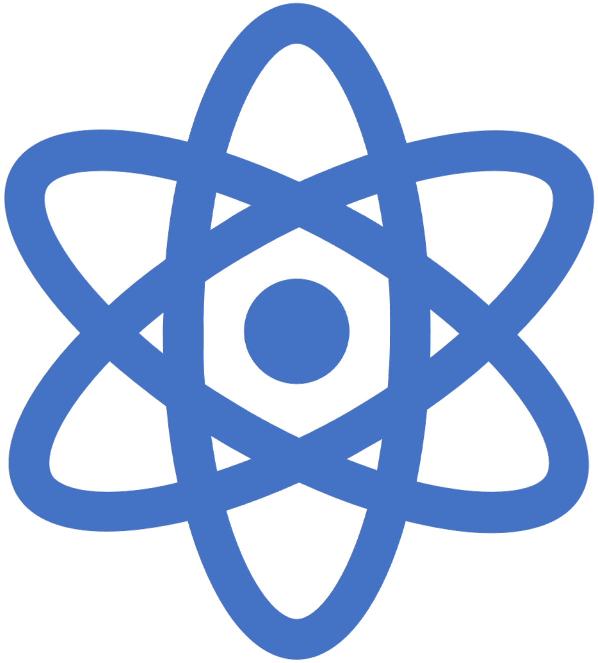
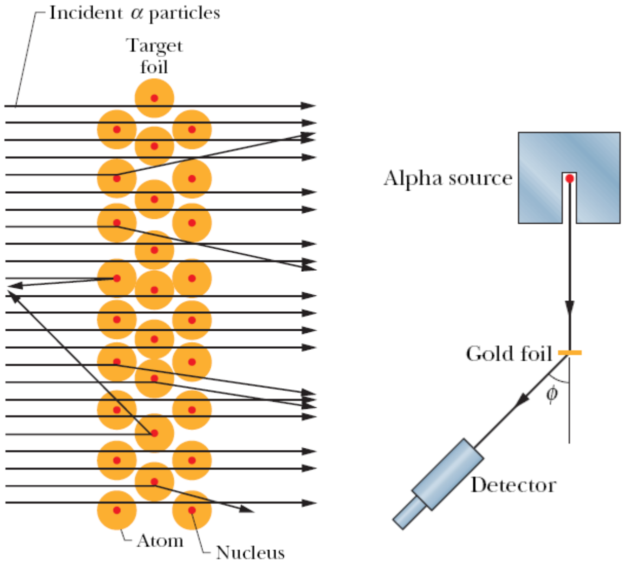
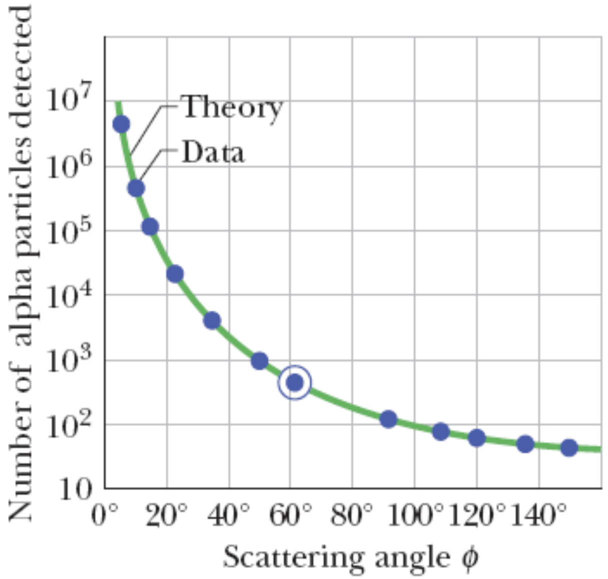
Nuclear Energy



Discovery of the Nucleus

In 1911 Ernest Rutherford proposed that the positive charge of the atom is densely concentrated at the center of the atom, forming its **nucleus,** and that, furthermore, the nucleus is responsible for most of the mass of the atom.

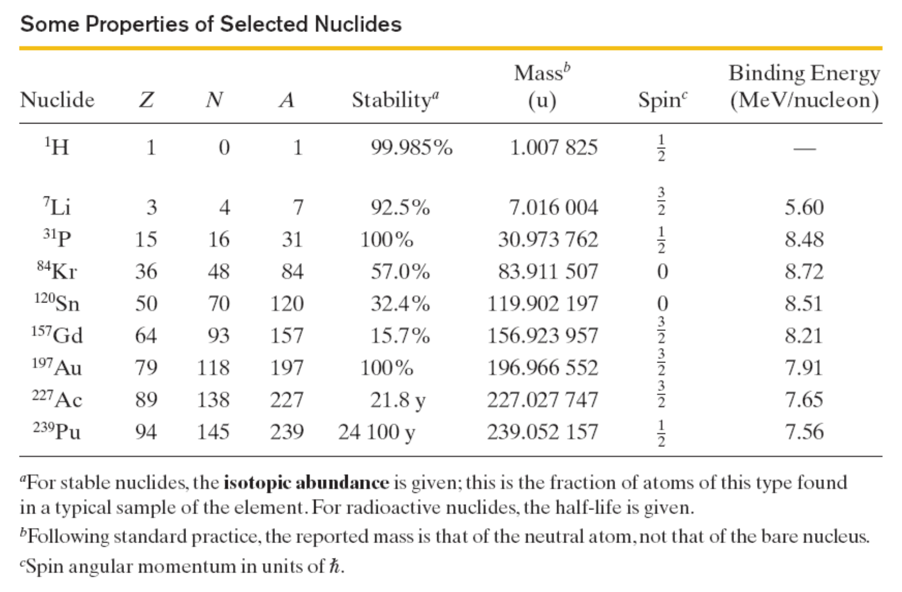




Some Nuclear Properties

Nuclei are made up of protons and neutrons. The number of protons in a nucleus is called the **atomic number of the nucleus**, and is represented by the symbol ***Z**;* the number of neutrons is the **neutron number**, and is represented by the symbol ***N**.*

