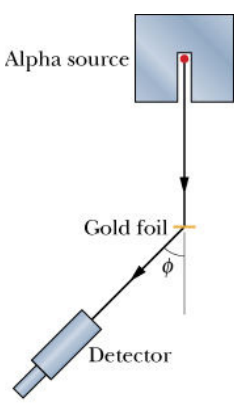
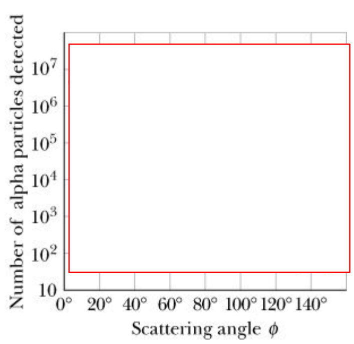
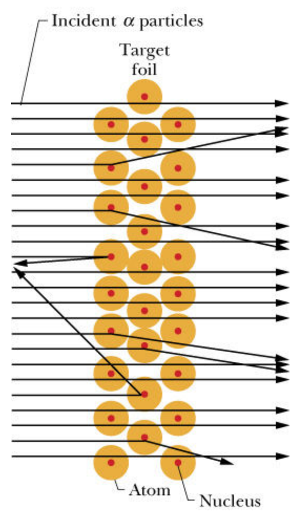
Nuclear Physics

For the last 90 years, a principal goal of physics has been to work out the quantum physics of nuclei themselves. In that same period, new applications ranging from radiation therapy in cancer treatment to detecting radon gas in basements have been developed.

Discovering the Nucleus







Rutherford, Geiger, Marsden experiments 1911-1913
→nucleus is small in size, dense, and positively charged.
Not plum pudding (evenly distributed)!

Some Nuclear Terminology

Atomic number or **proton number**: Z

Number of neutrons or **neutron number**: N

Total number of neutrons and protons, **mass number**: A

$$A =$$

Protons and neutrons are called **nucleons**.

$$^{197}\text{Au:}\ \ A = 197,\ \ \text{Au} \rightarrow Z = 79,\ N =$$

Nuclides with same Z but different A are called **isotopes,** e.g., ^{173}Au to ^{204}Au.

Radionuclides decay (or **disintegrate**) by emitting a particle, thereby transforming into a different nuclide.

Some Nuclear Properties

Some Properties of Selected Nuclides

Nuclide	Z	N	A	Stability	Mass (u)	Spin	Binding Energy (MeV/nucleon)
^{1}H	1	0	1	99.985%	1.007 825	1/2	—
^{7}Li	3	4	7	92.5%	7.016 004	1/2	5.60
^{31}P	15	16	31	100%	30.973 762	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	3/2	8.21
^{197}Au	79	118	197	100%	196.966 552	3/2	7.91
^{227}Ac	89	138	227	21.8 y	227.027 747	3/2	7.65
^{239}Pu	94	145	239	24 100 y	239.052 157	1/2	7.56

Q. What is the primary difference between ^{13}C and ^{12}C?

a) The number of electrons is different.

b) The number of protons is different.

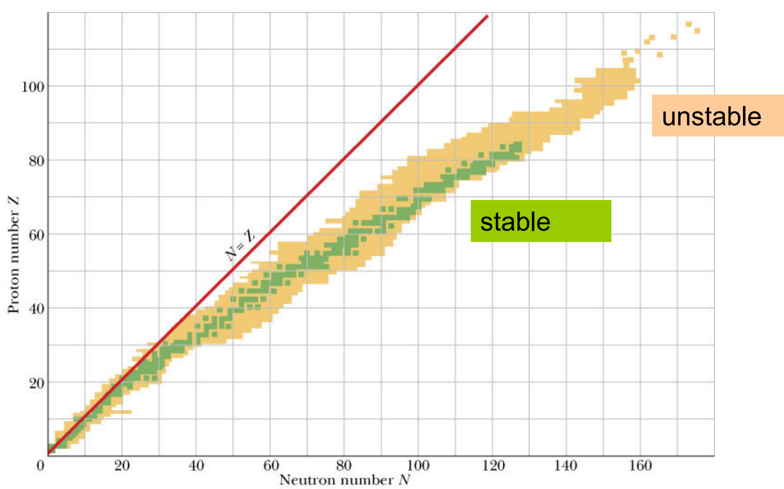
c) The number of neutrons is different.

d) The chemical behavior is different.

e) Only ^{12}C is true carbon. The other is called carbomite.

