfer reactions,

employing ion beams from an accelerator. Beams with even higher energies can be used to create nuclei at very high temperatures, and there are signs that these experiments have produced a phase transition from normal nuclear matter to a new state, the quark-gluon plasma, in which the quarks mingle with one another, rather than being segregated in triplets as they are in neutrons and protons.

Modern topics in nuclear physics

Spontaneous changes from one nuclide to another: nuclear decay

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

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

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

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

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

Chapter- 1

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

$$\frac{A(A-1)}{2}$$

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:

$$R = r_0 A^{1/3}.$$

Quantum charge integers:

$$\begin{aligned} Q &= Ze \\ Z^2 &= Z(Z-1) . \end{aligned}$$

Integration by substitution:

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

Potential energy of charge distribution:

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

Electrostatic Coulomb constant:

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

The value of a_C using the fine structure constant:

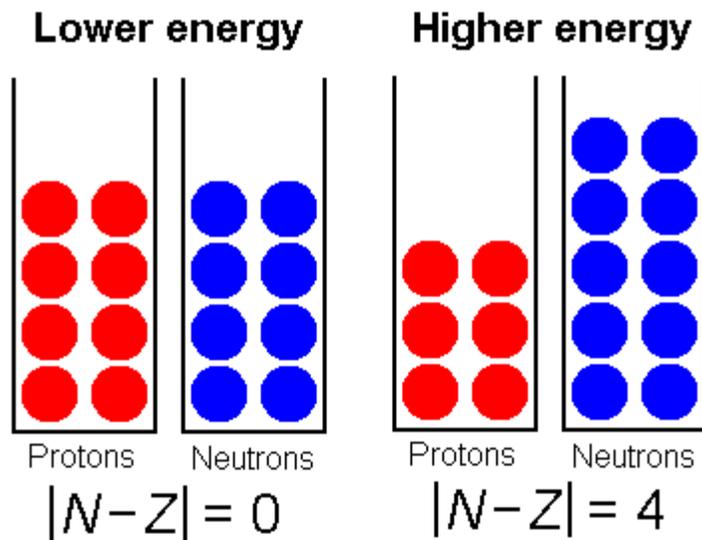
$$a_C = \frac{3}{5} \left(\frac{\hbar c \alpha}{r_0} \right)$$

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

$$A = 16$$



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 $\epsilon_{Fp}, \epsilon_{Fn}$ are their Fermi energies. Since the latter are proportional to $N_p^{2/3}$ and $N_n^{2/3}$, respectively, one gets

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

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

$$\epsilon_F \equiv \epsilon_{Fp} = \epsilon_{Fn} \text{ multiplied by } \frac{3}{5} (N_p + N_n)^{2/3}. \text{ Thus we get}$$

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

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	<i>n/a</i>	<i>n/a</i>
δ (even-even)	<i>n/a</i>	-33.5	+11.18
δ (odd-odd)	<i>n/a</i>	+33.5	-11.18
δ (even-odd)	<i>n/a</i>	0	0

- Wapstra: *Atomic Masses of Nuclides*, A. H. Wapstra, Springer, 1958
- Rohlf: *Modern Physics from α to Z_0* , James William Rohlf, Wiley, 1994

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

Examples for consequences of the formula

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

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

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

$$\begin{array}{r}
 1 \quad 1/2 \\
 \quad -1/2 \\
 1 \quad 1 \quad 0 \quad 1/2 \\
 \quad \quad -1/2 \\
 \quad \quad -1 \quad 1/2 \\
 \quad \quad \quad -1/2
 \end{array}$$

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 .

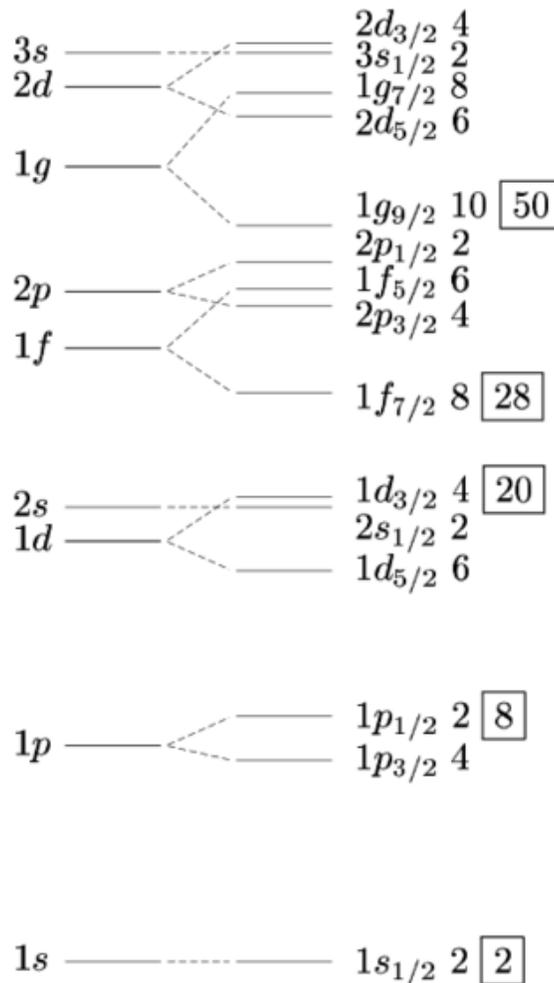
For example, consider the states at level 4:

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

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

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

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

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

state of the nucleus is a superposition of them. Thus the real (measured) nuclear magnetic moment is somewhere in between the possible answers.

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

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

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.

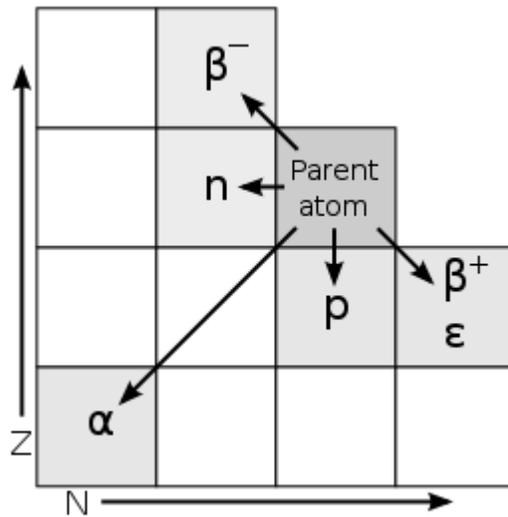
Danger of radioactive substances



The danger classification sign of radioactive materials



Ionizing radiation hazard symbol (recently introduced)



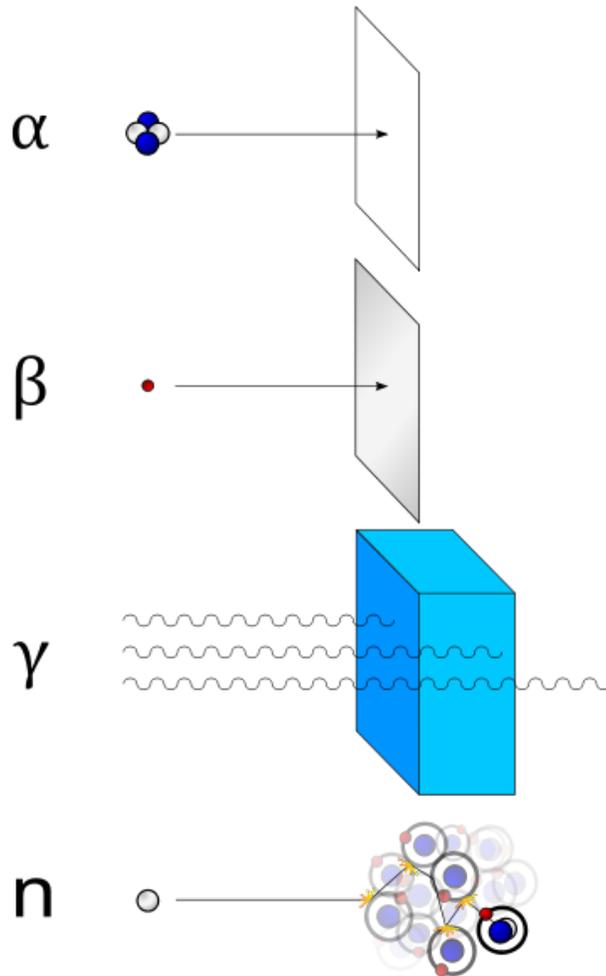
Different types of decay of a radionuclide. Vertical: atomic number Z , Horizontal: neutron number N

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 (^4He) 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.

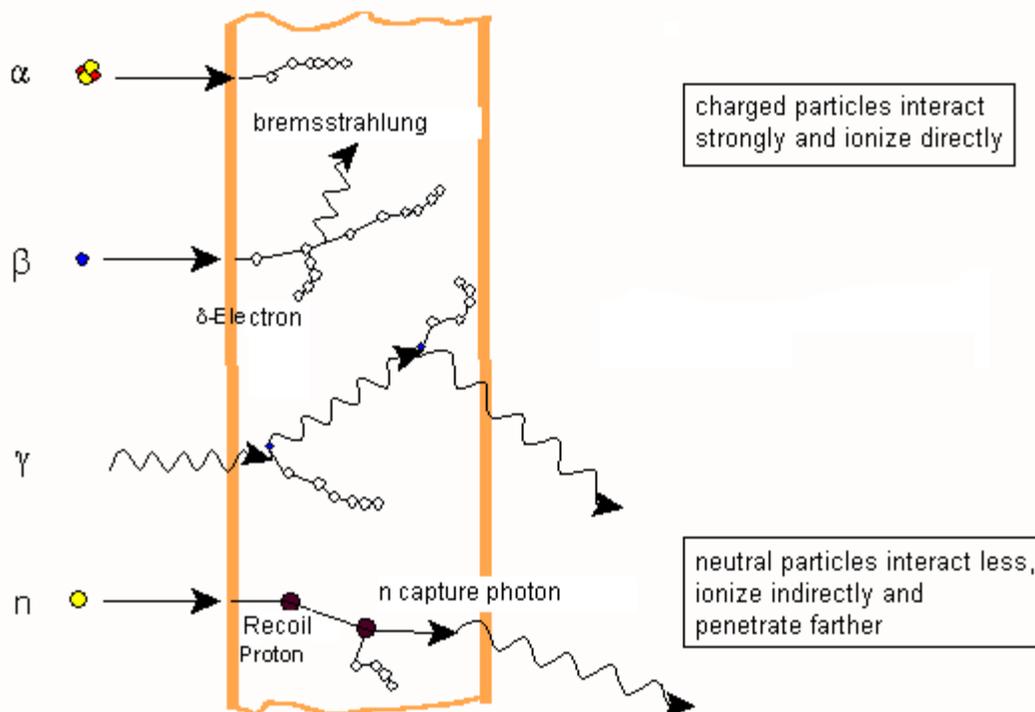
Photons interact electromagnetically with charged particles, so photons of sufficiently high energy also are ionizing. The energy at which this begins to happen with photons (light) is in the high frequency end of the ultraviolet region of the electromagnetic spectrum.

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.

Interaction of ionizing Radiation with Matter



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. $1 \text{ Roentgen} = 2.58 \times 10^{-4} \text{ C/kg}$

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. $100 \text{ rad} = 1 \text{ Gy}$.

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 premature 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 $i = I_0 e^{-ux}$

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	$(A, Z - 2)$

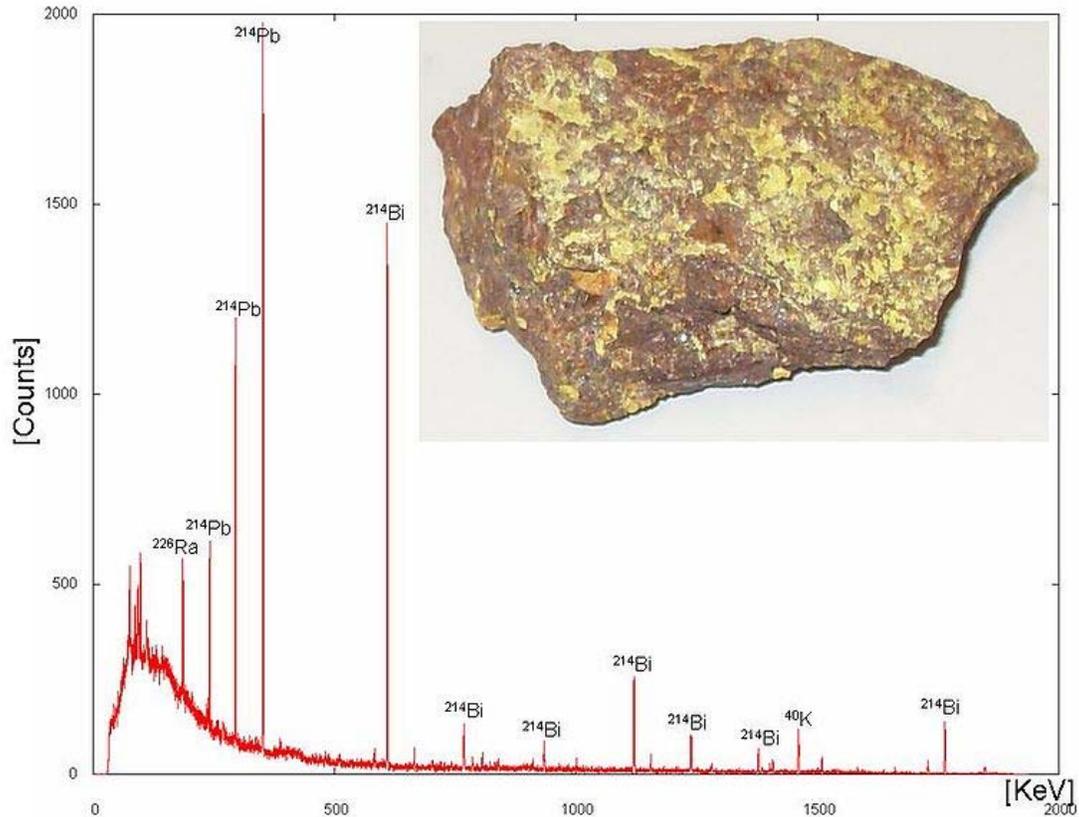
Transitions between states of the same nucleus:

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:

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

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 :

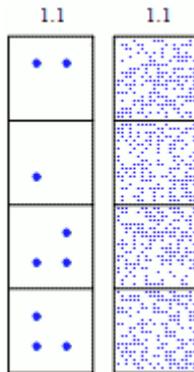
$$\left(-\frac{dN}{N}\right) = \lambda \cdot dt.$$

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 $t_{1/2}$). 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 $t_{1/2}$ for marker-times, are only for convenience, and from convention. They reflect a fundamental principle only in so much as they show that the *same proportion* of a given radioactive substance will decay, during any time-period that one chooses.

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

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

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

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 ^7Be , 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.