The total number of neutrons and protons in a nucleus is called its **mass number *A*.** Neutrons and protons, when considered collectively, are called **nucleons.**



Some Properties of Selected Nuclides

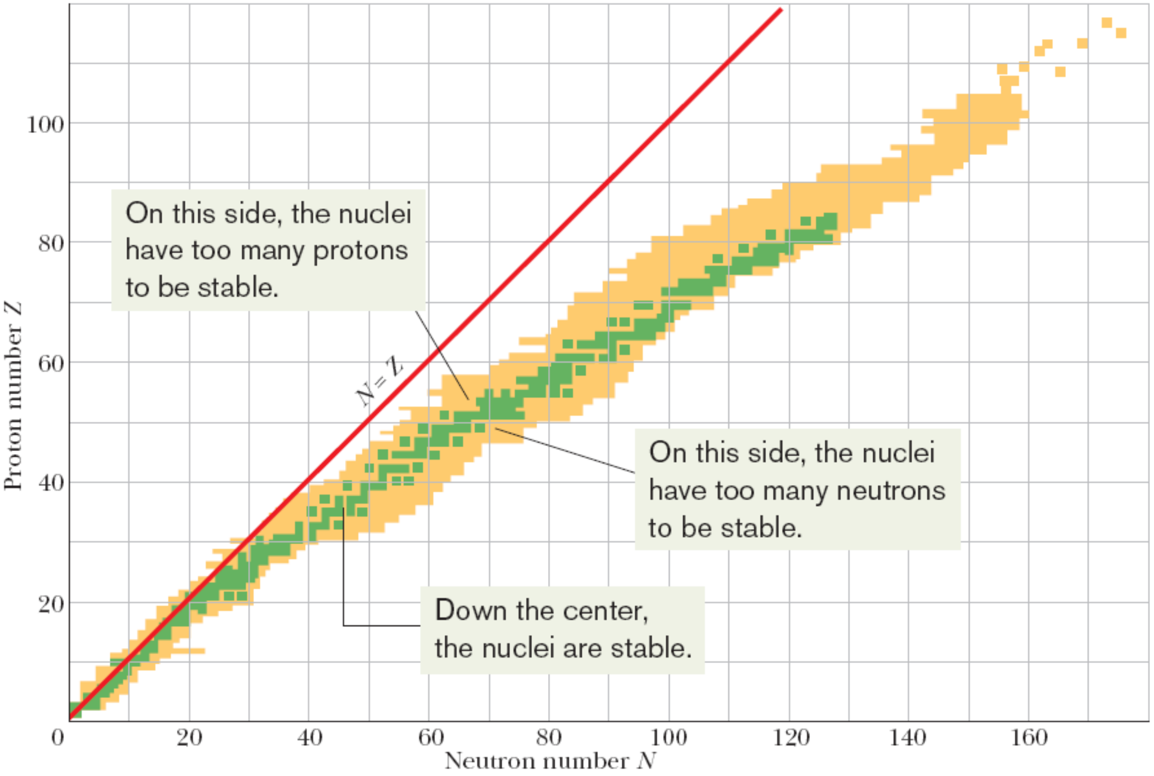
Nuclide	Z	N	A	Stability[a]	Mass[b] (u)	Spin[c]	Binding Energy (MeV/nucleon)
^{1}H	1	0	1	99.985%	1.007 825	$\frac{1}{2}$	—
^{7}Li	3	4	7	92.5%	7.016 004	$\frac{3}{2}$	5.60
^{31}P	15	16	31	100%	30.973 762	$\frac{1}{2}$	8.48
^{84}Kr	36	48	84	57.0%	83.911 507	0	8.72
^{120}Sn	50	70	120	32.4%	119.902 197	0	8.51
^{157}Gd	64	93	157	15.7%	156.923 957	$\frac{3}{2}$	8.21
^{197}Au	79	118	197	100%	196.966 552	$\frac{3}{2}$	7.91
^{227}Ac	89	138	227	21.8 y	227.027 747	$\frac{3}{2}$	7.65
^{239}Pu	94	145	239	24 100 y	239.052 157	$\frac{1}{2}$	7.56

[a] For stable nuclides, the **isotopic abundance** is given; this is the fraction of atoms of this type found in a typical sample of the element. For radioactive nuclides, the half-life is given.

[b] Following standard practice, the reported mass is that of the neutral atom, not that of the bare nucleus.

[c] Spin angular momentum in units of $\hbar$.

Some Nuclear Properties



On this side, the nuclei have too many protons to be stable.

On this side, the nuclei have too many neutrons to be stable.

Down the center, the nuclei are stable.

Some Nuclear Properties

- The nucleus, like the atom, is not a solid object with a well-defined surface.
- Although most nuclides are spherical, some are notably ellipsoidal.
- Electron-scattering experiments (as well as experiments of other kinds) allow us to assign to each nuclide an effective radius given by the equation to the right, where *A* is the mass number and $r_0 = 1.2$ *fm.*