Organizing the Nuclides

Nuclidic Chart



Nuclear Radii

$$1 \text{ femtometer} = 1 \text{ fermi} = 1 \text{ fm} = 10^{-15} \text{ m}$$

$$r = $$

$$r_0 \approx 1.2 \text{ fm}$$

does not apply to halo nuclides, neutron-rich nuclides in which some neutrons form a large halo around a spherical core of protons.

For example, ^{8}Li+n→ ^{9}Li, r increases 4%,
but when ^{9}Li+2n→ ^{11}Li (halo nuclide), r increases 30%.

Atomic Masses

$$1 \text{ u} = 1.66053873 \times 10^{-27} \text{ kg}$$

The actual mass of a nucleus is not simply the sum of the masses of all its constituent nucleons. Energy (Q = , which is equivalent to mass) can be released or absorbed in nuclear reaction forming the nucleus.

$$c^2 = 931.494013 \text{ MeV/u}$$

$$\Delta = \qquad \text{(excess mass)}$$

M is the actual mass of the atom in atomic mass units and A is the mass number for the nucleus.

Nuclear Binding Energies

The mass M of the nucleus is less than the total mass of its individual nucleons Σm → nucleus has less energy Mc^2 than all the separated nucleons $\Sigma(mc^2)$ → this energy difference (**binding energy**) favors the nucleons binding into a nucleus.

$$\Delta E_{\text{be}} = \sum \boxed{} \qquad \text{(binding energy)}$$

If we could tear apart a nucleus into its separate nucleons, the work required would be ΔE_{be}.

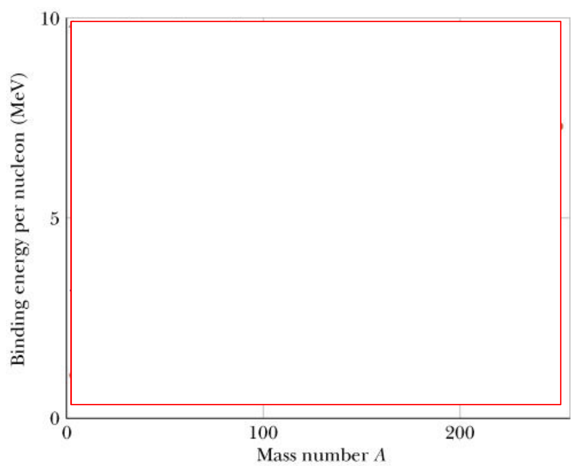
Binding energy per nucleon

$$\Delta E_{\text{ben}} = \boxed{\phantom{\frac{\Delta E}{A}}} \qquad \text{(binding energy per nucleon)}$$

ΔE_{ben} represents the average energy holding each nucleon into the nucleus.

Nuclear Binding Energies

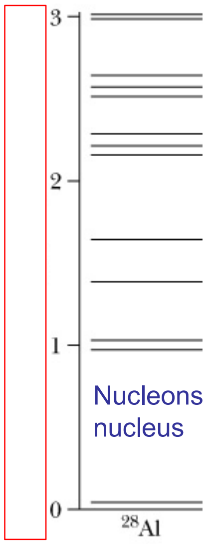
If weakly bound nuclei transform into more strongly bound nuclei, the total mass can be reduced and the mass energy of the final state is lower than the mass energy of the initial state. Where does the excess initial mass energy go?



Fission: A nucleus with a larger mass (U, Pu) splits into nuclei with smaller total mass (larger binding energy). Energy is released, e.g., nuclear reactor, nuclear weapons.

Fusion: Two nuclei combine to form a single more tightly bound nucleus, e.g., H+H →He hydrogen bomb and the Sun.

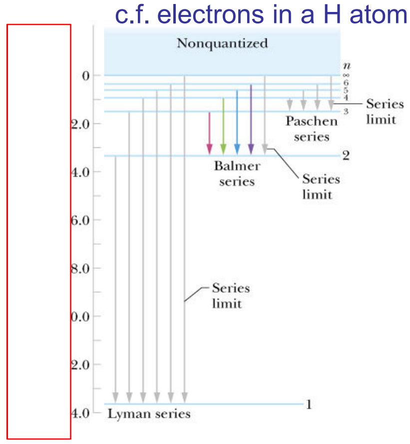
Nuclear Energy Levels



Energy levels of nucleons confined in a nucleus are quantized just as for electrons confined in an atom. Do you notice a major quantitative difference?