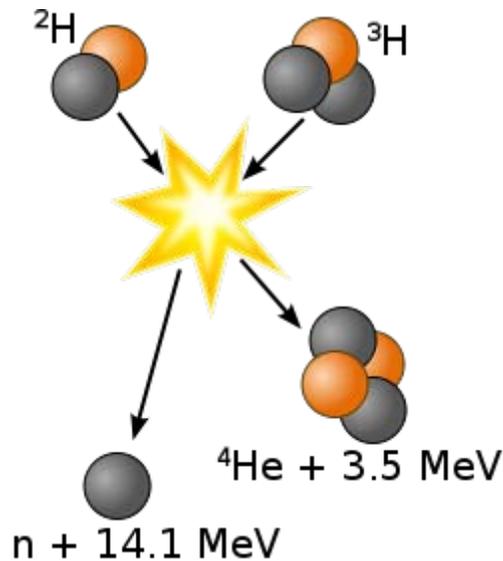
Nuclear fusion occurs naturally in all active stars. Synthetic fusion as a result of human actions has also been achieved, although this has not yet been completely controlled as a source of nuclear power. In the laboratory, successful nuclear physics experiments have been carried out that involve the 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.

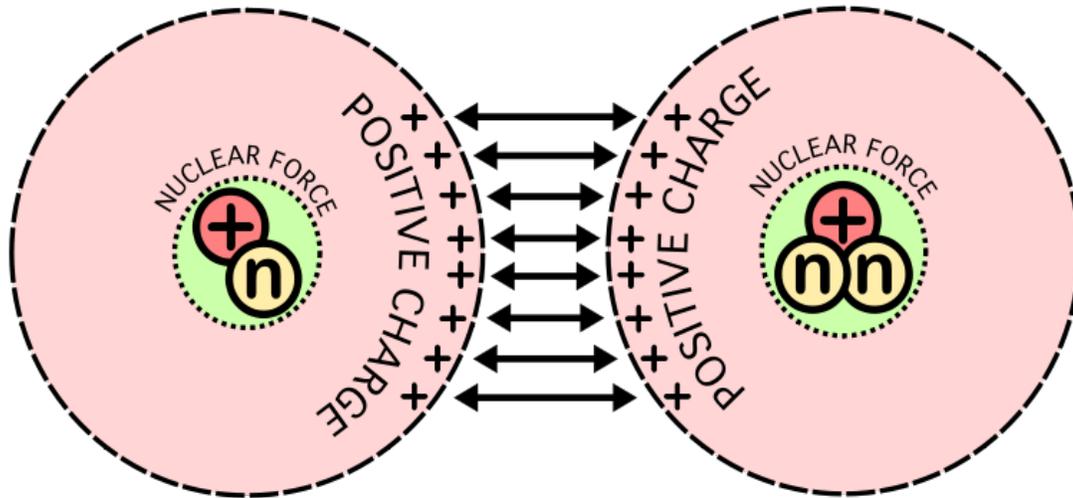
The energy released in most nuclear reactions is much larger than that in chemical reactions, because the binding energy that holds a nucleus together is far greater than the energy that holds electrons to a nucleus. For example, the ionization energy gained by adding an electron to a hydrogen nucleus 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 ${}^{62}\text{Ni}$, ${}^{58}\text{Fe}$, ${}^{56}\text{Fe}$, and ${}^{60}\text{Ni}$. Even though the nickel isotope, ${}^{62}\text{Ni}$, is more stable, the iron isotope ${}^{56}\text{Fe}$ is an order of magnitude more common. This is due to a greater disintegration rate for ${}^{62}\text{Ni}$ in the interior of stars driven by photon absorption.

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

The situation is similar if two nuclei are brought together. As they approach each other, all the protons in one nucleus repel all the protons in the other. Not until the two nuclei actually come in contact can the strong nuclear force take over. Consequently, even when

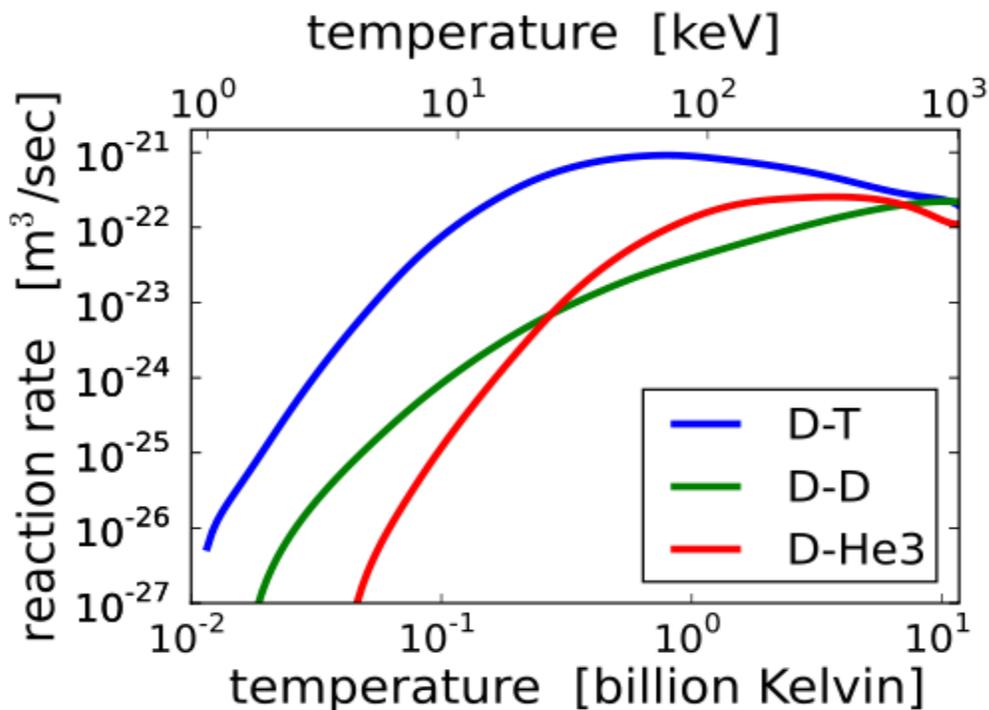
the final energy state is lower, there is a large energy barrier that must first be overcome. It is called the Coulomb barrier.

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

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

If the energy to initiate the reaction comes from accelerating one of the nuclei, the process is called *beam-target* fusion; if both nuclei are accelerated, it is *beam-beam* fusion. If the nuclei are part of a plasma near thermal equilibrium, 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 $\langle\sigma v\rangle$ 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 $(1/2)n^2$.

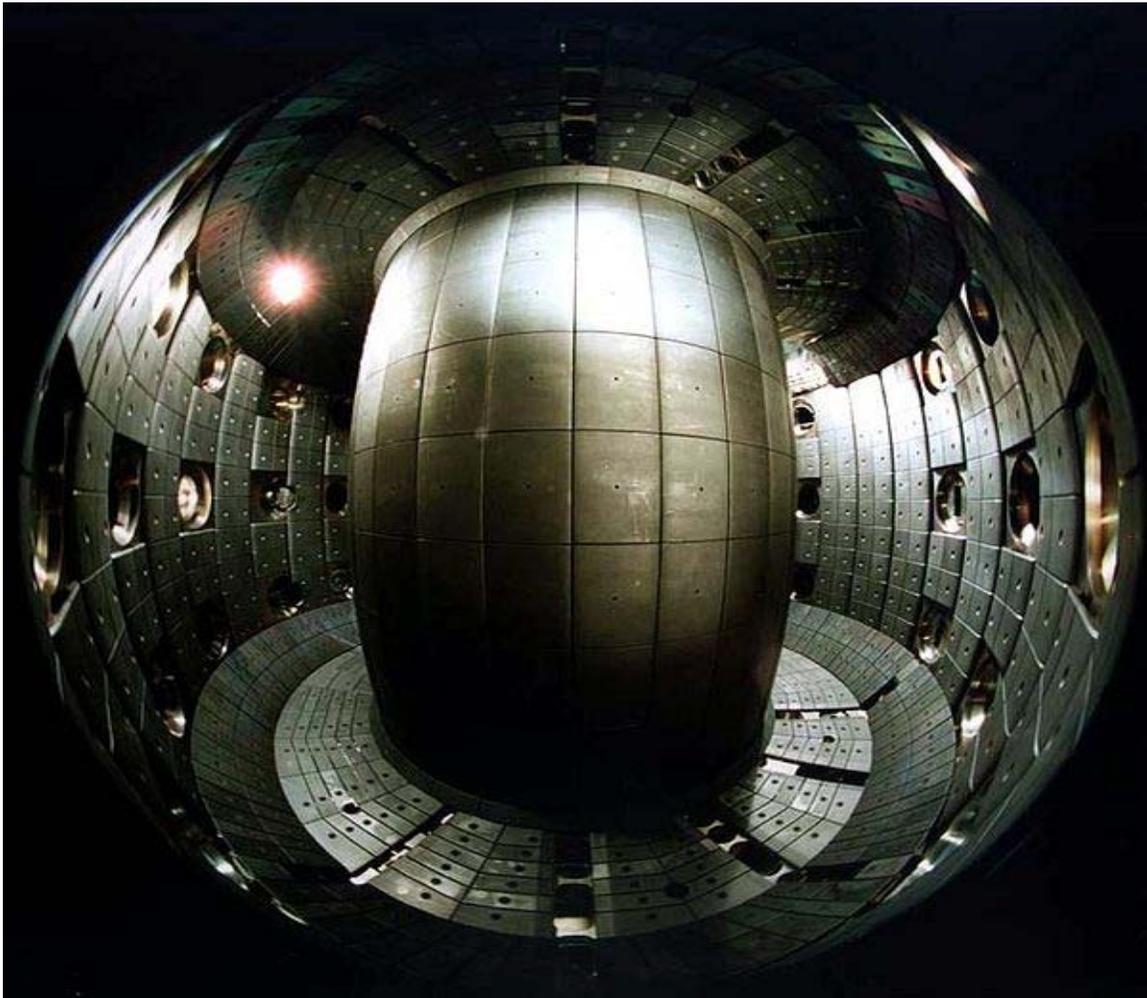
$\langle\sigma v\rangle$ increases from virtually zero at room temperatures up to meaningful magnitudes at temperatures of 10–100 keV. At these temperatures, well above typical ionization energies (13.6 eV in the hydrogen case), the fusion reactants exist in a plasma state.

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-clad 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.

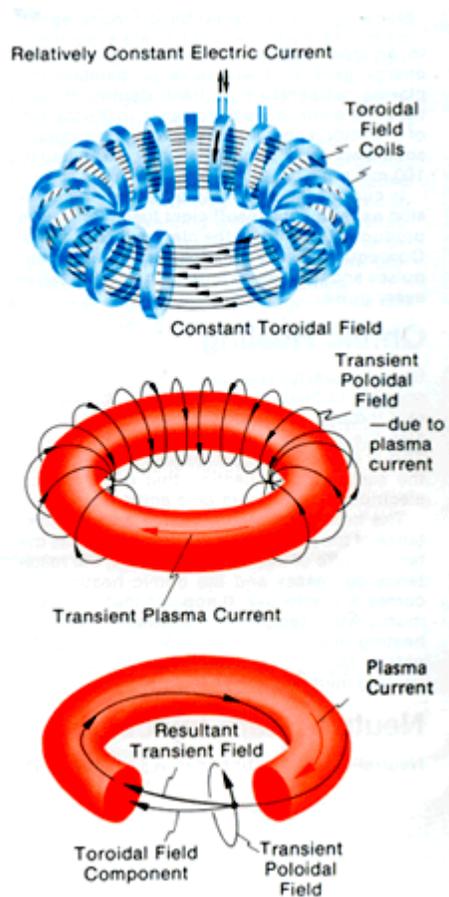
Magnetic mirrors

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 μ s half-life, and the chance that a muon will bind to the new alpha particle and thus stop catalyzing fusion.

Generally cold, locally hot fusion

Accelerator-based light-ion fusion 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.