$$r = r_0 A^{1/3},$$

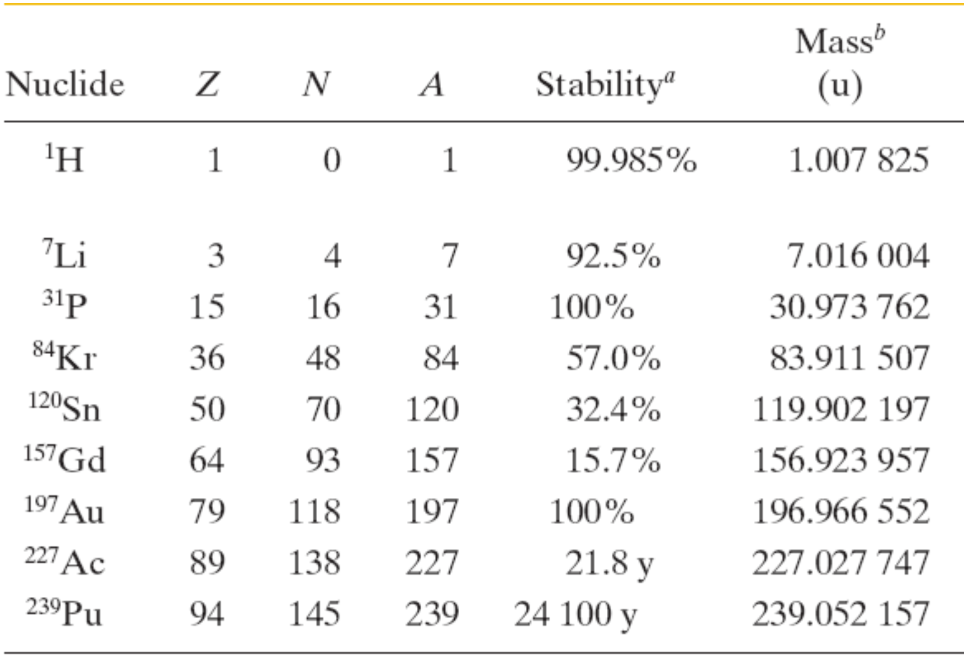
Some Nuclear Properties

- Atomic masses are often reported in *atomic mass units,* a system in which the atomic mass of neutral ^{12}C is defined to be exactly 12 u, where 1 u =1.660 538 86 × 10^{-27} kg.
- The mass number A of a nuclide gives such an approximate mass in atomic mass units. For example, the approximate mass of both the nucleus and the neutral atom for ^{197}Au is 197 u, which is close to the actual atomic mass of 196.966 552 u.
- If the total mass of the participants in a nuclear reaction changes by an amount Δm, there is an energy release or absorption given by $Q=mc^2$.
- The atom's *mass excess,* Δ, is defined by the equation on the right.
- Here, M is the actual mass of the atom in atomic units, and A is the mass number for that atom's nucleus.

$$\Delta = M - A$$

Example Problem

Using the table below determine the effective radius and mass excess for hydrogen (H), krypton (Kr), and silver (Au).



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Example Problem

Using the table below determine the effective radius and mass excess for hydrogen (H), krypton (Kr), and silver (Au).

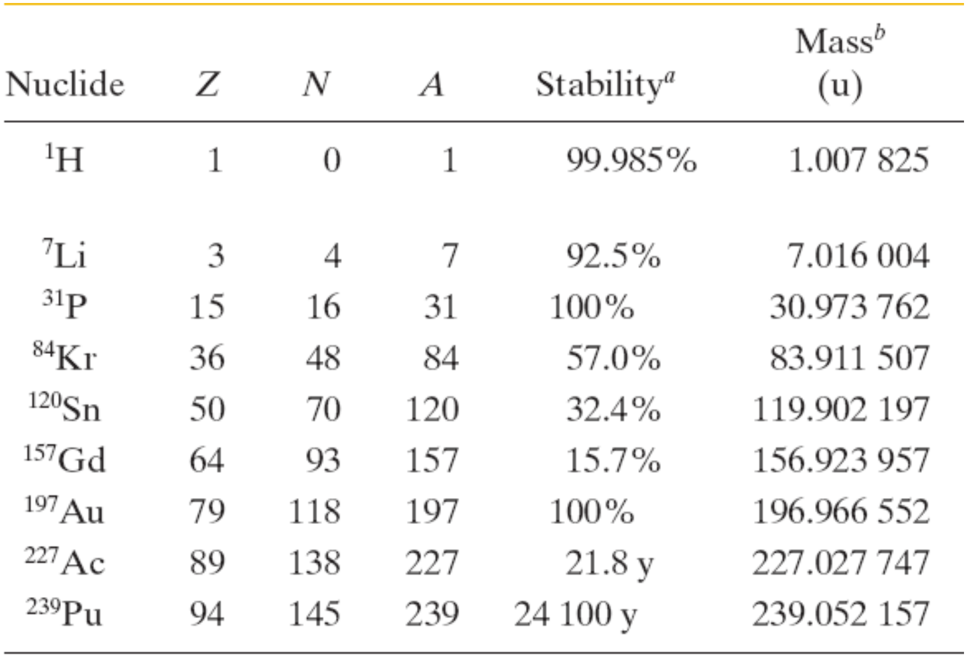
Remember that

$$r = r_0 A^{1/3}, \qquad \Delta = M - A$$

For hydrogen:

r = $(1.2 \times 10^{-15})*(1)^{1/3} = 1.2 \times 10^{-15}$

$\Delta = 1.007825 - 1 = 0.007825$



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Example Problem

Using the table below determine the effective radius and mass excess for hydrogen (H), krypton (Kr), and gold (Au).