Nucleons in an ^{28}Al nucleus

c.f. electrons in a H atom



Nuclear Spin and Magnetism

Many nuclides have an intrinsic *nuclear magnetic moment*, which leads to intrinsic *nuclear angular momentum* or spin. While nuclear angular momentum is similar in magnitude to angular momenta of atomic electrons, nuclear magnetic moments are much smaller than typical atomic magnetic moments.

The Nuclear Force

Attractive, short-range binds quarks together to form protons and neutrons. This force "spills over" to bind nucleons in nuclei, overcoming the repulsive Coulomb force between protons.

Radioactive Decay

Most known nuclides are unstable/radioactive.

Nuclear decay rate dN/dt is proportional to the number N of nuclei that can decay

$$\frac{N}{N_0} = e^{-\lambda t}$$

$$N = N_0 e^{-\lambda t} \qquad \text{(radioactive decay)}$$

Radioactive Decay, cont'd

Radioactive decay rate $R = - dN/dt$:

$$R = -\frac{dN}{dt} =$$

$$R = \qquad \text{(radioactive decay)}$$

$$R = \lambda N$$

The total decay rate of one or more nuclides is called the **activity**, with SI units **becquerel:**

$$1 \text{ becquerel} = 1 \text{ Bq} \; = 1 \text{ decay per second}$$

An older unit for activity, the **curie**, is still commonly used:

$$1 \text{ curie} = 1 \text{ Ci} \; = 3.7 \times 10^{10} \text{ Bq}$$

Radioactive Decay, cont'd

Two common time measures of how long any given type of radionuclides lasts are half life and mean life.

Half-life $T_{½}$ (1/2 of starting nuclides have decayed) and an exponential life τ (1/e of starting nuclides have decayed, sometimes called the mean life):

$$R\left(T_{1/2}\right) = \tfrac{1}{2} R_0 = R_0 e^{-\lambda T_{1/2}} \Rightarrow T_{1/2} = \boxed{}$$

$$R\left(\tau\right) = \frac{1}{e} R_0 = R_0 e^{-\lambda \tau} \Rightarrow \tau = \boxed{}$$

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

Q. What portion of a radioactive sample remains after two half-lives have passed?

a) None is left.

b) All remains.

c) one quarter

d) one half

e) three quarters

Q. An isotope of cesium has a half-life of two years. If we had 100 grams of this isotope today, how much would we have left ten years from now?

a) about three grams

b) about six grams

c) about twelve grams

d) about twenty-five grams

e) about fifty grams

Q. In 1986, a nuclear accident occurred at Chernobyl in the former Soviet Union. During the accident, a radioactive isotope of iodine was released into the surrounding region that undergoes beta decay with a half-life of 8.040 days. How long did it take for the radioactivity from this iodine to be reduced to one percent of its initial value?

a) 64 days

b) 53 days

c) 48 days

d) 44 days

e) 32 days

Alpha Decay

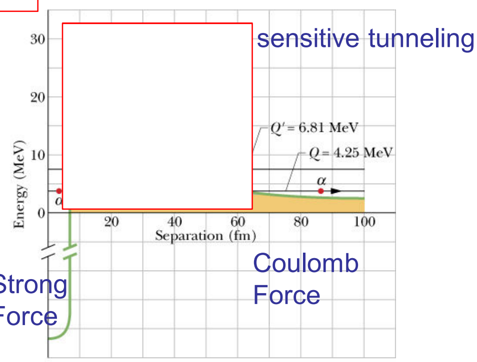
When a nucleus undergoes **alpha decay**, it transforms to a different nuclide by emitting an alpha particle (a helium nucleus, ^{4}He).

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

The alpha decay of ^{238}U can occur spontaneously (without an external source of energy) since the mass of ^{238}U is greater than the mass of the total decay products. Disintegration energy $Q =$ $T_{1/2}$ is 4.5x10^9 y. Why so long? Why don't all ^{238}U decay immediately?

Two Alpha Emitters Compared

Radionuclide	Q	Half-Life
^{238}U	4.25 MeV	4.5 x 10^9 y
^{228}U	6.81 MeV	9.1 min



Beta Decay

A nucleus that decays spontaneously by emitting an electron or a positron (positively charged particle with mass of an electron) is said to undergo **beta decay**.

Beta-minus (β^-) decay $\quad {}^{32}\mathrm{P} \rightarrow \quad (T_{1/2} = 14.3\ \mathrm{d})$

Beta-plus (β^+) decay $\quad {}^{64}\mathrm{Cu} \rightarrow \quad (T_{1/2} = 12.7\ \mathrm{h})$

ν is the symbol for a neutrino, a neutral particle with a very small mass.