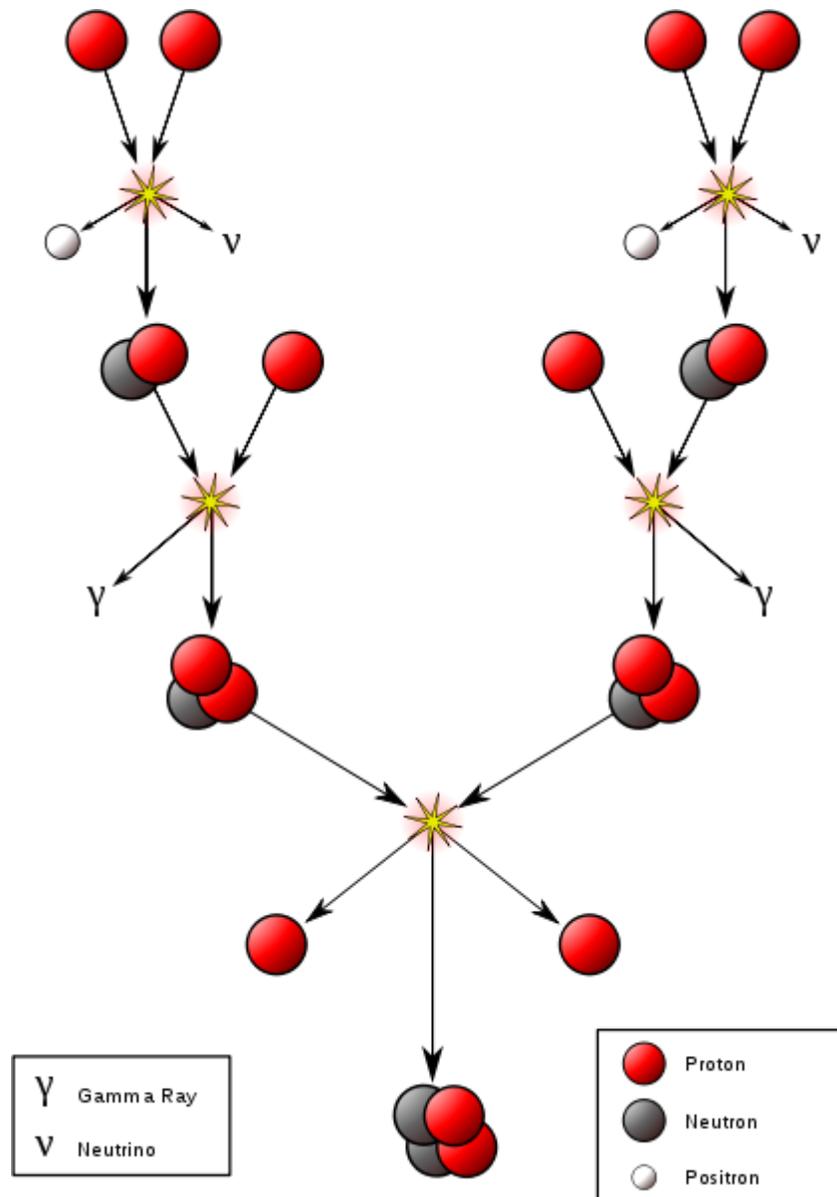
Hot fusion

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

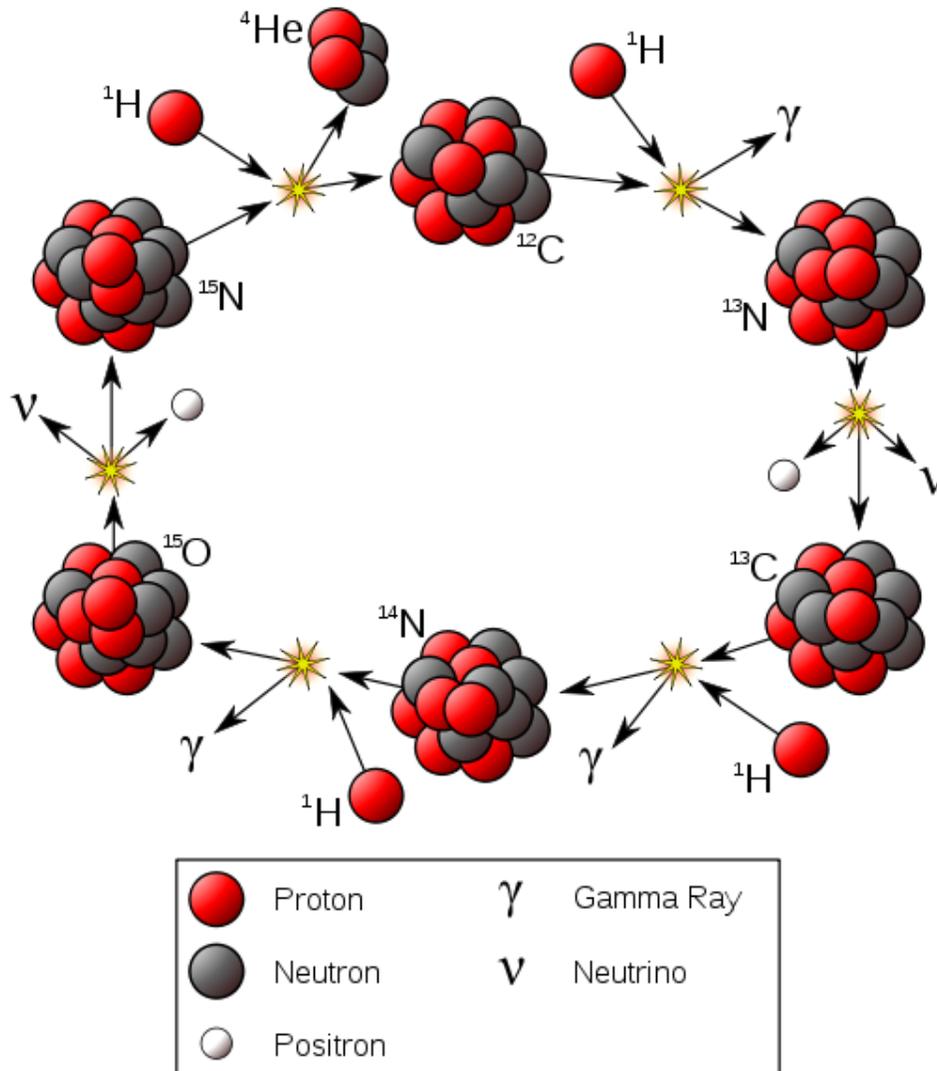
The methods in the second group are examples of non-equilibrium systems, in which very high temperatures and pressures are produced in a relatively small region adjacent to material of much lower temperature. In his doctoral thesis for MIT, Todd Rider did a theoretical study of all quasineutral, isotropic, 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 ($T \approx 15 \text{ MK}$) and density (160 g/cm^3), the energy release rate is only $276 \mu\text{W/cm}^3$ —about a quarter of the volumetric rate at which a resting human body generates heat. Thus, reproduction of stellar core conditions in a lab for nuclear fusion power production is completely

impractical. Because nuclear reaction rates strongly depend on temperature ($\exp(-E/kT)$), achieving reasonable energy production rates in terrestrial fusion reactors requires 10–100 times higher temperatures (compared to stellar interiors): $T \approx 0.1\text{--}1.0$ GK.

Criteria and candidates for terrestrial reactions

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

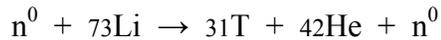
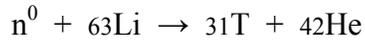
To be a useful energy source, a fusion reaction must satisfy several criteria. It must

- **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 ^4He the most common product because of its extraordinarily tight binding, although ^3He and ^3H also show up.
- **Involve low Z nuclei:** This is because the electrostatic repulsion must be overcome before the nuclei are close enough to fuse.
- **Have two reactants:** At anything less than stellar densities, three body collisions are too improbable. 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 $\text{D-}^6\text{Li}$ reaction has no advantage compared to p^+-^{11}B because it is roughly as difficult to burn but produces substantially more neutrons through $^2\text{D-}^2\text{D}$ side reactions. There is also a p^+-^7Li reaction, but the cross section is far too low, except possibly when $T_i > 1$ MeV, but at such high temperatures an endothermic, direct neutron-producing reaction also becomes very significant. Finally there is also a p^+-^9Be reaction, which is not only difficult to burn, but ^9Be can be easily induced to split into two alpha particles and a neutron.

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



To evaluate the usefulness of these reactions, in addition to the reactants, the products, and the energy released, one needs to know something about the cross section. Any given fusion device 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]	$\langle\sigma v\rangle/T^2$ [$\text{m}^3/\text{s}/\text{keV}^2$]
${}^2\text{D}-{}^3\text{T}$	13.6	1.24×10^{-24}
${}^2\text{D}-{}^2\text{D}$	15	1.28×10^{-26}
${}^2\text{D}-{}^3\text{He}$	58	2.24×10^{-26}
$\text{p}^+-{}^6\text{Li}$	66	1.46×10^{-27}
$\text{p}^+-{}^{11}\text{B}$	123	3.01×10^{-27}

Note that many of the reactions form chains. For instance, a reactor fueled with ${}^3\text{T}$ and ${}^3\text{He}$ creates some ${}^2\text{D}$, which is then possible to use in the ${}^2\text{D}-{}^3\text{He}$ reaction if the energies are "right". An elegant idea is to combine the reactions (8) and (9). The ${}^3\text{He}$ from reaction (8) can react with ${}^6\text{Li}$ 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 $21\text{D}-21\text{D}$ reaction entails some difficulties, though. To begin with, one must average over the two branches (2) and (3). More difficult is to decide how to treat the 31T and 32He products. 31T burns so well in a deuterium plasma that it is almost impossible to extract from the plasma. The $21\text{D}-32\text{He}$ reaction is optimized at a much higher temperature, so the burnup at the optimum $21\text{D}-21\text{D}$ temperature may be low, so it seems reasonable to assume the 31T but not the 32He gets burned up and adds its energy to the net reaction. Thus we count the $21\text{D}-21\text{D}$ fusion energy as $E_{\text{fus}} = (4.03+17.6+3.27)/2 = 12.5$ MeV and the energy in charged particles as $E_{\text{ch}} = (4.03+3.5+0.82)/2 = 4.2$ MeV.

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

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

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

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

Of course, the reactants should also be mixed in the optimal proportions. This is the case when each reactant ion plus its associated electrons accounts for half the pressure. Assuming that the total pressure is fixed, this means that density of the non-hydrogenic ion is smaller than that of the hydrogenic ion by a factor $2/(Z+1)$. Therefore the rate for these reactions is reduced by the same factor, on top of any differences in the values of $\langle\sigma v\rangle/T^2$. On the other hand, because the 21D-21D reaction has only one reactant, the rate is twice as high as if the fuel were divided between two hydrogenic species.

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

We can now compare these reactions in the following table.

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

⁶³Li

p ⁺ - ¹¹⁵ B	3.01×10 ⁻²⁷	1/3	1240	500	0.014	2500
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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 ²¹D-³¹T 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 ²¹D-³¹T 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 ²¹D-³¹T 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)	$P_{fusion}/P_{Bremsstrahlung}$
²¹ D- ³¹ T	50	140
²¹ D- ²¹ D	500	2.9
²¹ D- ³² He	100	5.3
³² He- ³² He	1000	0.72
p ⁺ - ⁶³ Li	800	0.21
p ⁺ - ¹¹⁵ B	300	0.57

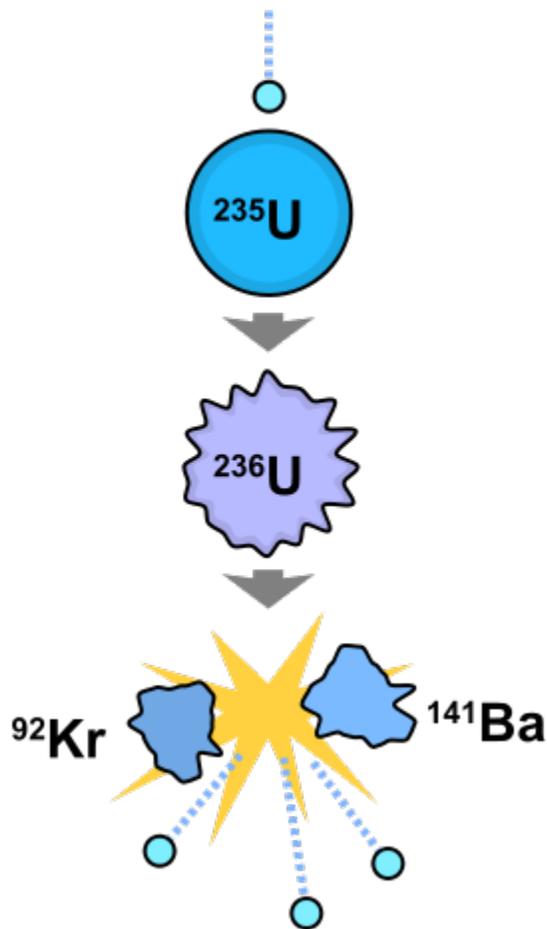
The actual ratios of fusion to Bremsstrahlung power will likely be significantly lower for several reasons. For one, the calculation assumes that the energy of the fusion products is transmitted completely to the fuel ions, which then lose energy to the electrons by collisions, which in turn lose energy 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 ${}^2\text{H}-{}^3\text{T}$ very much because the Bremsstrahlung fraction is low, but it will push the other fuels into regimes where the power density relative to ${}^2\text{H}-{}^3\text{T}$ is even lower and the required confinement even more difficult to achieve. For ${}^2\text{H}-{}^2\text{H}$ and ${}^2\text{H}-{}^3\text{He}$, Bremsstrahlung losses will be a serious, possibly prohibitive problem. For ${}^3\text{He}-{}^3\text{He}$, $\text{p}^+-{}^6\text{Li}$ and $\text{p}^+-{}^{11}\text{B}$ 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

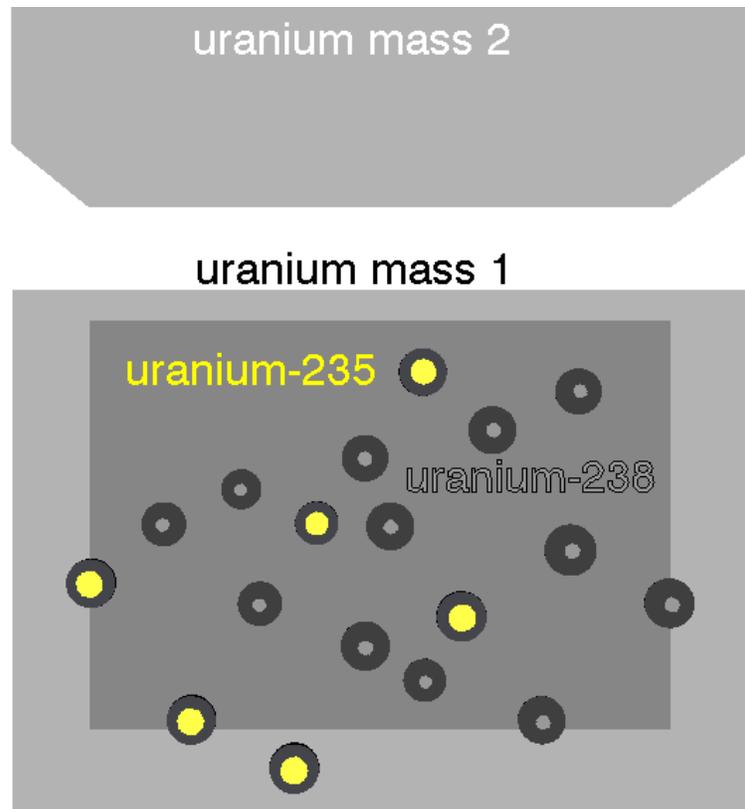
electromagnetic radiation and as kinetic energy of the fragments (heating the bulk material where fission takes place). For fission to produce energy, the total binding energy of the resulting elements has to be lower than that of the starting element. Fission is a form of nuclear transmutation because 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 $\sim 6\%$), 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 $8.8 \text{ MeV} / 202.5 \text{ MeV} = 4.3\%$ of the energy which is released as antineutrinos is not captured by the reactor material as heat, and escapes directly through all materials (including the Earth) at nearly the speed of light, and into interplanetary space (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

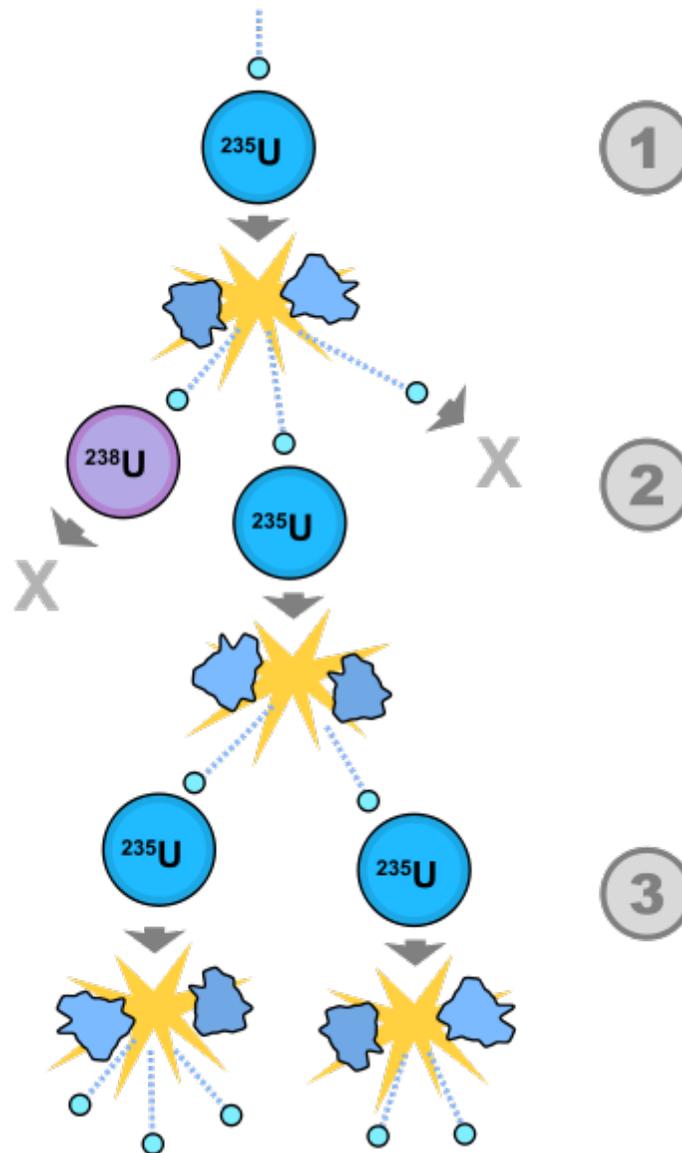
Nuclear fission of heavy elements produces energy because the specific binding energy (binding energy per mass) of intermediate-mass nuclei with atomic numbers and atomic masses close to ^{62}Ni and ^{56}Fe is greater than the nucleon-specific binding energy of very heavy nuclei, so that energy is released 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 $\Delta m = M - Mp$ 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. ^2H and ^3H). The nuclear chain reaction is unique since it releases several million times more energy per reaction than any chemical reaction.