Remember that

$$r = r_0 A^{1/3}, \qquad \Delta = M - A$$

For hydrogen:

$r = (1.2 \times 10^{-15}) * (1)^{1/3} = 1.2 \times 10^{-15}$

$\Delta = 1.007825 - 1 = 0.007825$

For krypton:

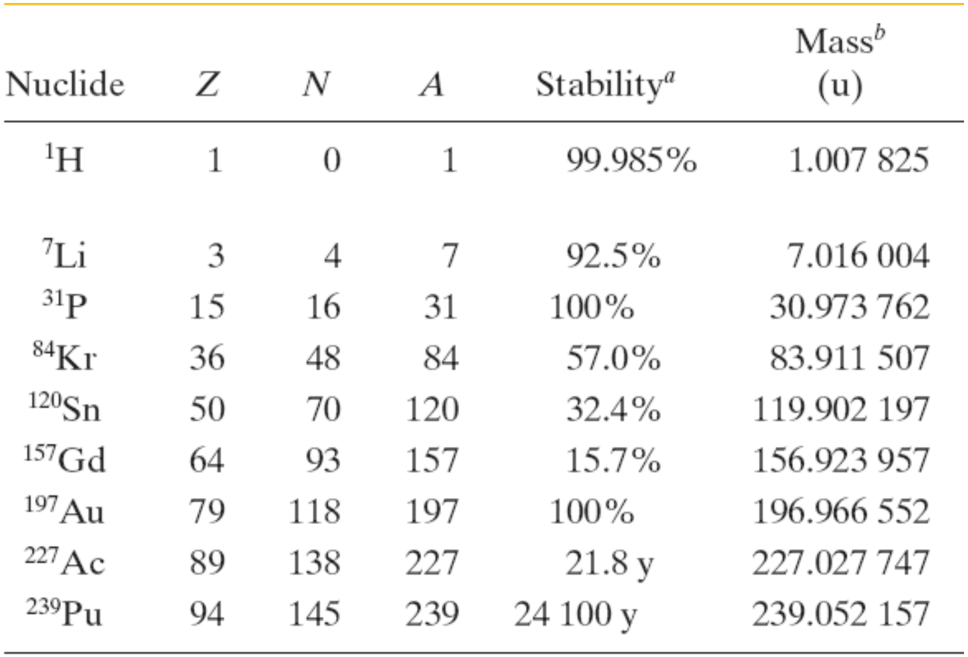
$r = (1.2 \times 10^{-15}) * (84)^{1/3} = 5.26 \times 10^{-15}$

$\Delta = 83.911507 - 84 = -0.088493$

For gold:

$r = (1.2 \times 10^{-15}) * (197)^{1/3} = 6.98 \times 10^{-15}$

$\Delta = 196.966552 - 197 = -0.033448$



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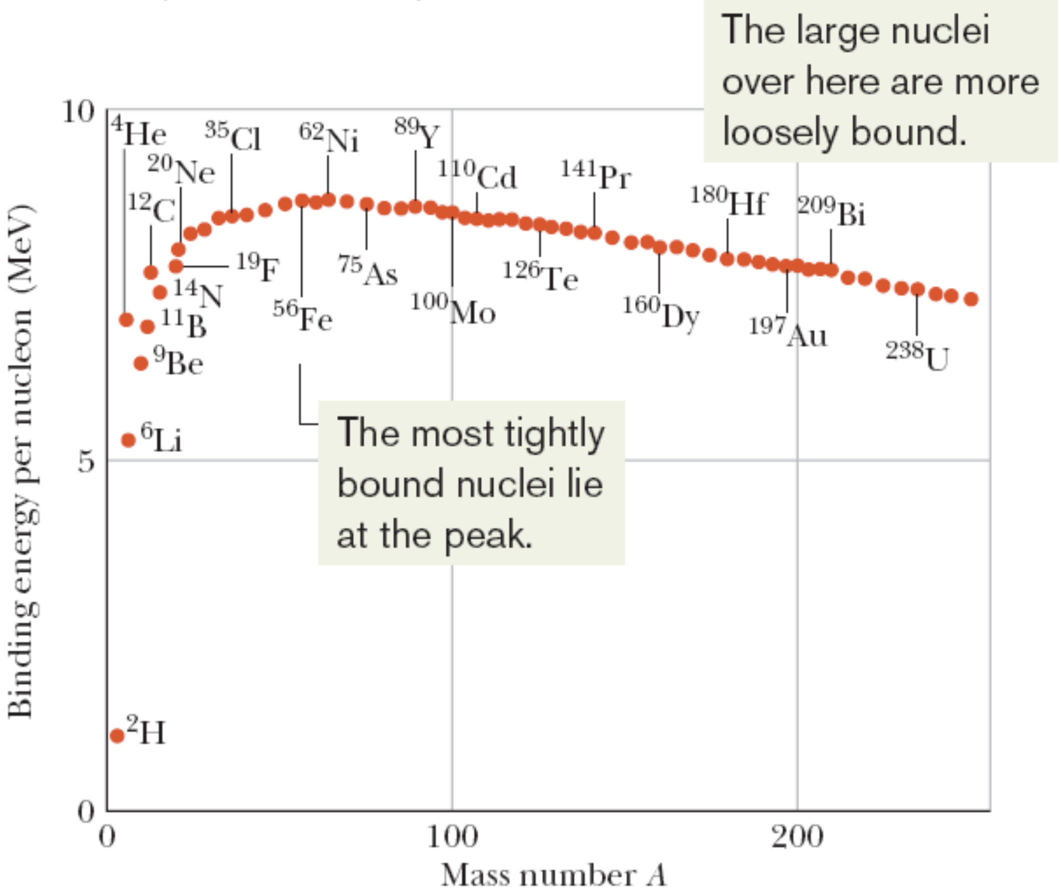
Nuclear Binding Energy

$$\Delta E_{\mathrm{be}} = \Sigma(mc^2) - Mc^2 \qquad \text{(binding energy).}$$

If the nucleus splits into two nuclei, the process is called ***fission***, and occurs naturally with large high mass number nuclei.

If a pair of nuclei were to combine to form a single nucleus, the process is called ***fusion***, and occurs naturally in stars.



The large nuclei over here are more loosely bound.

The most tightly bound nuclei lie at the peak.

Radioactive Decay

> There is absolutely no way to predict whether any given nucleus in a radioactive sample will be among the small number of nuclei that decay during the next second. All have the same chance.