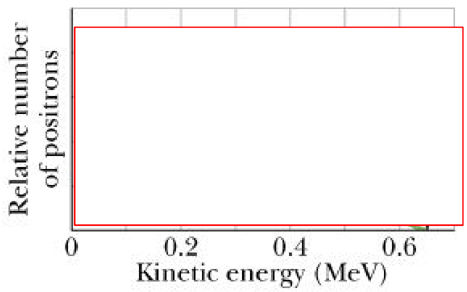
Both charge and nucleon number are conserved in beta decay.

$$\text{charge: } (+15e) =$$
$$\text{nucleon: } (+32) =$$

Beta Decay, cont'd

Beta-minus decay $\mathrm{n} \rightarrow$ $\boxed{}$

Beta-plus decay $\mathrm{p} \rightarrow$ $\boxed{}$



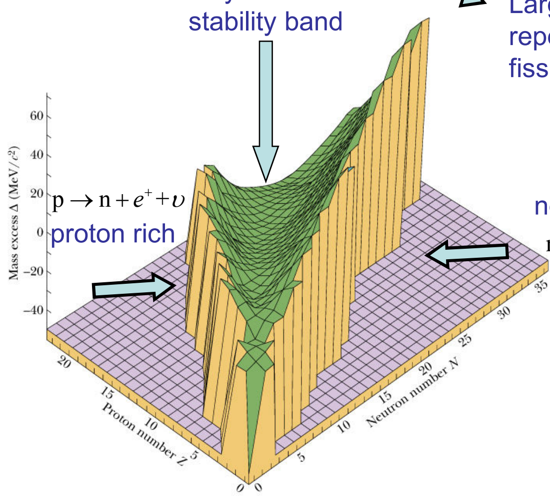
In both alpha and beta decay, the same amount of energy is released in the decay of a particular radionuclide (governed by the mass difference between the initial and final states). In beta-minus (plus) decay the energy is shared between the electron (positron) and the neutrino, so the electron (positron) energy can range from 0 to $K_{\max} = Q$.

$Q = \boxed{}$

Radioactivity and the Nuclidic Chart

Valley of nuclides stability band

Large A, decay into valley by repeated alpha emission and fission



$\mathrm{p} \rightarrow \mathrm{n} + e^{+} + \upsilon$

proton rich

neutron rich

$\mathrm{n} \rightarrow \mathrm{p} + e^{-} + \upsilon$

Q. By what method can a nucleus decay to a nucleus with a larger atomic number?

a) There is no radioactivity process that will result in a nucleus with a different atomic number than the original nucleus.

b) There is no radioactivity process that will result in a nucleus with a larger atomic number.

c) alpha decay

d) beta decay

e) gamma decay

Q. When krypton ^{89}Kr undergoes beta decay, what nucleus is produced?

a) ^{88}Rb

b) ^{88}Br

c) ^{85}Se

d) ^{88}Sr

e) ^{89}Rb

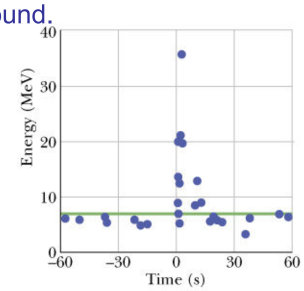
The Neutrino

•In 1930 Wolfgang Pauli predicted the existence of the neutrino to explain (1) the wide range of energies for electrons and positrons in beta decay and (2) the missing angular momentum in beta decay measurements.

•Neutrinos are hard to detect; the mean free path of an energetic neutrino in water is several thousand light years! Earth is almost completely transparent to them.

•Neutrinos were first detected in laboratory by Reines and Cowan in 1953.

•The Sun emits a large number of neutrinos from its core. Exploding stars (supernovas) emit strong neutrino bursts, which have been detected on Earth by elaborate detectors located deep underground.



Radioactive Dating

If you know the half-life of a radionuclide, you can use the decay of that radionuclide as a clock to measure time intervals.

Age of rocks: $^{40}K \rightarrow {}^{40}Ar$ with $T_{1/2}$=1.25 x 10^9 y, ratio of ^{40}K to ^{40}Ar in a rock can be used to determine when the rock was formed (and the ^{40}K in the rock started transforming into stable ^{40}Ar). This type of technique is used to date the Earth and Moon with a maximum age of about 4.5 x 10^9 y.