History

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

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

In 1936, Szilárd attempted to create a chain reaction using beryllium and indium, but was unsuccessful. In 1939, Szilárd and Enrico Fermi discovered neutron multiplication in uranium, proving that a chain reaction was indeed possible. This discovery prompted the letter from Albert Einstein to President Franklin D. Roosevelt warning of the possibility that Nazi Germany might be attempting to build an atomic bomb.

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

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

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).

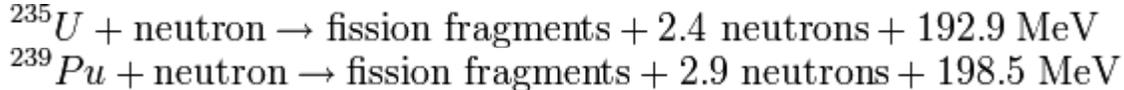
Fission reaction products

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 $E=\Delta mc^2$:

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

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:



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

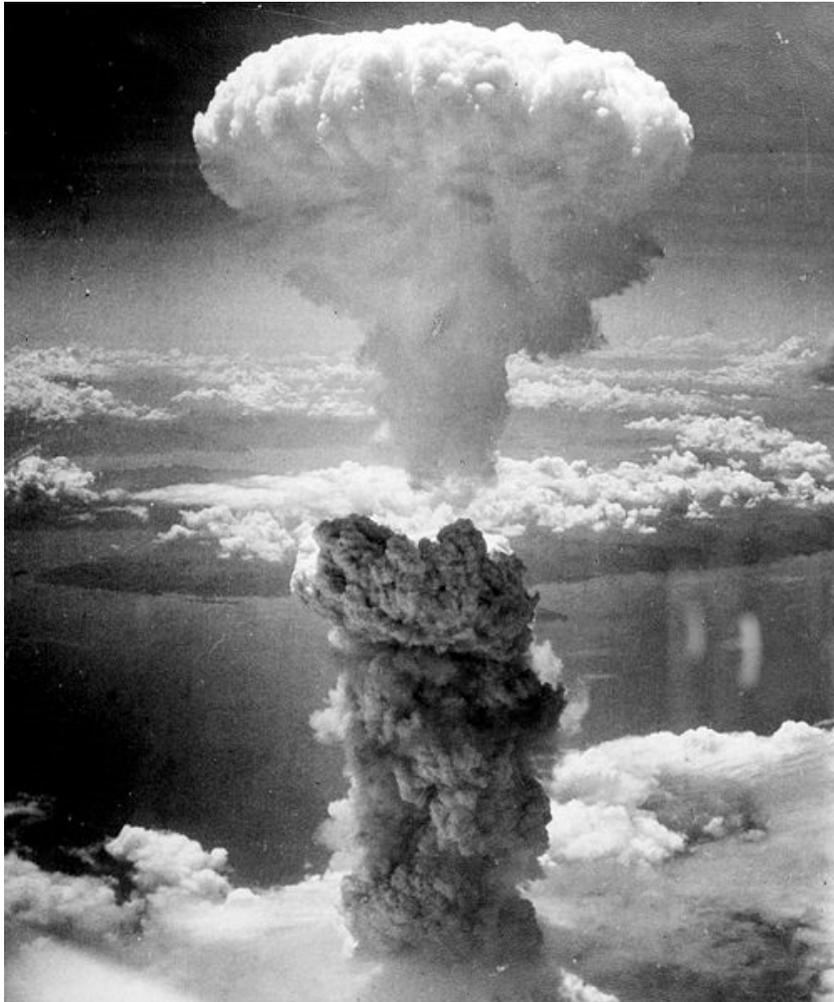
Critical fission reactors are the most common type of nuclear reactor. In a critical fission reactor, neutrons produced by fission of fuel atoms are used to induce yet more fissions, to sustain a controllable amount of energy release. Devices that produce engineered but non-self-sustaining fission reactions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

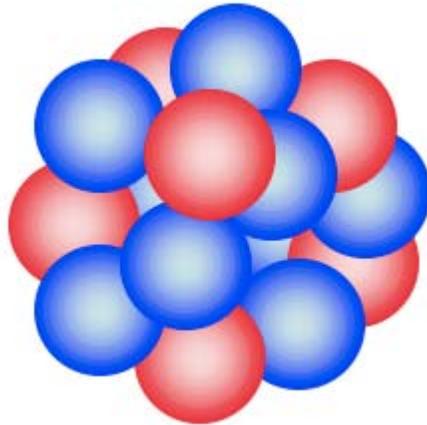
In the years after World War II, many countries were involved in the further development of nuclear fission for the purposes of nuclear reactors and nuclear weapons.

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 $1.6726 \times 10^{-27} \text{ kg}$ or $938.27 \text{ MeV}/c^2$, while the neutron is $1.6749 \times 10^{-27} \text{ kg}$ or $939.57 \text{ MeV}/c^2$. 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.

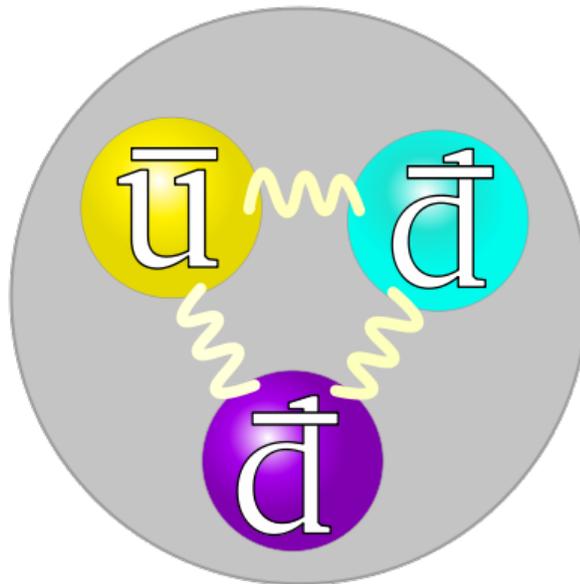
Stability of nucleons

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 \bar{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.

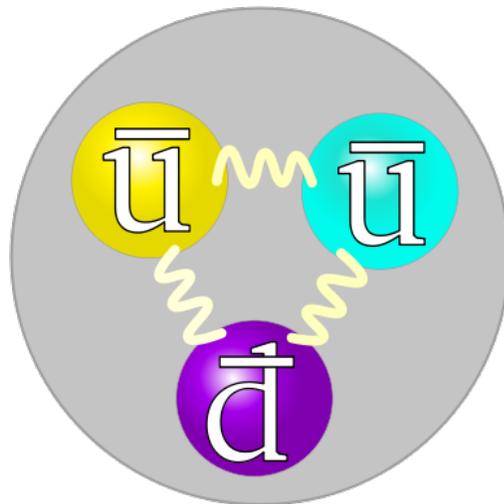
Since the antineutron is electrically neutral, it cannot easily be observed directly. Instead, the products of its annihilation with ordinary matter are observed. In theory, a free antineutron should decay into an antiproton, a positron and a neutrino in a process analogous to the beta decay of free 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 $1.91 \mu_N$ for the antineutron but $-1.91 \mu_N$ for the neutron (relative to the direction of the spin). Here μ_N is the nuclear magneton.

Antiproton



The quark structure of the antiproton

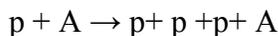
The **antiproton** (\bar{p} , pronounced *p-bar*) is the antiparticle of the proton. Antiprotons are stable, but they are typically short-lived since any collision with a proton will cause both particles to be annihilated in a burst of energy.

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 ($\bar{u}\bar{u}\bar{d}$). 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:



The secondary antiprotons (\bar{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 $p \rightarrow \mu^- + X$ and 300,000 yr for $p \rightarrow e^- + \gamma$

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

Isotope

Isotopes are different types of atoms (nuclides) of the same chemical element, each having a different number of neutrons. In a corresponding manner, isotopes differ in mass number (or total number of nucleons per atom) but never in atomic number. The number of protons (the atomic number) is the same among different isotopes of one element, because it is always equal to the number of electrons in the atom's shell, which is what determines the chemical properties of the atom and, thus, characterizes a chemical element. For example, carbon-12, carbon-13 and carbon-14 are three isotopes of the element carbon with mass numbers 12, 13 and 14, respectively. The atomic number of carbon is 6 (every atom of carbon has exactly 6 protons and 6 electrons, the latter is what makes it carbon); the neutron numbers in these isotopes of carbon are therefore $12-6 = 6$, $13-6 = 7$, and $14-6 = 8$.

A *nuclide* is an atomic nucleus with a specified composition of protons and neutrons. The *nuclide* concept emphasizes nuclear properties over chemical properties, while the *isotope* concept emphasizes chemical over nuclear. The neutron number has drastic effects on nuclear properties, but its effect on chemical properties is negligible in most elements, and still quite small in the case of the very lightest elements, where it does matter slightly. Since *isotope* is the older term, it is better known, and is still sometimes used in contexts where *nuclide* might be more appropriate, such as nuclear technology.

An isotope and/or nuclide is specified by the name of the particular element (this indicates the atomic number implicitly) followed by a hyphen and the mass number (e.g. helium-3, carbon-12, carbon-13, iodine-131 and uranium-238). When a chemical symbol is used, e.g., "C" for carbon, standard notation is to indicate the number of nucleons with a superscript at the upper left of the chemical symbol and to indicate the atomic number with a subscript at the lower left (e.g. ^3He , ^4He , ^{12}C , ^{14}C , ^{235}U , and ^{239}U). Since the atomic number is implied by the element symbol, it is common to state only the mass number in the superscript and leave out the atomic number subscript.

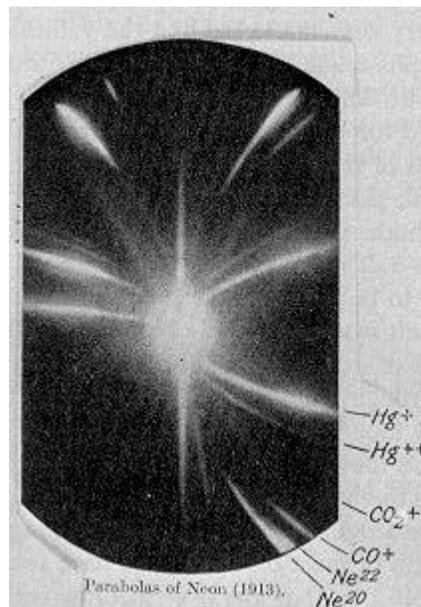
Some isotopes are radioactive and are therefore described as radioisotopes or radionuclides, while others have never been observed to undergo radioactive decay and are described as stable isotopes. For example, ^{14}C is a radioactive form of carbon while ^{12}C and ^{13}C are stable isotopes. There are about 339 naturally occurring nuclides on Earth, of which 288 are primordial nuclides. These include 31 nuclides with very long half lives (over 80 million years) and 257 which are formally considered as "stable".

About 30 of these "stable" isotopes have actually been observed to decay, but with half lives too long to be estimated so far. This leaves 227 nuclides that have not been observed to decay at all.

Many more apparently "stable" isotopes are predicted by theory to be radioactive, with extremely long half-lives (this does not count the possibility of proton decay, which would make all nuclides unstable). Of the 227 nuclides never observed to decay, only 90 of these (all from the first 40 elements) are stable in theory to all known forms of decay. Element 41 (niobium) is theoretically unstable to spontaneous fission, but this has never been detected. Many other stable nuclides are in theory energetically susceptible to other known forms of decay such as alpha decay or double beta decay, but no decay has yet been observed. The half lives for these processes often exceed a million times the estimated age of the universe.

Adding in the radioactive nuclides that have been created artificially, there are more than 3100 currently known nuclides.. These include 905 nuclides which are either stable, or have half lives longer than 60 minutes.

History of the term



In the bottom right corner of JJ Thomson's photographic plate are the separate impact marks for the two isotopes of neon: neon-20 and neon-22.

The term *isotope* was coined in 1913 by Margaret Todd, a Scottish physician, during a conversation with Frederick Soddy (to whom she was distantly related by marriage). Soddy, a chemist at Glasgow University, explained that it appeared from his investigations as if each position in the periodic table was occupied by multiple entities.

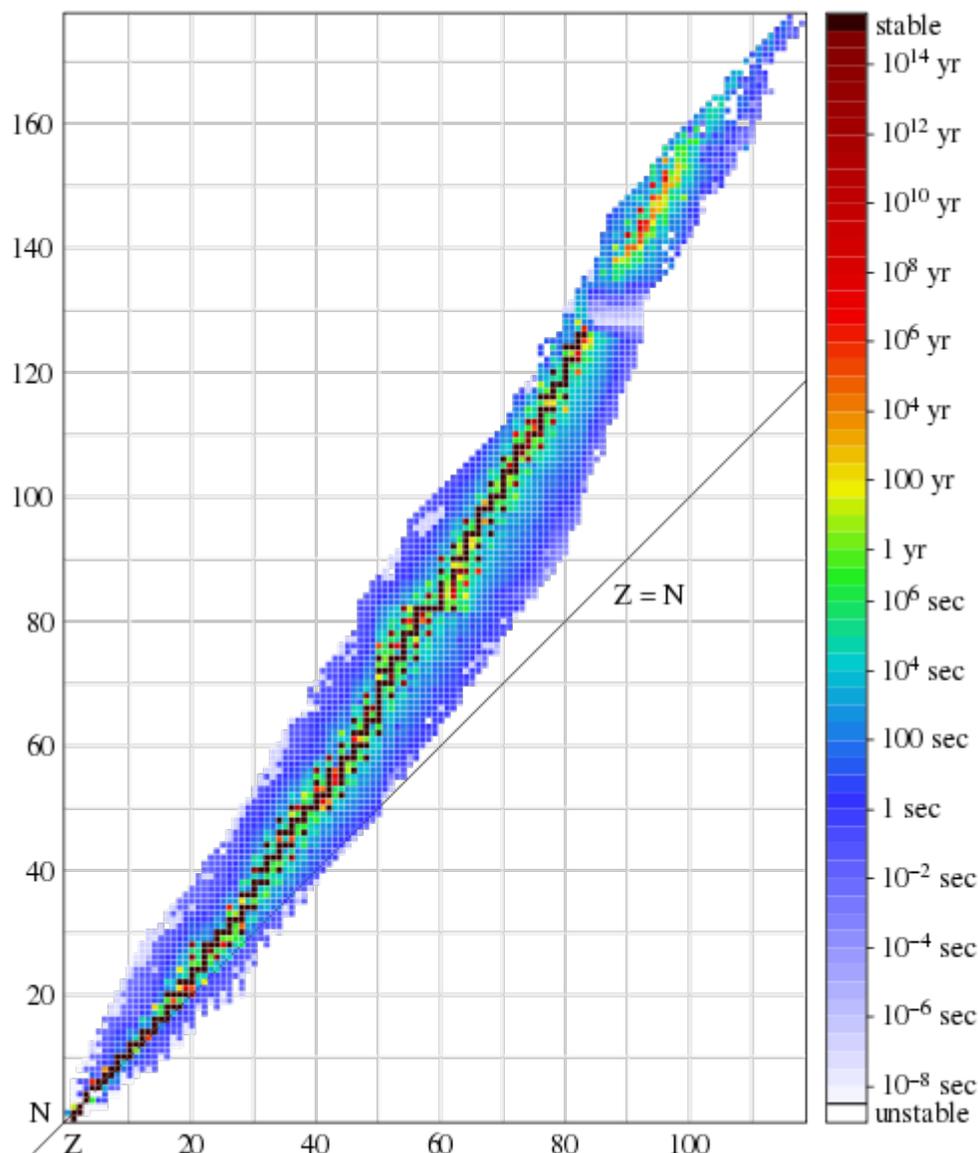
Hence Todd made the suggestion, which Soddy adopted, that a suitable name for such an entity would be the Greek term for "at the same place".