The decay rate is defined as,

$$R = R_0 e^{-\lambda t} \qquad \text{(radioactive decay),}$$

The half life-time ($T_{1/2}$) is the time at which both N and R have been reduced to one-half their initial values and λ is the decay energy.

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

Here τ is the ***mean life-time,*** which is the time at which both N and R have been reduced to e^{-1} of their initial values.

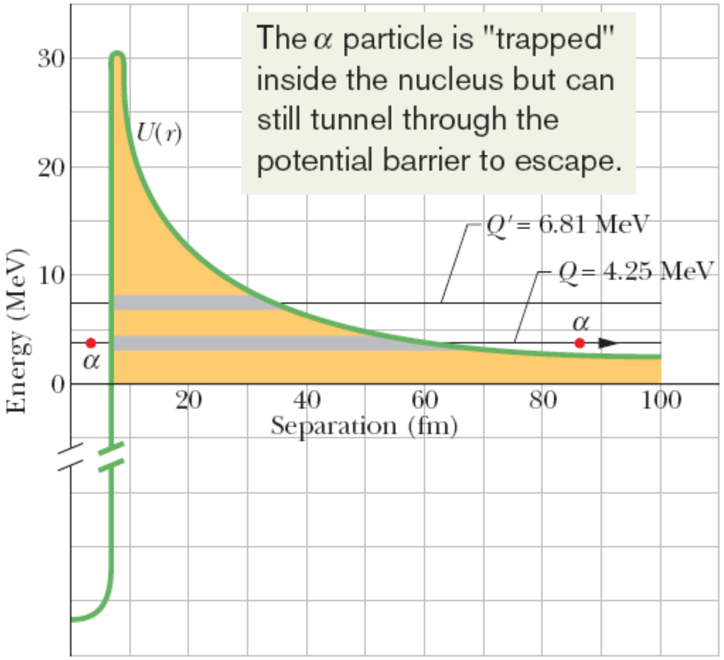
Alpha Decay

When a nucleus undergoes **alpha decay,** it transforms to a different nuclide by emitting an alpha particle (a helium nucleus, ^{4}He). For example, when uranium ^{238}U undergoes alpha decay, it transforms to thorium ^{234}Th:

$$^{238}\mathrm{U} \rightarrow {}^{234}\mathrm{Th} + {}^{4}\mathrm{He}.$$

The ***disintegration energy,*** *Q,* for the decay above is 4.25.

The potential energy shown in the figure below is a combination of the potential energy associated with the (attractive) strong nuclear force that acts in the nuclear interior and a Coulomb potential associated with the (repulsive) electric force that acts between the two particles (^{234}Th and ^{4}He) before and after the decay has occurred.



Beta Decay

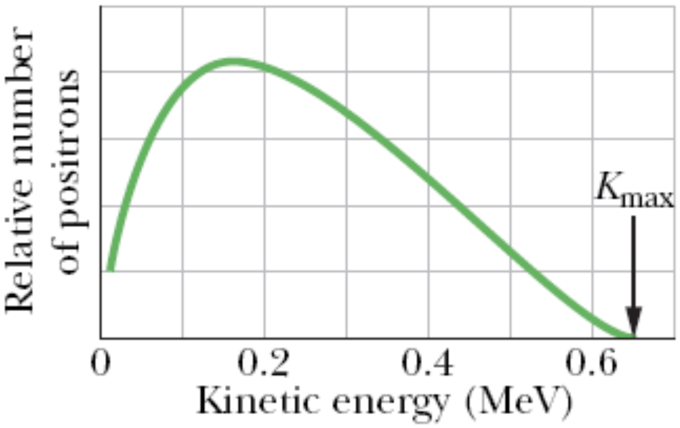
A nucleus that decays spontaneously by emitting an electron or a positron (a positively charged particle with the mass of an electron) is said to undergo **beta decay.** Like alpha decay, this is a spontaneous process, with a definite disintegration energy and half-life.

Examples: $^{32}\mathrm{P} \rightarrow {}^{32}\mathrm{S} + \mathrm{e}^{-} + \nu \qquad (T_{1/2} = 14.3\ \mathrm{d}).$ (b^{-} decay)

$^{64}\mathrm{Cu} \rightarrow {}^{64}\mathrm{Ni} + \mathrm{e}^{+} + \nu \qquad (T_{1/2} = 12.7\ \mathrm{h}).$ (b^{+} decay)

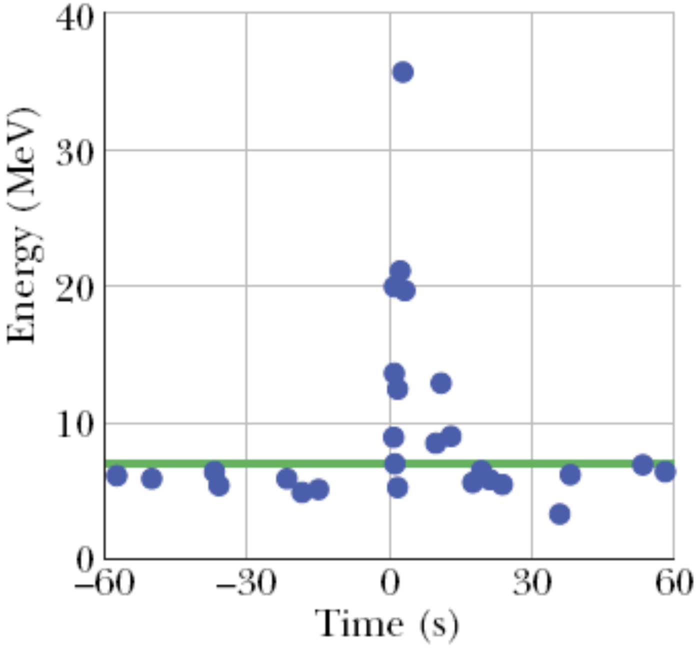
Here, n is a neutrino, a neutral particle which has a very small mass, that is emitted from the nucleus along with the electron or positron during the decay process.