Shorter time intervals (prehistoric and historic dating): $^{14}C \rightarrow {}^{12}C$ with $T_{1/2}$=5730 y, ^{14}C is produced at constant rate in upper atmosphere. Living organisms absorb both ^{14}C and ^{12}C while alive, maintaining a constant ratio. Once dead, no more C is absorbed and the remaining ^{14}C begins to decay into stable ^{12}C. By measuring ^{14}C to ^{12}C in organic matter (bones, fossils, parchment) one can determine when the organism that produced the organic matter died. This type of technique is used to date artifacts ranging from the charcoal in ancient campfires to the Dead Sea Scrolls.

Q. At an archeological dig, the remains of a saber-tooth tiger are found. In a carbon dating (^{14}C has a half-life of 5730 years) test to determine the age of the cat, a scientist finds that the amount of ^{14}C is about 1/32 the amount of ^{14}C in living animals. How long ago did this saber-tooth tiger die?

a) about 50 000 years ago

b) about 40 000 years ago

c) about 30 000 years ago

d) about 20 000 years ago

e) about 10 000 years ago

Measuring Radiation Dosage

Radiation (cosmic rays, radioactive emission from elements in Earth's crust, human activity/industry) can damage living tissue. There are two parts in evaluating the effect of radiation on living tissue.

1. *Absorbed Dose*. Measure of radiation dose (energy per unit mass) actually absorbed by a specific object (for example, a patient's hand or chest). SI unit is the **gray** (Gy). Older, commonly used unit is the **rad** (**r**adiation **a**bsorbed **d**ose).

$$1\ \mathrm{Gy} = 1\ \mathrm{J/kg} = 100\ \mathrm{rad}$$

A whole-body, short-term gamma-ray dose of 3 Gy (300 rad) will cause death in 50% of the population exposed to it. The typical average dose from natural and human origin is only 2 mGy (0.2 rad) per year.

Measuring Radiation Dosage, cont'd

2. *Dose Equivalent*. Although different types of radiation (gamma rays, neutrons, etc.) may deliver the same energy to the body, they do not have the same biological effect. Dose equivalent allows us to rescale the absorbed dose to reflect the damage that a particular type of radiation can cause. The scaling factor is the **RBE** (**r**elative **b**iological **e**ffectiveness).

   Dose Equivalent =

   For x-rays and electrons: RBE = 1

   For slow neutrons: RBE = 5

   For alpha particles: RBE = 10

   The SI unit for dose equivalent is the **sievert** (Sv). An earlier unit **rem** (**r**oentgen **e**quivalent **m**an) is still commonly used.

$$1\ \mathrm{Sv} = 100\ \mathrm{rem}$$

   The National Council on Radiation Protection recommends that no one should receive an equivalent dose greater than 5 mSv per year.

Energy from the Nucleus

Can we get useful energy from nuclear sources as people have from atomic sources (burning wood, coal, fossil fuels) for thousands of years?
Electrons held in atoms by Coulomb force→energy scale ~eV
Nucleons held in nuclei by strong force→energy scale $Q=$

Energy Released by 1 kg of Matter

Form of Matter	Process	Time to Light 100W Bulb
Water	A 50 m waterfall	5 s
Coal	Burning	8 h
Enriched UO_2	Fission in reactor	690 y
^{235}U	Complete fission	3×10^4 y
Hot deuterium gas	Complete fusion	3×10^4 y
Matter and antimatter	Complete annihilation	3×10^7 y

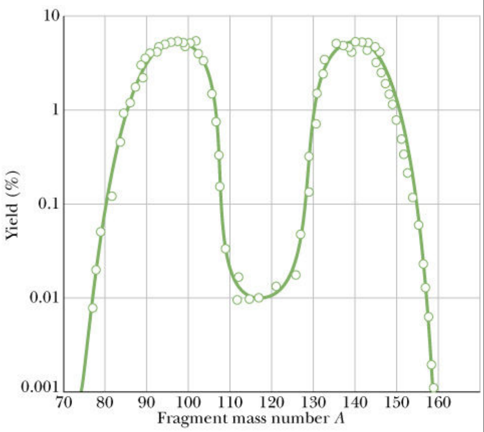
Nuclear Fission: The Basic Process

•1932: Chadwick discovers the neutron.

•1934: Fermi uses neutrons to bombard nuclei→ produces new radioactive elements.

•1939: Meitner, Hahn, and Strassmann bombard U (Z = 92) with neutrons to produce Ba (Z = 56)

•1939: Meitner and Frisch → fission!



