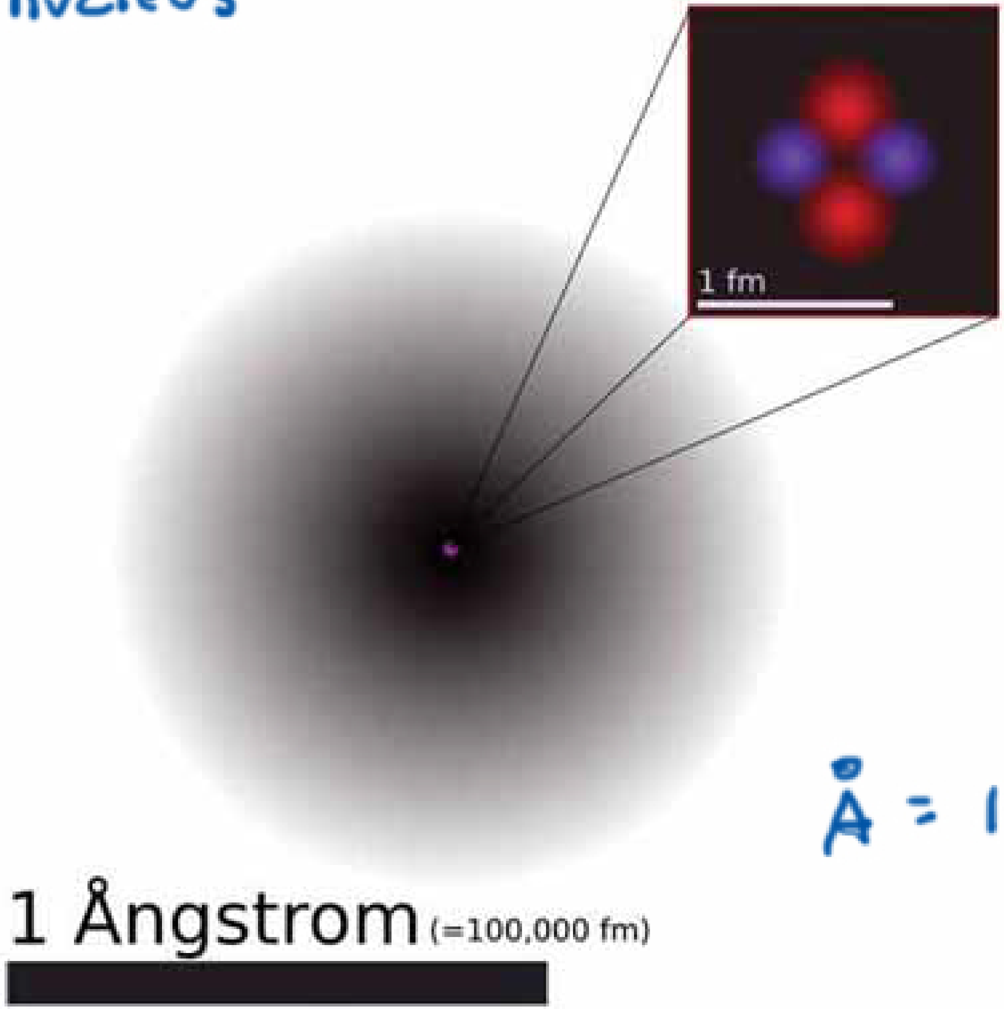
Module 13

Nuclear Physics

Session Slides with Notes

Nuclear Physics

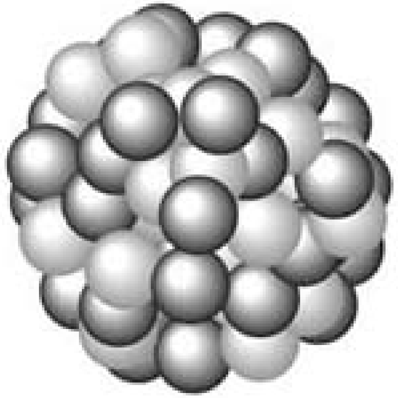
The nucleus



fm = 10^{-15} m

Å = 10^{-10} m

The Nucleus



$$^{A}_{Z}\mathrm{X}$$

chemical symbol, X, for the element

atomic number, Z, equals the number of protons in the nucleus.

mass number, A, equals the number of nucleons (protons plus neutrons) in the nucleus.

neutron number, $N = A - Z$

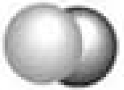
Isotopes of an element have the same number of protons but a different number of neutrons in the nucleus, in other words, the same atomic number, Z*, but different neutron number,* N*, and, therefore, different mass number,* A.