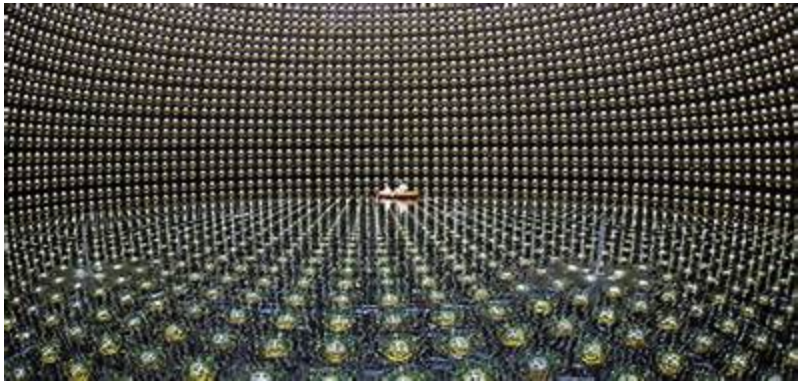
In a beta decay the energy of the emitted electrons or positrons may range from zero up to a certain maximum K_{max}, since, unlike the alpha decay, the Q energy is shared by two components.



Beta Decay and the Neutrino

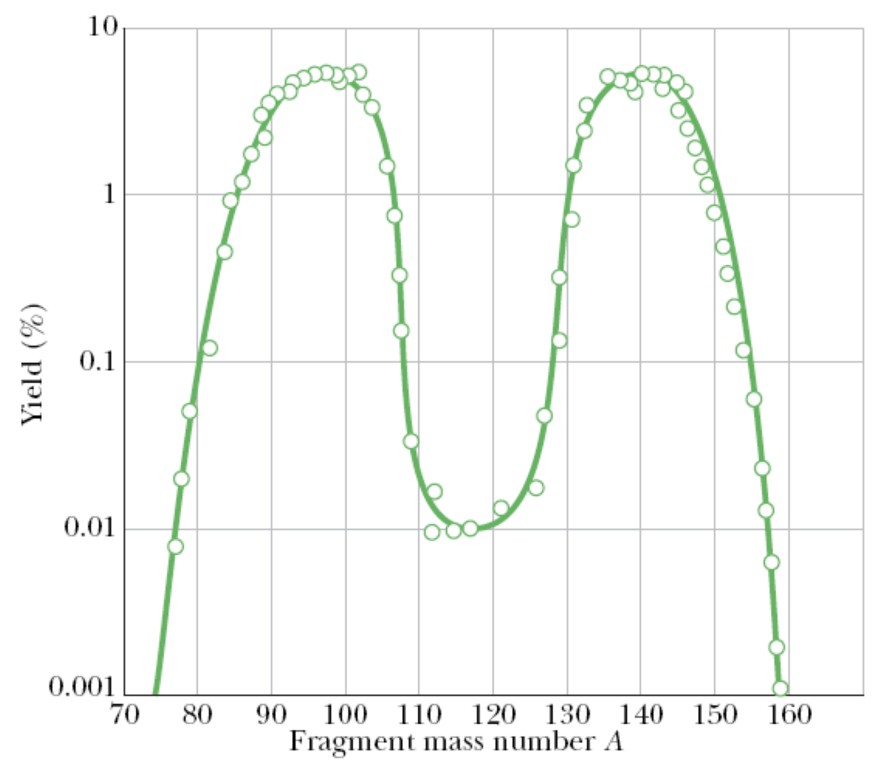
- Wolfgang Pauli first suggested the existence of neutrinos in 1930.
- Billions of them pass through our bodies every second, leaving no trace.
- Despite their elusive character, neutrinos have been detected in the laboratory.





Nuclear Fission

The most probable mass numbers, occurring in about 7% of the fission events, are centered around *A* ~95 and *A*~140.



Nuclear Fission

The energy released by the fission, *Q,* is: $Q = \begin{pmatrix}\text{total final}\\ \text{binding energy}\end{pmatrix} - \begin{pmatrix}\text{initial}\\ \text{binding energy}\end{pmatrix}.$

$$Q = \begin{pmatrix}\text{final}\\ \Delta E_{\text{ben}}\end{pmatrix}\begin{pmatrix}\text{final number}\\ \text{of nucleons}\end{pmatrix} - \begin{pmatrix}\text{initial}\\ \Delta E_{\text{ben}}\end{pmatrix}\begin{pmatrix}\text{initial number}\\ \text{of nucleons}\end{pmatrix}.$$

For a high-mass nuclide (*A ~240),* the binding energy per nucleon is about 7.6 MeV/nucleon. For middle-mass nuclides (*A~120),* it is about 8.5 MeV/nucleon. Thus, the energy released by fission of a high-mass nuclide to two middle-mass nuclides is