Closer Look at Fission

^{235}U fragments when bombarded by thermal (slow) neutrons:

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow \boxed{}$$

Number of protons and neutrons conserved in this process.

Nuclear Fission: The Basic Process

Closer Look at Fission, cont'd

$$^{140}\mathrm{Xe} \rightarrow \boxed{}$$

$T_{1/2}$	14 s	64 s	13 d	40 h	Stable
Z	54	55	56	57	58

Neutron rich

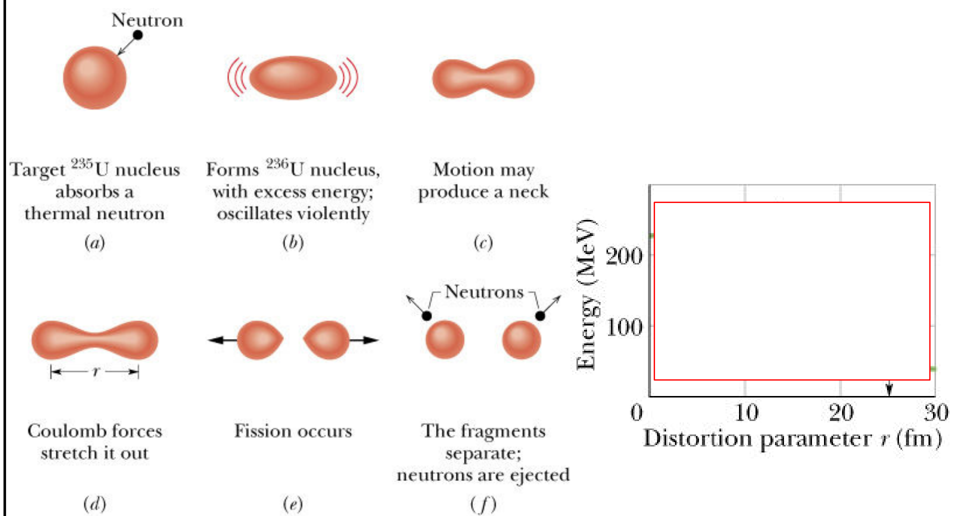
$$^{94}\mathrm{Sr} \rightarrow \boxed{}$$

$T_{1/2}$	75 s	19 min	Stable
Z	38	39	40

Recall the beta decay process:

$$\mathrm{n} \rightarrow \boxed{}$$

A Model for Nuclear Fission



Nuclear Fission: The Basic Process

Energy Release by Fission

$$Q = \left(\quad\right) - \left(\quad y\right)$$

$$Q = \left(\quad\right)\left(\quad\right) - \left(\quad\right)\left(\quad\right)$$

Fission of high mass nucleus (A~240, binding energy per nucleon ΔE_{ben}=7.6 MeV/nucleon)→two middle mass nuclei (A~120, binding energy per nucleon ΔE_{ben} = 8.5 MeV/nucleon)

$$Q = \left(\quad\right)\left(2\ \text{nuclei}\right)\left(\quad\right)$$

$$-\left(7.6\ \frac{\text{MeV}}{\text{nucleon}}\right)\left(240\ \text{nucleons}\right) \approx 200\ \text{MeV}$$

A Model for Nuclear Fission, cont'd

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow {}^{236}\mathrm{U}$$

E_b = tunneling barrier height

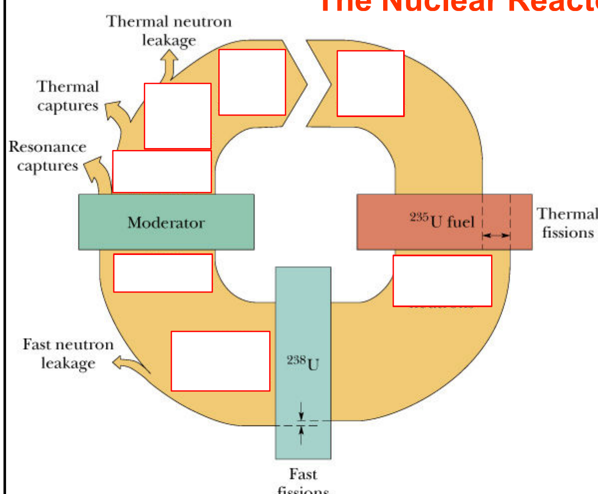
E_n = neutron excitation energy

Masses:
=235.043922 u
=1.008664 u
=236.045562 u
=7.024 x 10^{-3} u (decrease)
This excess energy will help the nuclide climb over/tunnel through the barrier (note the kinetic energy of the *thermal* neutron can be neglected).