Soddy's own studies were of radioactive (unstable) atoms. The first observation of different stable isotopes for an element was by J. J. Thomson in 1913. As part of his exploration into the composition of canal rays, Thomson channeled streams of neon ions through a magnetic and an electric field and measured their deflection by placing a photographic plate in their path. Each stream created a glowing patch on the plate at the point it struck. Thomson observed two separate patches of light on the photographic plate (see image), which suggested two different parabolas of deflection. Thomson eventually concluded that some of the atoms in the neon gas were of higher mass than the rest. F.W. Aston subsequently discovered different stable isotopes for numerous elements using a mass spectrograph.

Variation in properties between isotopes

Chemical and molecular properties

A neutral atom has the same number of electrons as protons. Thus, different isotopes of a given element all have the same number of protons and electrons and share a similar electronic structure. Because the chemical behavior of an atom is largely determined by its electronic structure, different isotopes exhibit nearly identical chemical behavior. The main exception to this is the kinetic isotope effect: due to their larger masses, heavier isotopes tend to react somewhat more slowly than lighter isotopes of the same element. This is most pronounced for protium (^1H) and deuterium (^2H), because deuterium has twice the mass of protium. The mass effect between deuterium and the relatively light protium also affects the behavior of their respective chemical bonds, by means of changing the center of gravity (reduced mass) of the atomic systems. However, for heavier elements, which have more neutrons than lighter elements, the ratio of the nuclear mass to the collective electronic mass is far greater, and the relative mass difference between isotopes is much less. For these two reasons, the mass-difference effects on chemistry are usually negligible.



Isotope half lives. Note that the plot for stable isotopes diverges from the line, protons $Z =$ neutrons N as the element number Z becomes larger

In similar manner, two molecules that differ only in the isotopic nature of their atoms (*isotopologues*) will have identical electronic structure and therefore almost indistinguishable physical and chemical properties (again with deuterium providing the primary exception to this rule). The **vibrational modes** of a molecule are determined by its shape and by the masses of its constituent atoms. As a consequence, isotopologues will have different sets of vibrational modes. Since vibrational modes allow a molecule to absorb photons of corresponding energies, isotopologues have different optical properties in the infrared range.

Nuclear properties and stability

Atomic nuclei consist of protons and neutrons bound together by the **residual strong force**. Because protons are positively charged, they repel each other. Neutrons, which are electrically neutral, stabilize the nucleus in two ways. Their copresence pushes protons slightly apart, reducing the electrostatic repulsion between the protons, and they exert the attractive nuclear force on each other and on protons. For this reason, one or more neutrons are necessary for two or more protons to be bound into a nucleus. As the number of protons increases, so does the ratio of neutrons to protons necessary to ensure a stable nucleus (see graph). For example, although the neutron:proton ratio of ^3_2He is 1:2, the neutron:proton ratio of $^{238}_{92}\text{U}$ is greater than 3:2. A number of lighter elements have stable nuclides with the ratio 1:1 ($Z = N$). The nuclide $^{40}_{20}\text{Ca}$ (calcium-40) is the heaviest stable nuclide with the same number of neutrons and protons; all heavier stable nuclides contain more neutrons than protons.

Numbers of isotopes per element

Of the **80** elements with a stable isotope, the largest number of stable isotopes observed for any element is ten (for the element tin). Xenon is the only element that has nine stable isotopes. Cadmium has eight stable isotopes. Five elements have seven stable isotopes, eight have six stable isotopes, ten have five stable isotopes, eight have four stable isotopes, nine have three stable isotopes, 16 have two stable isotopes (counting $^{180\text{m}}_{73}\text{Ta}$ as stable), and 26 elements have only a single stable isotope (of these, 19 are so-called mononuclidic elements, having a single primordial stable isotope that dominates and fixes the atomic weight of the natural element to high precision; 3 radioactive **mononuclidic** elements occur as well). In total, there are 257 nuclides that have not been observed to decay. For the 80 elements that have one or more stable isotopes, the average number of stable isotopes is $257/80 = 3.2$ isotopes per element.

Even and odd nucleon numbers

	Even/odd N		
Mass	E	O	All
Stable	145	101	246
Longlived	20	6	26
Primordial	165	107	272

The proton:neutron ratio is not the only factor affecting nuclear stability. Adding neutrons to isotopes can vary their nuclear spins and nuclear shapes, causing differences in neutron capture cross-sections and gamma spectroscopy and nuclear magnetic resonance properties.

Even mass number

Beta decay of an even-even nucleus produces an odd-odd nucleus, and vice versa. An even number of protons or of neutrons are more stable (lower binding energy) because of pairing effects, so even-even nuclei are much more stable than odd-odd. One effect is that there are few stable odd-odd nuclei, but another effect is to prevent beta decay of many even-even nuclei into another even-even nucleus of the same mass number but lower energy, because decay proceeding one step at a time would have to pass through an odd-odd nucleus of higher energy. This makes for a larger number of stable even-even nuclei, up to three for some mass numbers, and up to seven for some atomic (proton) numbers. Double beta decay directly from even-even to even-even skipping over an odd-odd nuclide is only occasionally possible, and even then with a half-life greater than a billion times the age of the universe.

Even-mass-number nuclides have integer spin and are bosons.

Even proton-even neutron

	Even/odd Z, N			
p,n	EE	OO	EO	OE
Stable	140	5	53	48
Longlived	16	4	2	4
Primordial	156	9	55	52

For example, the extreme stability of helium-4 due to a double pairing of 2 protons and 2 neutrons prevents *any* nuclides containing five or eight nucleons from existing for long enough to serve as platforms for the buildup of heavier elements during fusion formation in stars.

There are 141 stable even-even isotopes, forming 55% of the 257 stable isotopes. There are also 16 primordial longlived even-even isotopes. As a result, many of the 41 even-numbered elements from 2 to 82 have many primordial isotopes. Half of these even-numbered elements have six or more stable isotopes.

All even-even nuclides have spin 0 in their ground state.

Odd proton-odd neutron

Only five stable nuclides contain both an odd number of protons and an odd number of neutrons: the first four odd-odd nuclides ${}^2_1\text{H}$, ${}^6_3\text{Li}$, ${}^{10}_5\text{B}$, and ${}^{14}_7\text{N}$ (where changing a proton to a neutron or vice versa would lead to a very lopsided proton-neutron ratio) and ${}^{180m}_{73}\text{Ta}$, which has not yet been observed to decay despite experimental attempts. Also, four long-lived radioactive odd-odd nuclides (${}^{4019}\text{K}$, ${}^{5023}\text{V}$, ${}^{13857}\text{La}$, ${}^{17671}\text{Lu}$) occur naturally.

Of these 9 primordial odd-odd nuclides, only ^{14}N is the most common isotope of a common element, because it is a part of the CNO cycle; ^6Li and ^{10}B are minority isotopes of elements that are rare compared to other light elements, while the other six isotopes make up only a tiny percentage of their elements.

Few odd-odd nuclides (and none of the primordial ones) have spin 0 in the ground state.

Odd mass number

There is only one beta-stable nuclide per odd mass number because there is no difference in binding energy between even-odd and odd-even comparable to that between even-even and odd-odd, and other nuclides of the same mass are free to beta decay towards the lowest-energy one. For mass numbers 5, 147, 151, and 209 and up, the one beta-stable isobar is able to alpha decay, so that there are no stable isotopes with these mass numbers. This gives a total of 101 stable isotopes with odd mass numbers.

Odd-mass-number nuclides have half-integer spin and are fermions.

Odd proton-even neutron

These form most of the stable isotopes of the odd-numbered elements, but there is only one stable odd-even isotope for each of the 41 odd-numbered elements from 1 to 81, except for technetium (^{43}Tc) and promethium (^{61}Pm) that have no stable isotopes, and chlorine (^{17}Cl), potassium (^{19}K), copper (^{29}Cu), gallium (^{31}Ga), bromine (^{35}Br), silver (^{47}Ag), antimony (^{51}Sb), iridium (Ir), and thallium (^{81}Tl), each of which has two, making a total of 48 stable odd-even isotopes. There are also four primordial long-lived odd-even isotopes, ^{87}Rb , ^{115}In , ^{151}Eu , and ^{187}Re .

Even proton-odd neutron

There are 54 stable isotopes that have an even number of protons and an odd number of neutrons. There are also four primordial long lived even-odd isotopes, ^{113}Cd (beta decay, half-life is 7.7×10^{15} years); ^{147}Sm ($1.06 \times 10^{11}\text{a}$); and ^{149}Sm ($>2 \times 10^{15}\text{a}$); and the fissile ^{235}U .

The only even-odd isotopes that are the most common one for their element are ^{195}Pt and ^9Be . Beryllium-9 is the only stable beryllium isotope because the expected beryllium-8 has higher energy than two alpha particles and therefore decays to them.

Odd neutron number

Even/odd N	
n	E O
Stable	188 58
Longlived	20 6

Primordial 208 64

The only odd-neutron-number isotopes that are the most common isotope of their element are ^{195}Pt , ^{94}Be and ^{147}N .

Actinides with odd neutron number are generally fissile, while those with even neutron number are generally not, though they are split when bombarded with fast neutrons.

Occurrence in nature

Elements are composed of one or more naturally occurring isotopes. The unstable (radioactive) isotopes are either primordial, in which case they have persisted down to the present because their rate of decay is so slow (e.g., uranium-238 and potassium-40), or they are postprimordial, created by cosmic ray bombardment as cosmogenic nuclides (e.g., tritium, carbon-14) or by the decay of a radioactive primordial isotope to a radioactive radiogenic nuclide daughter (e.g., uranium to radium).

As discussed above, only 80 elements have any stable isotopes, and 26 of these have only one stable isotope. Thus, about two thirds of stable elements occur naturally on Earth in multiple stable isotopes, with the largest number of stable isotopes for an element being ten, for tin ($_{50}\text{Sn}$). There are about 94 elements found naturally on Earth (up to plutonium inclusive), though some are detected only in very tiny amounts, such as plutonium-244. Scientists estimate that the elements that occur naturally on Earth (some only as radioisotopes) occur as 339 isotopes (nuclides) in total. Only 257 of these naturally occurring isotopes are stable in the sense of either never having been observed to decay as of the present time (227 nuclides), or having been observed to decay but with a half life too long to estimate (30 nuclides). An additional 31 primordial nuclides (to a total of 288 primordial nuclides), are radioactive with known half lives, but have half lives longer than 80 million years, allowing them to exist from the beginning of the solar system.

All the known stable isotopes occur naturally on Earth; the other naturally occurring-isotopes are radioactive but occur on Earth due to their relatively long half-lives, or else due to other means of ongoing natural production. These include the afore-mentioned cosmogenic nuclides and the short-lived radioisotopes formed by decay of a primordial radioactive isotope, such as radon and radium from uranium.

An additional ~3000 radioactive isotopes not found in nature have been created in nuclear reactors and in particle accelerators. Many short-lived isotopes not found naturally on Earth have also been observed by spectroscopic analysis, being naturally created in stars or supernovae. An example is aluminum-26, which is not naturally found on Earth, but which is found in abundance on an astronomical scale.

The tabulated atomic masses of elements are averages that account for the presence of multiple isotopes with different masses. Before the discovery of isotopes, empirically determined noninteger values of atomic mass confounded scientists. For example, a

sample of chlorine contains 75.8% chlorine-35 and 24.2% chlorine-37, giving an average atomic mass of 35.5 atomic mass units.

According to generally accepted cosmology theory, only isotopes of hydrogen and helium, and traces of some isotopes of lithium and beryllium were created at the Big Bang, while all other isotopes were synthesized later, in stars and supernovae, and in interactions between energetic particles such as cosmic rays, and previously produced isotopes. The respective abundances of isotopes on Earth result from the quantities formed by these processes, their spread through the galaxy, and the rates of decay for isotopes that are unstable. After the initial coalescence of the solar system, isotopes were redistributed according to mass, and the isotopic composition of elements varies slightly from planet to planet. This sometimes makes it possible to trace the origin of meteorites.

Atomic mass of isotopes

The atomic mass (m_r) of an isotope is determined mainly by its mass number (i.e. number of nucleons in its nucleus). Small corrections are due to the binding energy of the nucleus, the slight difference in mass between proton and neutron, and the mass of the electrons associated with the atom, the latter because the electron:nucleon ratio differs among isotopes.

The mass number is a dimensionless quantity. The atomic mass, on the other hand, is measured using the atomic mass unit based on the mass of the carbon atom. It is denoted with symbols "u" (for unit) or "Da" (for Dalton).

The atomic masses of naturally occurring isotopes of an element determine the atomic weight of the element. When the element contains N isotopes, the equation below is applied for the atomic weight M :

$$M = m_1x_1 + m_2x_2 + \dots + m_Nx_N$$

where m_1, m_2, \dots, m_N are the atomic masses of each individual isotope, and x_1, \dots, x_N are the relative abundances of these isotopes.

Applications of isotopes

Several applications exist that capitalize on properties of the various isotopes of a given element. Isotope separation is a significant technological challenge, particularly with heavy elements such as uranium or plutonium. Lighter elements such as lithium, carbon, nitrogen, and oxygen are commonly separated by gas diffusion of their compounds such as CO and NO. The separation of hydrogen and deuterium is unusual since it is based on chemical rather than physical properties, for example in the Girdler sulfide process. Uranium isotopes have been separated in bulk by gas diffusion, gas centrifugation, laser ionization separation, and (in the Manhattan Project) by a type of production mass spectroscopy.

Use of chemical and biological properties

- Isotope analysis is the determination of isotopic signature, the relative abundances of isotopes of a given element in a particular sample. For biogenic substances in particular, significant variations of isotopes of C, N and O can occur. Analysis of such variations has a wide range of applications, such as the detection of adulteration of food products. The identification of certain meteorites as having originated on Mars is based in part upon the isotopic signature of trace gases contained in them.
- Another common application is isotopic labeling, the use of unusual isotopes as tracers or markers in chemical reactions. Normally, atoms of a given element are indistinguishable from each other. However, by using isotopes of different masses, they can be distinguished by mass spectrometry or infrared spectroscopy. For example, in 'stable isotope labeling with amino acids in cell culture (SILAC)' stable isotopes are used to quantify proteins. If radioactive isotopes are used, they can be detected by the radiation they emit (this is called *radioisotopic labeling*).
- A technique similar to radioisotopic labeling is radiometric dating: using the known half-life of an unstable element, one can calculate the amount of time that has elapsed since a known level of isotope existed. The most widely known example is radiocarbon dating used to determine the age of carbonaceous materials.
- Isotopic substitution can be used to determine the mechanism of a reaction via the kinetic isotope effect.

Use of nuclear properties

- Several forms of spectroscopy rely on the unique nuclear properties of specific isotopes. For example, nuclear magnetic resonance (NMR) spectroscopy can be used only for isotopes with a nonzero nuclear spin. The most common isotopes used with NMR spectroscopy are ^1H , ^2D , ^{15}N , ^{13}C , and ^{31}P .
- Mössbauer spectroscopy also relies on the nuclear transitions of specific isotopes, such as ^{57}Fe .
- Radionuclides also have important uses. Nuclear power and nuclear weapons development require relatively large quantities of specific isotopes.