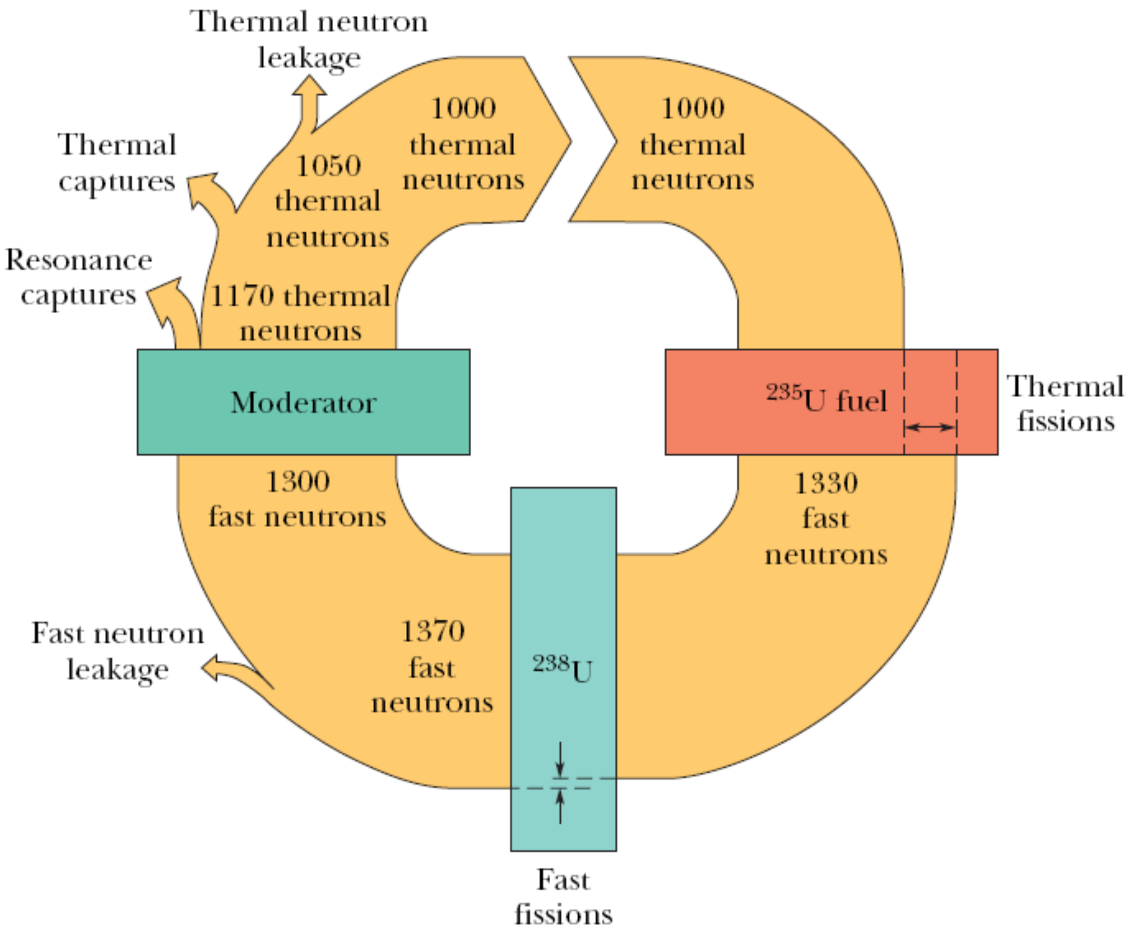
$$Q = \left(8.5\,\frac{\text{MeV}}{\text{nucleon}}\right)(2\text{ nuclei})\left(120\,\frac{\text{nucleons}}{\text{nucleus}}\right) - \left(7.6\,\frac{\text{MeV}}{\text{nucleon}}\right)(240\text{ nucleons}) \approx 200\text{ MeV}.$$

Test of the Fissionability of Four Nuclides

Target Nuclide	Nuclide Being Fissioned	E_n (MeV)	E_b (MeV)	Fission by Thermal Neutrons?
^{235}U	^{236}U	6.5	5.2	Yes
^{238}U	^{239}U	4.8	5.7	No
^{239}Pu	^{240}Pu	6.4	4.8	Yes
^{243}Am	^{244}Am	5.5	5.8	No