Test of 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

The Nuclear Reactor



1. Neutron Leakage Problem
2. Neutron Energy Problem
3. Neutron Capture Problem (resonant, non-fission capture in 100-1 eV range on way to 0.04 eV)

Multiplication factor k = number of neutrons at beginning of particular generation/number of neutrons at beginning of previous generation.

k = 1→reactor critical, steady power operation

k < 1 →subcritical, not self-sustaining

k > 1 →supercritical, reaction grows

Q. A certain fission reaction releases three neutrons. How many of these neutrons must go on to produce a subsequent fission if a chain reaction is to be sustained?

a) 1

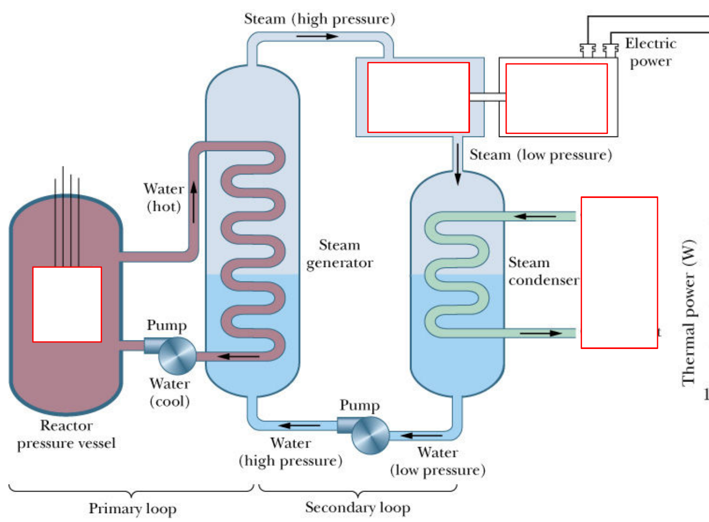
b) 2

c) 3

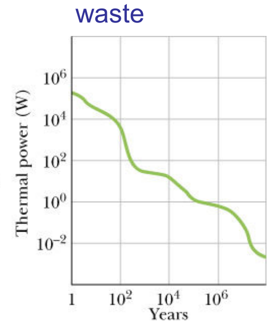
d) It could be zero as long as there are other neutrons from other fission processes available.

The Nuclear Reactor, cont'd

Pressurized-water reactor



Radiation from radioactive waste

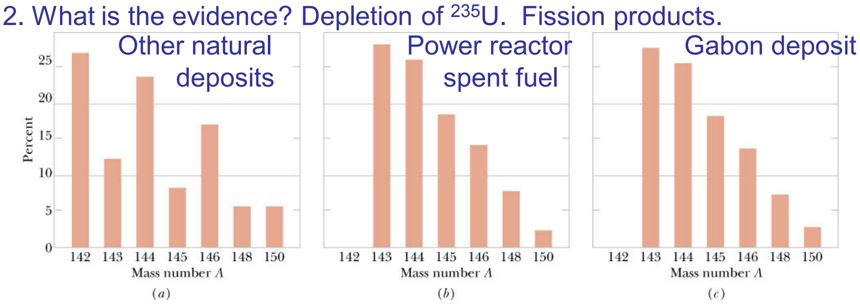


A Natural Nuclear Reactor

2 billion years ago in a uranium deposit in Gabon, West Africa, a natural fission reactor ran for several hundred thousand years!

1. Was there enough fuel? Today ^{235}U constitutes only 0.72% of natural uranium. Ratio of ^{235}U to ^{238}U was greater 2 billion years ago, perhaps as large as 3.8%. Low concentrations (~0.44%) of ^{235}U in parts of this deposit suggest that some of it may have been consumed in fission.

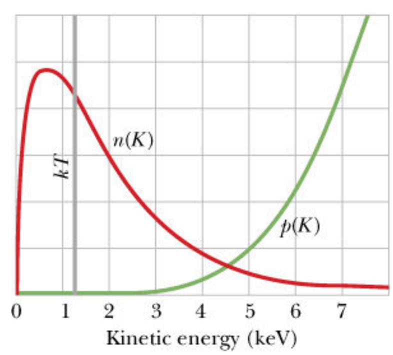
2. What is the evidence? Depletion of ^{235}U. Fission products.