Chapter- 7

Nuclear Power



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



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



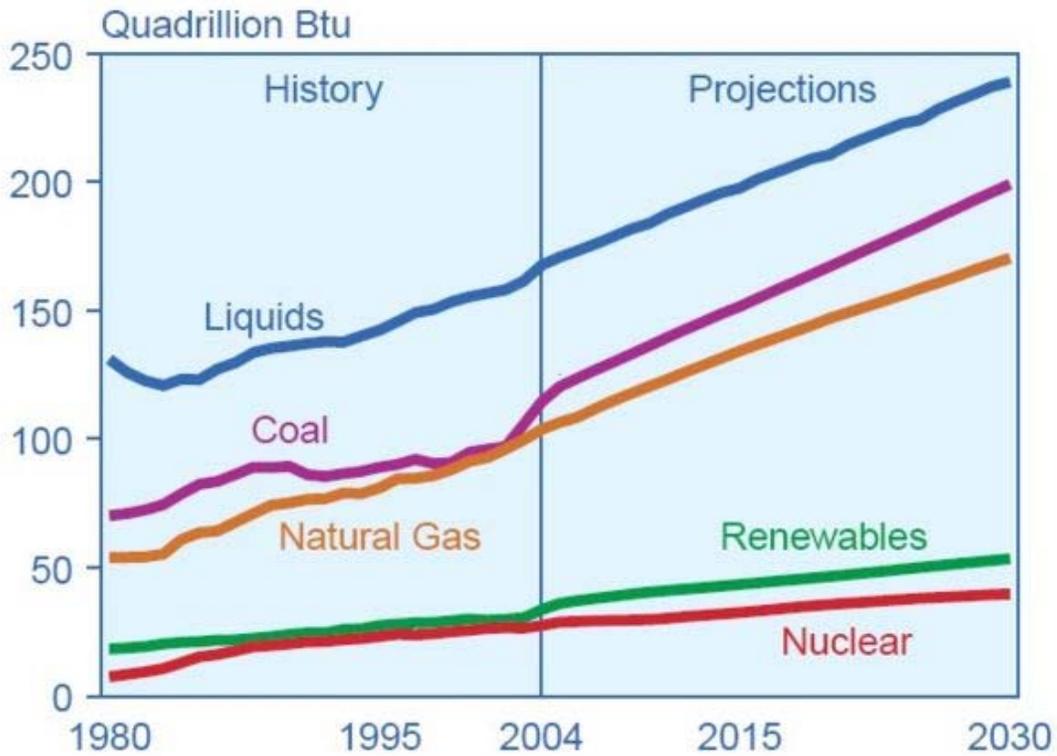
Three nuclear powered ships, (top to bottom) nuclear cruisers USS Bainbridge and USS Long Beach with *USS Enterprise* the first nuclear powered aircraft carrier in 1964. Crew members are spelling out Einstein's mass-energy equivalence formula $E = mc^2$ on the flight deck.

Nuclear power is produced by controlled (i.e., non-explosive) nuclear reactions. Commercial and utility plants currently use nuclear fission reactions to heat water to produce steam, which is then used to generate electricity.

In 2009, 13–14% of the world's electricity came from nuclear power. Also, more than 150 naval vessels using nuclear propulsion have been built.

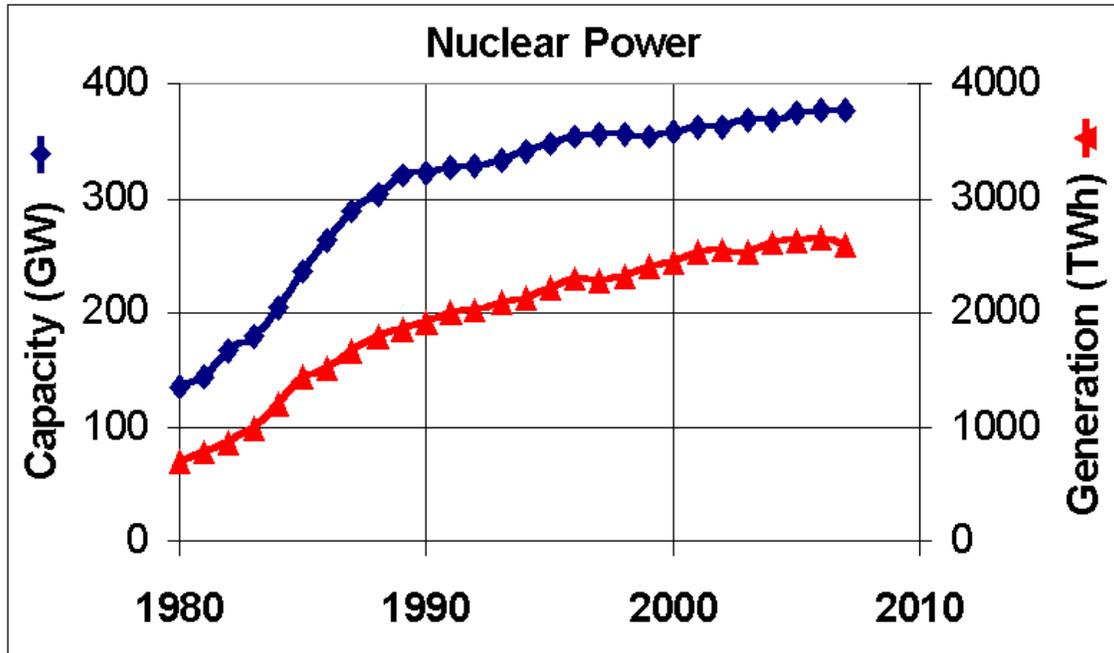
Use

Figure 4. World Marketed Energy Use by Fuel Type, 1980-2030

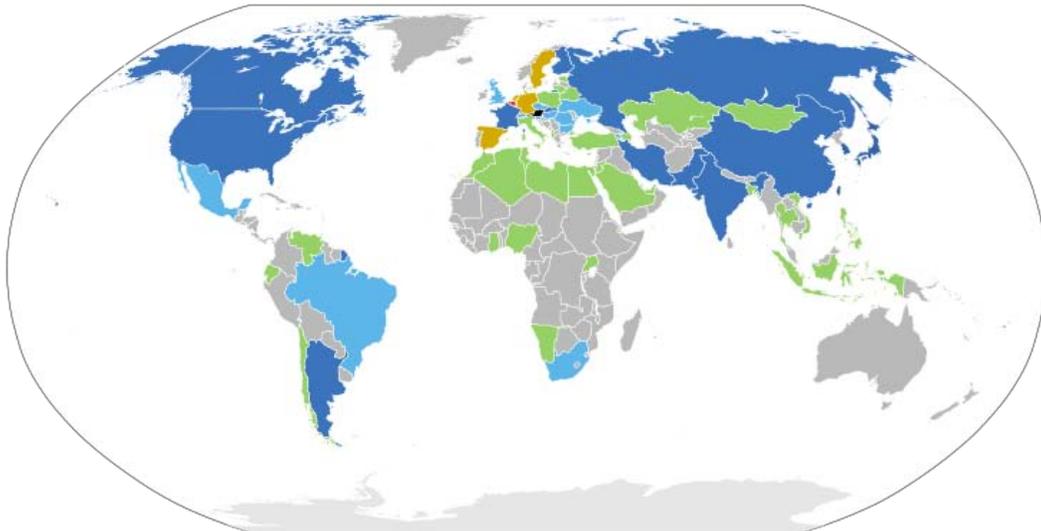


Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2004* (May-July 2006), web site www.eia.doe.gov/iea. **Projections:** EIA, *System for the Analysis of Global Energy Markets* (2007).

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



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



The status of nuclear power globally



The CANDU Bruce Nuclear Generating Station is the second largest nuclear power plant in the world.

As of 2005, nuclear power provided 6.3% of the world's energy and 15% of the world's electricity, with the U.S., France, and Japan together accounting for 56.5% of nuclear generated electricity. In 2007, the IAEA reported there were 439 nuclear power reactors in operation in the world, operating in 31 countries. As of December 2009, the world had 436 reactors. Since commercial nuclear energy began in the mid 1950s, 2008 was the first year that no new nuclear power plant was connected to the grid, although two were connected in 2009.

Annual generation of nuclear power has been on a slight downward trend since 2007, decreasing 1.8% in 2009 to 2558 TWh with nuclear power meeting 13–14% of the world's electricity demand. One factor in the nuclear power percentage decrease since 2007 has been the prolonged shutdown of large reactors at the Kashiwazaki-Kariwa Nuclear Power Plant in Japan following the Niigata-Chuetsu-Oki earthquake.

The United States produces the most nuclear energy, with nuclear power providing 19% of the electricity it consumes, while France produces the highest percentage of its electrical energy from nuclear reactors—80% as of 2006. In the European Union as a whole, nuclear energy provides 30% of the electricity. Nuclear energy policy differs between European Union countries, and some, such as Austria, Estonia, and Ireland, have no active nuclear power stations. In comparison, France has a large number of these plants, with 16 multi-unit stations in current use.

In the US, while the coal and gas electricity industry is projected to be worth \$85 billion by 2013, nuclear power generators are forecast to be worth \$18 billion.

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

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

Nuclear fusion

Nuclear fusion reactions have the potential to be safer and generate less radioactive waste than fission. These reactions appear potentially viable, though technically quite difficult and have yet to be created on a scale that could be used in a functional power plant. Fusion power has been under intense theoretical and experimental investigation since the 1950s.

Use in space

Both fission and fusion appear promising for space propulsion applications, generating higher mission velocities with less reaction mass. This is due to the much higher energy density of nuclear reactions: some 7 orders of magnitude (10,000,000 times) more energetic than the chemical reactions which power the current generation of rockets.

Radioactive decay has been used on a relatively small (few kW) scale, mostly to power space missions and experiments by using radioisotope thermoelectric generators such as those developed at Idaho National Laboratory.

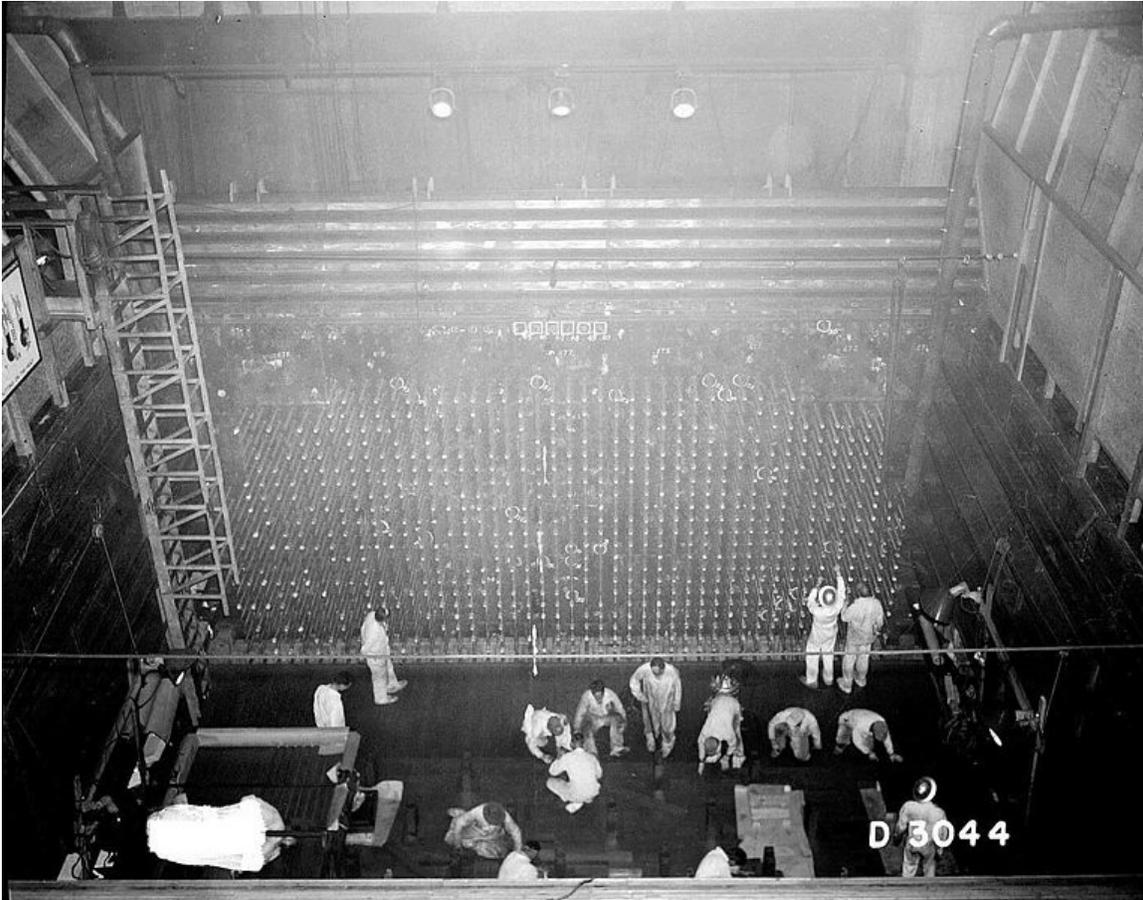
History

Origins

The pursuit of nuclear energy for electricity generation began soon after the discovery in the early 20th century that radioactive elements, such as radium, released immense amounts of energy, according to the principle of mass–energy equivalence. However, means of harnessing such energy was impractical, because intensely radioactive elements were, by their very nature, short-lived (high energy release is correlated with short half-lives). However, the dream of harnessing "atomic energy" was quite strong, even it was dismissed by such fathers of nuclear physics like Ernest Rutherford as "moonshine." This situation, however, changed in the late 1930s, with the discovery of nuclear fission.

In 1932, James Chadwick discovered the neutron, which was immediately recognized as a potential tool for nuclear experimentation because of its lack of an electric charge. Experimentation with bombardment of materials with neutrons led Frédéric and Irène Joliot-Curie to discover induced radioactivity in 1934, which allowed the creation of radium-like elements at much less the price of natural radium. Further work by Enrico Fermi in the 1930s focused on using slow neutrons to increase the effectiveness of induced radioactivity. Experiments bombarding uranium with neutrons led Fermi to believe he had created a new, transuranic element, which he dubbed hesperium.

But in 1938, German chemists Otto Hahn and Fritz Strassmann, along with Austrian physicist Lise Meitner and Meitner's nephew, Otto Robert Frisch, conducted experiments with the products of neutron-bombarded uranium, as a means of further investigating Fermi's claims. They determined that the relatively tiny neutron split the nucleus of the massive uranium atoms into two roughly equal pieces, contradicting Fermi. This was an extremely surprising result: all other forms of nuclear decay involved only small changes to the mass of the nucleus, whereas this process—dubbed "fission" as a reference to biology—involved a complete rupture of the nucleus. Numerous scientists, including Leo Szilard, who was one of the first, recognized that if fission reactions released additional neutrons, a self-sustaining nuclear chain reaction could result. Once this was experimentally confirmed and announced by Frédéric Joliot-Curie in 1939, scientists in many countries (including the United States, the United Kingdom, France, Germany, and the Soviet Union) petitioned their governments for support of nuclear fission research, just on the cusp of World War II.