Courtesy U.S. Department of Energy

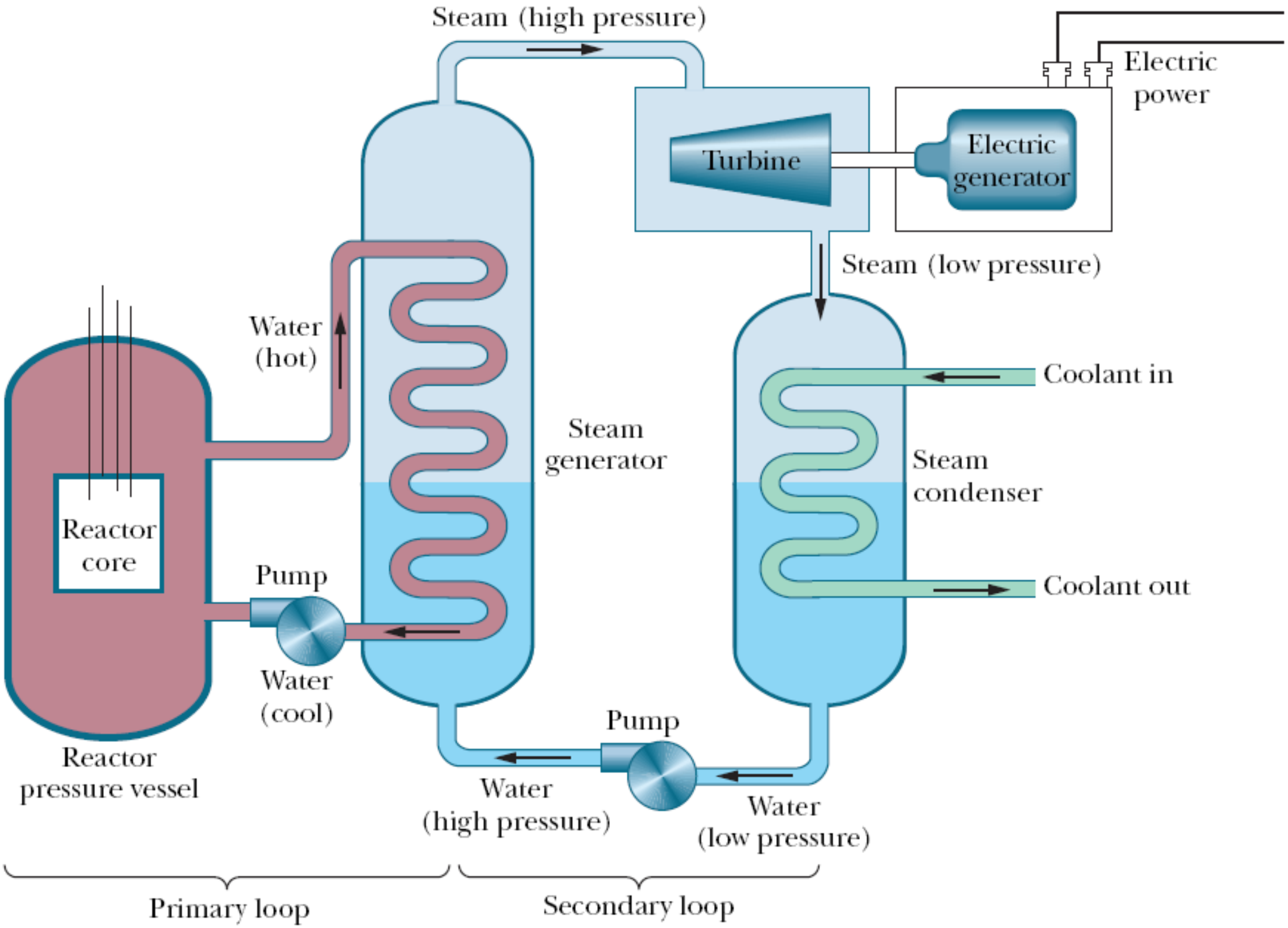
Nuclear Reactors



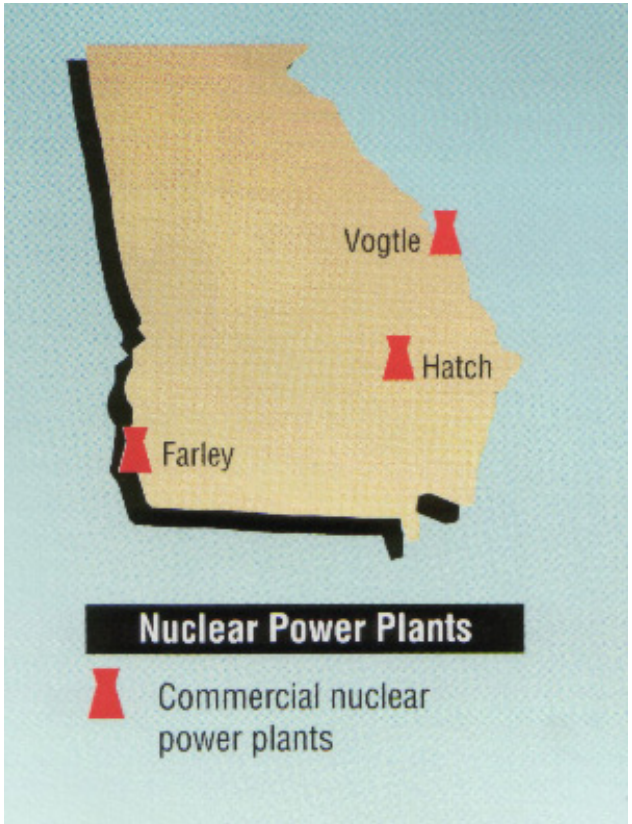
Three main difficulties stand in the way of a working reactor:

1. The Neutron Leakage Problem: Some neutrons produced by fission leak out from the reactor.
2. The Neutron Energy Problem: Fast neutrons are not as effective in producing fission as slower thermal neutrons.
3. The Neutron Capture Problem: Non-fission capture of neutrons

Nuclear Reactors



Nuclear Reactors



Nuclear Fusion

For controlled terrestrial use one could consider two deuteron–deuteron (d-d), and one deuteron-tritium reactions:

$$^{2}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \mathrm{n} \qquad (Q = +3.27\,\mathrm{MeV}),$$

$$^{2}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + {}^{1}\mathrm{H} \qquad (Q = +4.03\,\mathrm{MeV}),$$

$$^{2}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} \qquad (Q = +17.59\,\mathrm{MeV}).$$

Three requirements for a successful thermonuclear reactor can be considered:

1. High Particle Density
2. High Plasma Temperature
3. Long Confinement Time

For the successful operation of a thermonuclear reactor using the d-t reaction, it is necessary to have Lawson's Criterion:

$$n\tau > 10^{20}\ \mathrm{s/m^3}.$$

Nuclear Fusion

1. **Magnetic Confinement**
    1. A suitably shaped magnetic field is used to confine the hot plasma in an evacuated doughnut-shaped chamber called a ***tokomak***. The magnetic forces acting on the charged particles that make up the hot plasma keep the plasma from touching the walls of the chamber.
    2. The plasma is heated by inducing a current in it and by bombarding it with an externally accelerated beam of particles. The first goal of this approach is to achieve ***breakeven***, which occurs when the Lawson criterion is met or exceeded.
    3. The ultimate goal is ***ignition*,** which corresponds to a self-sustaining thermonuclear reaction and a net generation of energy.

2. **Inertial Confinement**
    1. A second approach, involves ***"zapping"*** a solid fuel pellet from all sides with intense laser beams, evaporating some material from the surface of the pellet. This boiled-off material causes an inward-moving shock wave that compresses the core of the pellet, increasing both its particle density and its temperature. The fuel is ***confined*** to the pellet and the particles do not escape from the heated pellet during the very short zapping interval because of their inertia .
    2. Laser fusion, using the inertial confinement approach, is being investigated in many laboratories in the United States and elsewhere.

Tokomaks