Thermonuclear Fusion: The Basics

Energy can be released by combining two lighter elements (**fusion**), but first they have to overcome the Coulomb repulsion between the positively charged nuclei (~400 keV for p-p).

To generate useful amounts of energy, fusion must occur in bulk matter. If temperature of matter is very high, particles may have enough energy due to thermal motions to overcome the Coulomb barrier→**thermonuclear fusion**.



$$K = kT$$

On Earth's surface T = 300K →K = $\boxed{}$

At Sun's core T = 1.3x10^7 K →K = $\boxed{}$

K is the average thermal energy of particles, but some have much higher energy!

Thermonuclear Fusion in the Sun and Other Stars

Proton-Proton Cycle

$${}^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow \qquad (Q = 0.42\ \mathrm{MeV})$$
$$\mathrm{e}^{+} + \mathrm{e}^{-} \rightarrow \gamma + \gamma \qquad (Q = 1.02\ \mathrm{MeV})$$

$${}^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow \qquad (Q = 0.42\ \mathrm{MeV})$$
$$\mathrm{e}^{+} + \mathrm{e}^{-} \rightarrow \gamma + \gamma \qquad (Q = 1.02\ \mathrm{MeV})$$

$${}^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow \qquad (Q = 5.49\ \mathrm{MeV})$$

$${}^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow \qquad (Q = 5.49\ \mathrm{MeV})$$

$${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow \qquad (Q = 12.86\ \mathrm{MeV})$$

Overall

$$4\ {}^{1}\mathrm{H} + 2\mathrm{e}^{-} \rightarrow$$
$$+2\mathrm{e}^{-} \rightarrow$$
$$\left(4\ {}^{1}\mathrm{H} + 4\mathrm{e}^{-}\right) \rightarrow$$

Thermonuclear Fusion in the Sun and Other Stars, cont'd

Energy Release for Overall Reaction

$$Q = -\Delta m c^{2}$$
$$= -\left[4.002603\ \mathrm{u} - (4)(1.007825\ \mathrm{u})\right]\left[931.5\ \mathrm{MeV/u}\right]$$
$$= 26.7\ \mathrm{MeV}$$

Energy Release by Adding All the Steps of the Reaction

$$Q = (2)(0.42\ \mathrm{MeV}) + (2)(1.02\ \mathrm{MeV}) + (2)(5.49\ \mathrm{MeV}) + 12.86\ \mathrm{MeV}$$
$$= 26.7\ \mathrm{MeV}$$

0.5 MeV of released energy is carried away from Sun by 2 neutrinos, rest is deposited in solar core as thermal energy.

Sun has been burning for ~5 x 10^{9} y, converting H to He. In 5 billion years, Sun's core will be mainly He→Sun will start cooling →start to collapse under own gravity →temperature at core will rise again →outer part of Sun will expand into *red giant* →He in core fuses to form C and other lighter elements. Heavier elements formed in stellar explosions (*supernovas*).

Controlled Thermonuclear Fusion

Deuteron-deuteron reactions:

$$^{2}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow \qquad (Q = +3.27 \ \mathrm{MeV}) \ (43\text{-}13)$$

$$^{2}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow \qquad (Q = +4.03 \ \mathrm{MeV}) \ (43\text{-}14)$$

Deuteron-triton reactions:

$$^{2}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow \qquad (Q = +17.59 \ \mathrm{MeV}) \ (43\text{-}15)$$

Requirements for a successful thermonuclear reactor

1. →d-d and d-t collision rates in **plasma** (ionized gas) must be high.
2. to overcome Coulomb repulsion between d's and t's.
3.

Lawson's Criterion:

$$n\tau > 10^{20} \ \mathrm{s/m^3} \qquad (43\text{-}16)$$

Controlled Thermonuclear Fusion

How does one keep the hot plasma together and away from the walls of the container holding it?

: Tokamak—plasma held in ring by strong magnetic fields, heated by induced currents and bombarding particle beam. Example, Plasma Physics Lab (Princeton).

occurs when Lawson's criterion is met or exceeded

corresponds to a self-sustaining reaction.

: Solid fuel pellet "zapped" from all sides by intense laser beams. Fuel is confined to pellet by imploding shock wave, and particles' inertia (mass) keeps them from escaping during the short pulse.

Example, at Lawrence Livermore Lab. 10 synchronized high-power lasers produce 200 kJ energy in 1 nanosecond at pellet→2 x 10^{14} W! 100 times the total installed power generating capacity of the WORLD! Plans to run 10-100 pulses per second to maintain reaction.