Constructing the core of B-Reactor at Hanford Site during the Manhattan Project

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

After World War II, the prospects of using "atomic energy" for good, rather than simply for war, were greatly advocated as a reason not to keep all nuclear research controlled by military organizations. However, most scientists agreed that civilian nuclear power would take at least a decade to master, and the fact that nuclear reactors also produced weapons-usable plutonium created a situation in which most national governments (such as those in the United States, the United Kingdom, Canada, and the USSR) attempted to keep reactor research under strict government control and classification. In the United States, reactor research was conducted by the U.S. Atomic Energy Commission, primarily at Oak Ridge, Tennessee, Hanford Site, and Argonne National Laboratory.



The first light bulbs ever lit by electricity generated by nuclear power at EBR-1 at what is now Idaho National Laboratory.

Work in the United States, United Kingdom, Canada, and USSR proceeded over the course of the late 1940s and early 1950s. Electricity was generated for the first time by a nuclear reactor on December 20, 1951, at the EBR-I experimental station near Arco, Idaho, which initially produced about 100 kW. Work was also strongly researched in the US on nuclear marine propulsion, with a test reactor being developed by 1953. (Eventually, the USS Nautilus, the first nuclear-powered submarine, would launch in 1955.) In 1953, US President Dwight Eisenhower gave his "Atoms for Peace" speech at the United Nations, emphasizing the need to develop "peaceful" uses of nuclear power quickly. This was followed by the 1954 Amendments to the Atomic Energy Act which allowed rapid declassification of U.S. reactor technology and encouraged development by the private sector.

Early years



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



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

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

Later in 1954, Lewis Strauss, then chairman of the United States Atomic Energy Commission (U.S. AEC, forerunner of the U.S. Nuclear Regulatory Commission and the United States Department of Energy) spoke of electricity in the future being "too cheap to meter". Strauss was referring to hydrogen fusion- which was secretly being developed as part of Project Sherwood at the time - but Strauss's statement was interpreted as a promise of very cheap energy from nuclear fission. The U.S. AEC itself had issued far more conservative testimony regarding nuclear fission to the U.S. Congress only months before, projecting that "costs can be brought down... [to]... about the same as the cost of electricity from conventional sources..." Significant disappointment would develop later on, when the new nuclear plants did not provide energy "too cheap to meter."

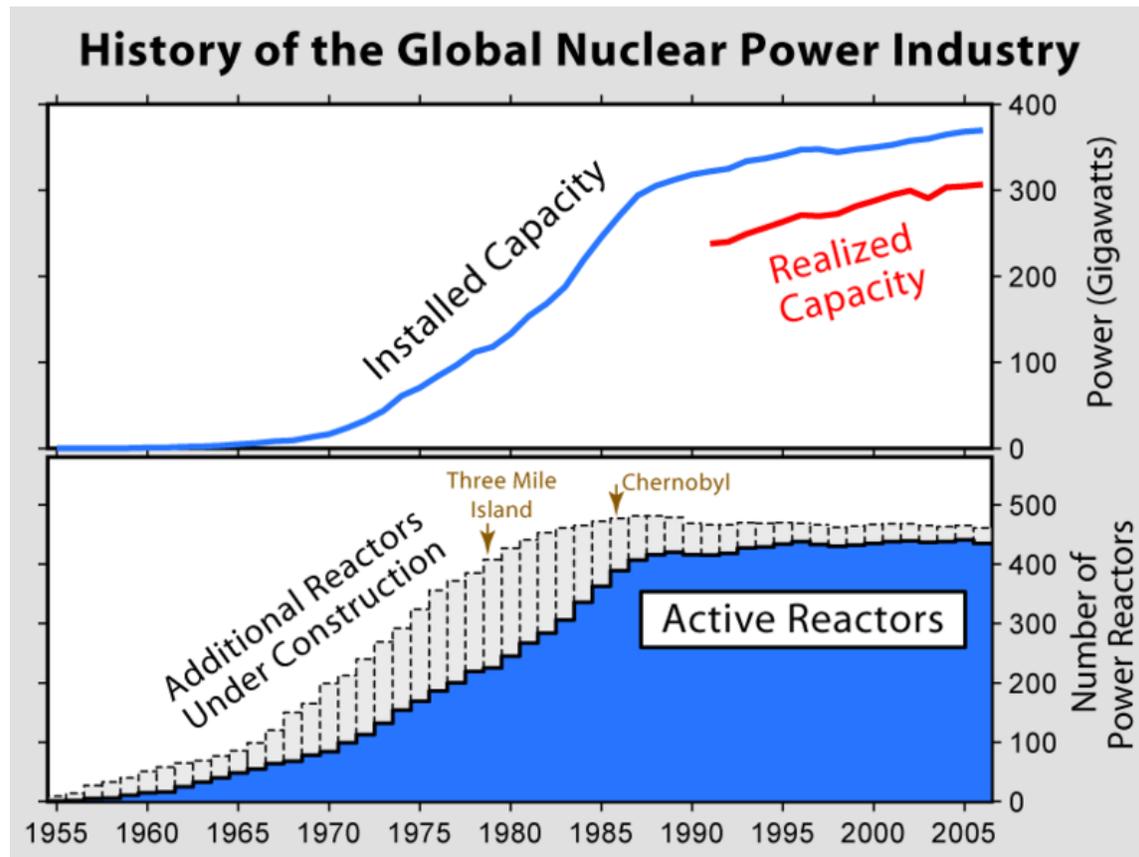
In 1955 the United Nations' "First Geneva Conference", then the world's largest gathering of scientists and engineers, met to explore the technology. In 1957 EURATOM was launched alongside the European Economic Community (the latter is now the European

Union). The same year also saw the launch of the International Atomic Energy Agency (IAEA).

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

One of the first organizations to develop nuclear power was the U.S. Navy, for the purpose of propelling submarines and aircraft carriers. It has an unblemished record in nuclear safety, perhaps because of the stringent demands of Admiral Hyman G. Rickover, who was the driving force behind nuclear marine propulsion as well as the Shippingport Reactor (Alvin Radkowsky was chief scientist at the U.S. Navy nuclear propulsion division, and was involved with the latter). The U.S. Navy has operated more nuclear reactors than any other entity, including the Soviet Navy, with no publicly known major incidents. The first nuclear-powered submarine, USS *Nautilus* (SSN-571), was put to sea in December 1954. Two U.S. nuclear submarines, USS *Scorpion* and USS *Thresher*, have been lost at sea. These vessels were both lost due to malfunctions in systems not related to the reactor plants. The sites are monitored and no known leakage has occurred from the onboard reactors. The United States Army also had a nuclear power program, beginning in 1954. The SM-1 Nuclear Power Plant, at Ft. Belvoir, Virginia, was the first power reactor in the US to supply electrical energy to a commercial grid (VEPCO), in April 1957, before Shippingport.

Development



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

Installed nuclear capacity initially rose relatively quickly, rising from less than 1 gigawatt (GW) in 1960 to 100 GW in the late 1970s, and 300 GW in the late 1980s. Since the late 1980s worldwide capacity has risen much more slowly, reaching 366 GW in 2005. Between around 1970 and 1990, more than 50 GW of capacity was under construction (peaking at over 150 GW in the late 70s and early 80s) — in 2005, around 25 GW of new capacity was planned. More than two-thirds of all nuclear plants ordered after January 1970 were eventually canceled. A total of 63 nuclear units were canceled in the USA between 1975 and 1980.



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

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

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

A general movement against nuclear power arose during the last third of the 20th century, based on the fear of a possible nuclear accident as well as the history of accidents, fears of radiation as well as the history of radiation of the public, nuclear proliferation, and on the opposition to nuclear waste production, transport and lack of any final storage plans. Protest movements against nuclear power first emerged in the USA in the late 1970s and spread quickly to Europe and the rest of the world. Anti-nuclear power groups emerged in every country that has had a nuclear power programme. Some of these anti-nuclear power organisations are reported to have developed considerable expertise on nuclear

power and energy issues. In 1992, the chairman of the Nuclear Regulatory Commission said that "his agency had been pushed in the right direction on safety issues because of the pleas and protests of nuclear watchdog groups".

Health and safety concerns, the 1979 accident at Three Mile Island, and the 1986 Chernobyl disaster played a part in stopping new plant construction in many countries, although the public policy organization Brookings Institution suggests that new nuclear units have not been ordered in the U.S. because of soft demand for electricity, and cost overruns on nuclear plants due to regulatory issues and construction delays.

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

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

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

Nuclear reactor technology



Cattenom Nuclear Power Plant

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

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

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

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

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

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

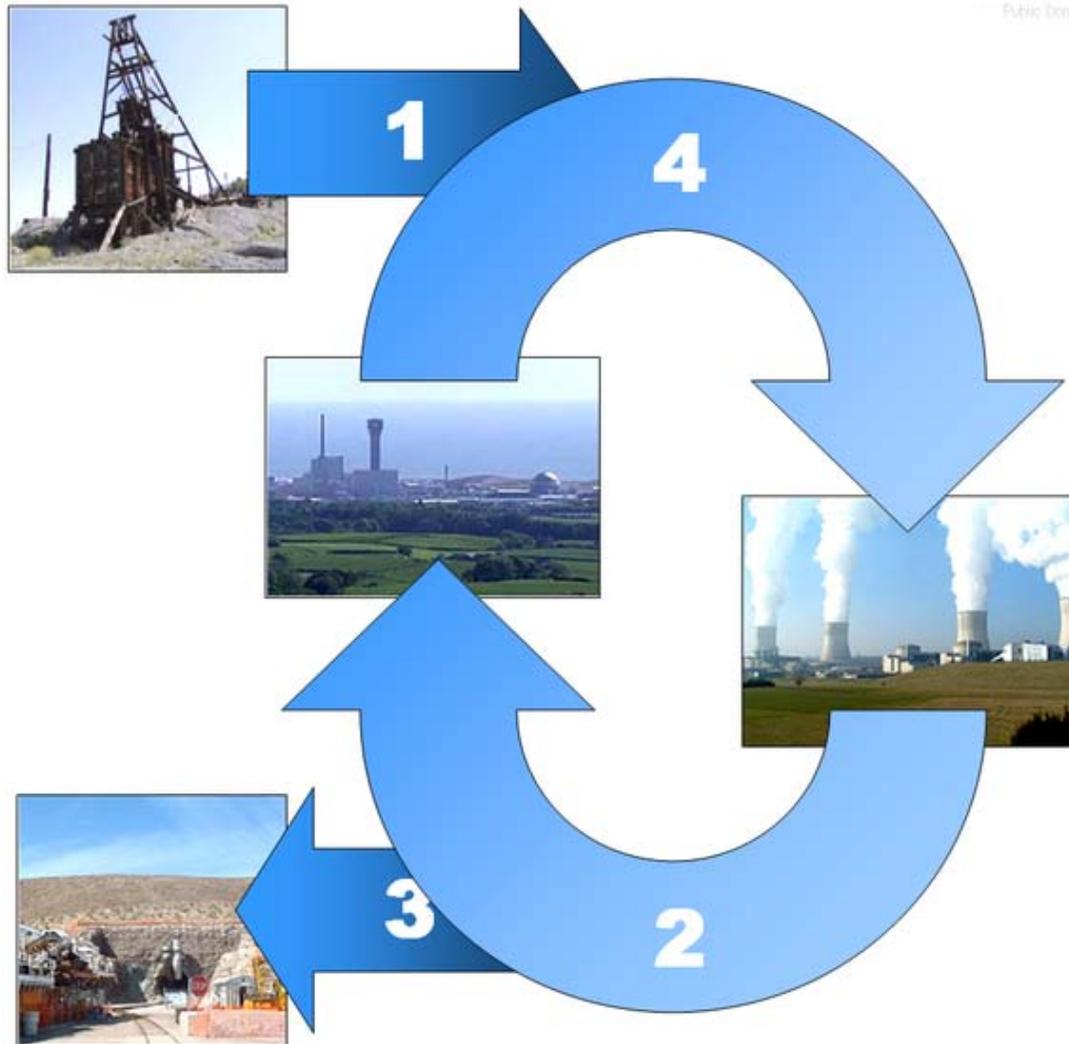
Flexibility of nuclear power plants

It is often claimed that nuclear stations are inflexible in their output, implying that other forms of energy would be required to meet peak demand. While that is true for certain reactors, this is no longer true of at least some modern designs.

Nuclear plants are routinely used in load following mode on a large scale in France.

Boiling water reactors normally have load-following capability, implemented by varying the recirculation water flow.

Life cycle



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

A nuclear reactor is only part of the life-cycle for nuclear power. The process starts with mining. Uranium mines are underground, open-pit, or in-situ leach mines. In any case, the uranium ore is extracted, usually converted into a stable and compact form such as

yellowcake, and then transported to a processing facility. Here, the yellowcake is converted to uranium hexafluoride, which is then enriched using various techniques. At this point, the enriched uranium, containing more than the natural 0.7% U-235, is used to make rods of the proper composition and geometry for the particular reactor that the fuel is destined for. The fuel rods will spend about 3 operational cycles (typically 6 years total now) inside the reactor, generally until about 3% of their uranium has been fissioned, then they will be moved to a spent fuel pool where the short lived isotopes generated by fission can decay away. After about 5 years in a cooling pond, the spent fuel is radioactively and thermally cool enough to handle, and it can be moved to dry storage casks or reprocessed.

Conventional fuel resources

Uranium is a fairly common element in the Earth's crust. Uranium is approximately as common as tin or germanium in Earth's crust, and is about 35 times more common than silver. Uranium is a constituent of most rocks, dirt, and of the oceans. The fact that uranium is so spread out is a problem because mining uranium is only economically feasible where there is a large concentration. Still, the world's present measured resources of uranium, economically recoverable at a price of 130 USD/kg, are enough to last for "at least a century" at current consumption rates. This represents a higher level of assured resources than is normal for most minerals. On the basis of analogies with other metallic minerals, a doubling of price from present levels could be expected to create about a tenfold increase in measured resources, over time. However, the cost of nuclear power lies for the most part in the construction of the power station. Therefore the fuel's contribution to the overall cost of the electricity produced is relatively small, so even a large fuel price escalation will have relatively little effect on final price. For instance, typically a doubling of the uranium market price would increase the fuel cost for a light water reactor by 26% and the electricity cost about 7%, whereas doubling the price of natural gas would typically add 70% to the price of electricity from that source. At high enough prices, eventually extraction from sources such as granite and seawater become economically feasible.

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

Breeding

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

Breeder technology has been used in several reactors, but the high cost of reprocessing fuel safely requires uranium prices of more than 200 USD/kg before becoming justified economically. As of December 2005, the only breeder reactor producing power is BN-

600 in Beloyarsk, Russia. The electricity output of BN-600 is 600 MW — Russia has planned to build another unit, BN-800, at Beloyarsk nuclear power plant. Also, Japan's Monju reactor is planned for restart (having been shut down since 1995), and both China and India intend to build breeder reactors.

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

Fusion

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

Solid waste

The most important waste stream from nuclear power plants is spent nuclear fuel. It is primarily composed of unconverted uranium as well as significant quantities of transuranic actinides (plutonium and curium, mostly). In addition, about 3% of it is fission products from nuclear reactions. The actinides (uranium, plutonium, and curium) are responsible for the bulk of the long-term radioactivity, whereas the fission products are responsible for the bulk of the short-term radioactivity.

High-level radioactive waste

After about 5 percent of a nuclear fuel rod has reacted inside a nuclear reactor that rod is no longer able to be used as fuel (due to the build-up of fission products). Today, scientists are experimenting on how to recycle these rods so as to reduce waste and use the remaining actinides as fuel (large-scale reprocessing is being used in a number of countries).

A typical 1000-MWe nuclear reactor produces approximately 20 cubic meters (about 27 tonnes) of spent nuclear fuel each year (but only 3 cubic meters of vitrified volume if reprocessed). All the spent fuel produced to date by all commercial nuclear power plants in the US would cover a football field to the depth of about one meter.

Spent nuclear fuel is initially very highly radioactive and so must be handled with great care and forethought. However, it becomes significantly less radioactive over the course of thousands of years of time. After 40 years, the radiation flux is 99.9% lower than it was the moment the spent fuel was removed from operation, although the spent fuel is still dangerously radioactive at that time. After 10,000 years of radioactive decay, according to United States Environmental Protection Agency standards, the spent nuclear fuel will no longer pose a threat to public health and safety.

When first extracted, spent fuel rods are stored in shielded basins of water (spent fuel pools), usually located on-site. The water provides both cooling for the still-decaying fission products, and shielding from the continuing radioactivity. After a period of time (generally five years for US plants), the now cooler, less radioactive fuel is typically moved to a dry-storage facility or dry cask storage, where the fuel is stored in steel and concrete containers. Most U.S. waste is currently stored at the nuclear site where it is generated, while suitable permanent disposal methods are discussed.

As of 2007, the United States had accumulated more than 50,000 metric tons of spent nuclear fuel from nuclear reactors. Permanent storage underground in U.S. had been proposed at the Yucca Mountain nuclear waste repository, but that project has now been effectively cancelled - the permanent disposal of the U.S.'s high-level waste is an as-yet unresolved political problem.

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

According to a 2007 story broadcast on *60 Minutes*, nuclear power gives France the cleanest air of any industrialized country, and the cheapest electricity in all of Europe. France reprocesses its nuclear waste to reduce its mass and make more energy. However, the article continues, "Today we stock containers of waste because currently scientists don't know how to reduce or eliminate the toxicity, but maybe in 100 years perhaps scientists will... Nuclear waste is an enormously difficult political problem which to date no country has solved. It is, in a sense, the Achilles heel of the nuclear industry... If France is unable to solve this issue, says Mandil, then 'I do not see how we can continue our nuclear program.'" Further, reprocessing itself has its critics, such as the Union of Concerned Scientists.

Low-level radioactive waste

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

Comparing radioactive waste to industrial toxic waste

In countries with nuclear power, radioactive wastes comprise less than 1% of total industrial toxic wastes, much of which remains hazardous indefinitely. Overall, nuclear power produces far less waste material by volume than fossil-fuel based power plants. Coal-burning plants are particularly noted for producing large amounts of toxic and mildly radioactive ash due to concentrating naturally occurring metals and mildly radioactive material from the coal. A recent report from Oak Ridge National Laboratory concludes that coal power actually results in more radioactivity being released into the environment than nuclear power operation, and that the population effective dose equivalent from radiation from coal plants is 100 times as much as from ideal operation of nuclear plants. Indeed, coal ash is much less radioactive than nuclear waste, but ash is released directly into the environment, whereas nuclear plants use shielding to protect the environment from the irradiated reactor vessel, fuel rods, and any radioactive waste on site.

Reprocessing

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

Unlike other countries, the US stopped civilian reprocessing from 1976 to 1981 as one part of US non-proliferation policy, since reprocessed material such as plutonium could be used in nuclear weapons: however, reprocessing is not allowed in the U.S. In the U.S., spent nuclear fuel is currently all treated as waste.

In February, 2006, a new U.S. initiative, the Global Nuclear Energy Partnership was announced. It is an international effort aimed to reprocess fuel in a manner making

nuclear proliferation unfeasible, while making nuclear power available to developing countries.

Depleted uranium

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

Economics

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

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

—The Future of Nuclear Power

Life-extending nuclear power plants beyond their original design lives, by replacing major components and other equipment modernisation, is often economic. Generation II reactors built in the 1960s to 1980s generally had an original design life of 30 to 40 years, and many are being life-extended to 50 or 60 years. In the U.S. every operating nuclear power plant has had a life extension, or is intending to have or apply for an extension, as of 2010. A second life-extension to 80 years may also be economic in many cases.

Accidents and safety

Nine nuclear power plant accidents with more than US\$300 million in property damage, to 2010

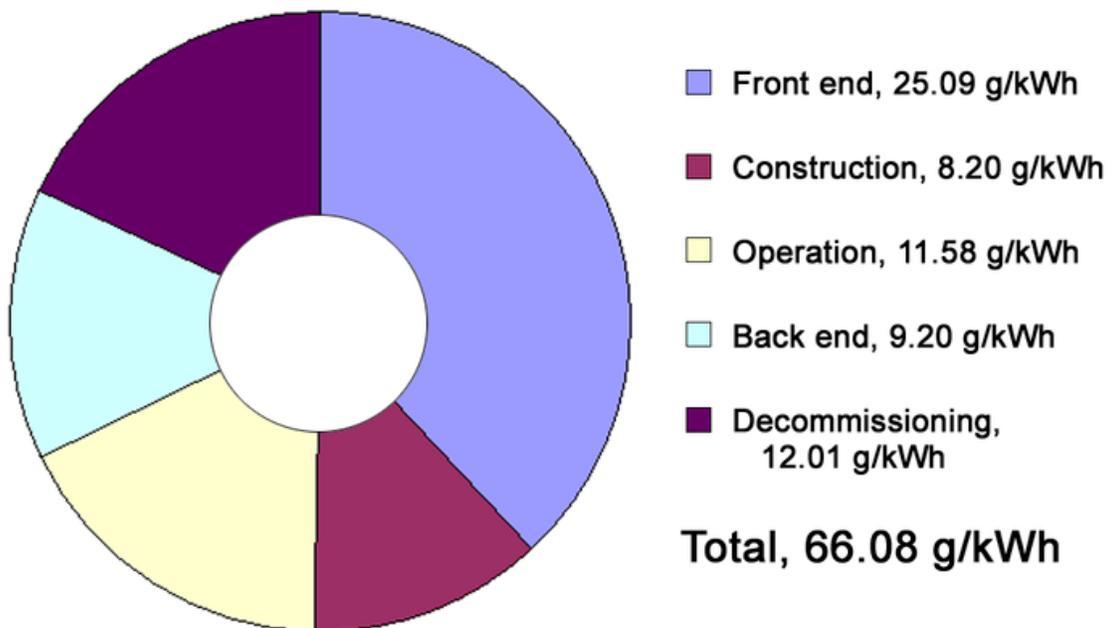
Date	Location	Description	Cost (in millions 2006 \$)
December 7, 1975	Greifswald, East Germany	Electrician's error causes fire in the main trough that destroys control lines and five main	US\$443

		coolant pumps	
February 22, 1977	Jaslovske Bohunice, Czechoslovakia	Severe corrosion of reactor and release of radioactivity into the plant area, necessitating total decommission	US\$1,700
March 28, 1979	Middletown, Pennsylvania, US	Loss of coolant and partial core meltdown	US\$2,400
March 9, 1985	Athens, Alabama, US	Instrumentation systems malfunction during startup, which led to suspension of operations at all three Browns Ferry Units - operations restarted in 1991 for unit 2, in 1995 for unit 3, and (after a \$1.8 billion recommissioning operation) in 2007 for unit 3	US\$1,830
April 11, 1986	Plymouth, Massachusetts, US	Recurring equipment problems force emergency shutdown of Boston Edison's Pilgrim Nuclear Power Plant	US\$1,001
April 26, 1986	Chernobyl, Kiev, Ukraine	Steam explosion and meltdown with 57 deaths necessitating the evacuation of 300,000 people from Kiev and dispersing radioactive material across Europe	US\$6,700
March 31, 1987	Delta, Pennsylvania, US	Peach Bottom units 2 and 3 shutdown due to cooling malfunctions and unexplained equipment problems	US\$400
September 2, 1996	Crystal River, Florida, US	Balance-of-plant equipment malfunction forces shutdown and extensive repairs at Crystal River Unit 3	US\$384
February 1, 2010	Montpelier, Vermont, US	Deteriorating underground pipes from the Vermont Yankee Nuclear Power Plant leak radioactive tritium into groundwater supplies	US\$10

Environmental effects of nuclear power

Carbon emissions from nuclear power

Sovacool life cycle study survey, 2008



Mean value of carbon dioxide emissions from qualified life cycle studies among 103 surveyed. Includes results of 1997 Vattenfall study.

A 2008 synthesis of 103 studies, published by Benjamin K. Sovacool, determined that the value of CO₂ emissions for nuclear power over the lifecycle of a plant was 66.08 g/kWh, based on the mean value of all the 103 studies. Comparative results for wind power, hydroelectricity, solar thermal power, and solar photovoltaic were 9-10 g/kWh, 10-13 g/kWh, 13 g/kWh and 32 g/kWh respectively.

Comparisons of life-cycle greenhouse gas emissions

Comparisons of life cycle analysis (LCA) of carbon dioxide emissions show nuclear power as comparable to renewable energy sources. A conclusion that is disputed by others studies.

Debate on nuclear power

The nuclear power debate is about the controversy which has surrounded the deployment and use of nuclear fission reactors to generate electricity from nuclear fuel for civilian

purposes. The debate about nuclear power peaked during the 1970s and 1980s, when it "reached an intensity unprecedented in the history of technology controversies", in some countries.

Proponents of nuclear energy contend that nuclear power is a sustainable energy source that reduces carbon emissions and increases energy security by decreasing dependence on foreign oil. Proponents claim that nuclear power produces virtually no conventional air pollution, such as greenhouse gases and smog, in contrast to the chief viable alternative of fossil fuel. Proponents also believe that nuclear power is the only viable course to achieve energy independence for most Western countries. Proponents claim that the risks of storing waste are small and can be further reduced by using the latest technology in newer reactors, and the operational safety record in the Western world is excellent when compared to the other major kinds of power plants.

Opponents believe that nuclear power poses many threats to people and the environment. These threats include the problems of processing, transport and storage of radioactive nuclear waste, the risk of nuclear weapons proliferation and terrorism, as well as health risks and environmental damage from uranium mining. They also contend that reactors themselves are enormously complex machines where many things can and do go wrong, and there have been serious nuclear accidents. Critics do not believe that the risks of using nuclear fission as a power source can be offset through the development of new technology. They also argue that when all the energy-intensive stages of the nuclear fuel chain are considered, from uranium mining to nuclear decommissioning, nuclear power is not a low-carbon electricity source.

Arguments of economics and safety are used by both sides of the debate.

Nuclear power organizations

Against

- Friends of the Earth International, a network of environmental organizations in 77 countries.
- Greenpeace International, a non-governmental environmental organization with offices in 41 countries.
- Nuclear Information and Resource Service (International)
- Sortir du nucléaire (Canada)
- Sortir du nucléaire (France)
- Pembina Institute (Canada)
- Institute for Energy and Environmental Research (United States)

Supportive

- World Nuclear Association, a confederation of companies connected with nuclear power production. (International)
- International Atomic Energy Agency (IAEA)

- Nuclear Energy Institute (United States)
- American Nuclear Society (United States)
- United Kingdom Atomic Energy Authority (United Kingdom)
- EURATOM (Europe)
- Atomic Energy of Canada Limited (Canada)
- Environmentalists for Nuclear Energy (International)

Future of the industry



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

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

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

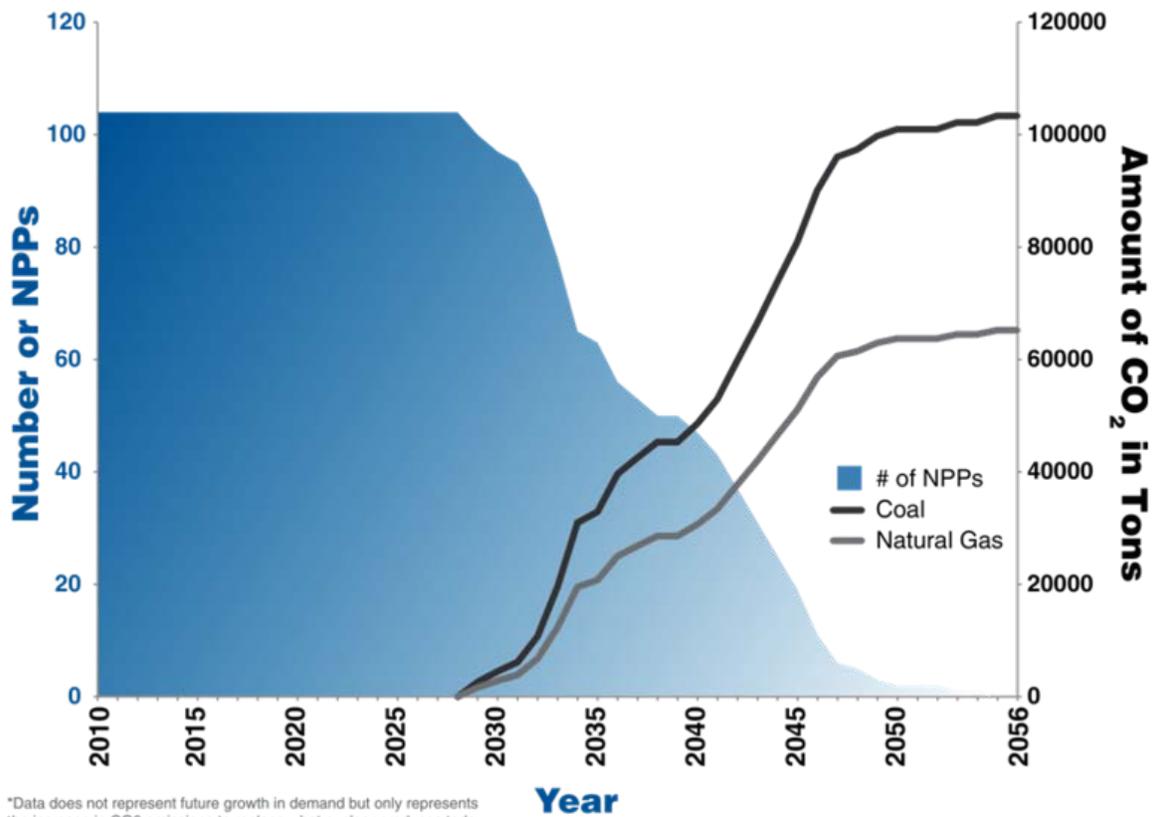


Brunswick Nuclear Plant discharge canal

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

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

Impact of NPP Retirement on Carbon Emissions



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

China plans to build more than 100 plants, while in the US the licenses of almost half its reactors have already been extended to 60 years, and plans to build more than 30 new ones are under consideration. China may achieve its long-term plan of having 40,000 megawatts of nuclear power capacity four to five years ahead of schedule. Further, the U.S. NRC and the U.S. Department of Energy have initiated research into Light water reactor sustainability which is hoped will lead to allowing extensions of reactor licenses beyond 60 years, in increments of 20 years, provided that safety can be maintained, as the

loss in non-CO₂-emitting generation capacity by retiring reactors "may serve to challenge U.S. energy security, potentially resulting in increased greenhouse gas emissions, and contributing to an imbalance between electric supply and demand." In 2008, the International Atomic Energy Agency (IAEA) predicted that nuclear power capacity could double by 2030, though that would not be enough to increase nuclear's share of electricity generation.