Isotopes of Hydrogen

$^{1}_{1}\mathrm{H}$

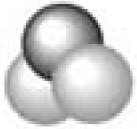
normal hydrogen nucleus

$^{2}_{1}\mathrm{H}$



deuterium nucleus

$^{3}_{1}\mathrm{H}$



tritium nucleus

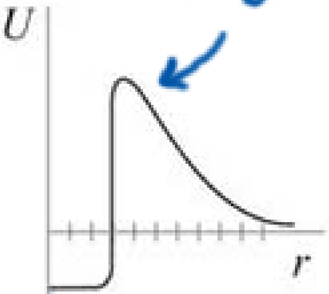
The femtometer (fm) is a convenient unit of length for nuclear physics because its value is on the order of nuclear radii:

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

Through observations of scattering experiments, nuclear physicists have developed a potential energy curve for the interaction of two protons. For a system of two protons, which of the the following is the best representation of potential energy versus separation in femtometers?

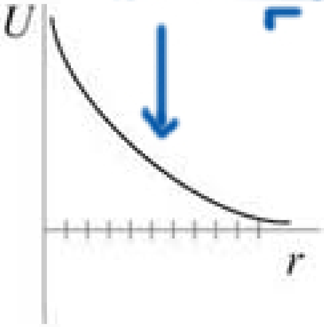
electrostatic barrier

strong nuclear force

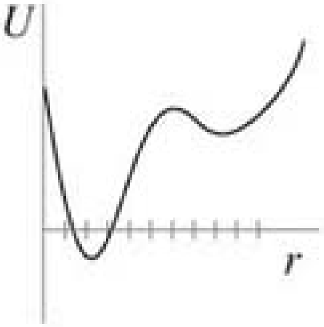


[✓ (a)]

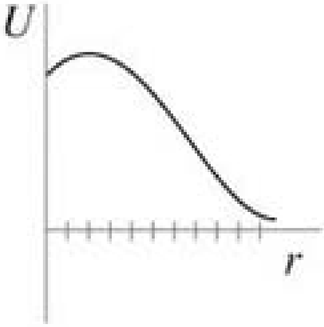
$U = \frac{kq_1q_2}{r}$



(b)



(c)



(d)

fm

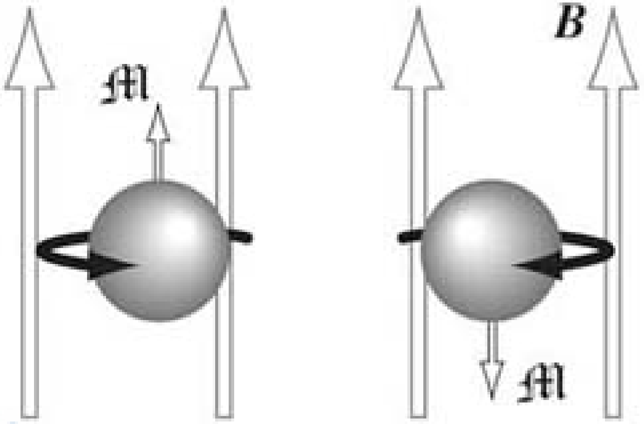
Nuclear Spin States

Nuclear spin quantum number, I.

Number of allowed spin states is $I + 1$.

Spin states: $-I$, $(-I+1)$, . . . , $(-I+1)$, I

Element	${}^{1}_{1}H$	${}^{2}_{1}H$	${}^{12}_{6}C$	${}^{13}_{6}C$
Spin Quant #, I	$\frac{1}{2}$	1	0	$\frac{1}{2}$
# of states	2	3	0	2

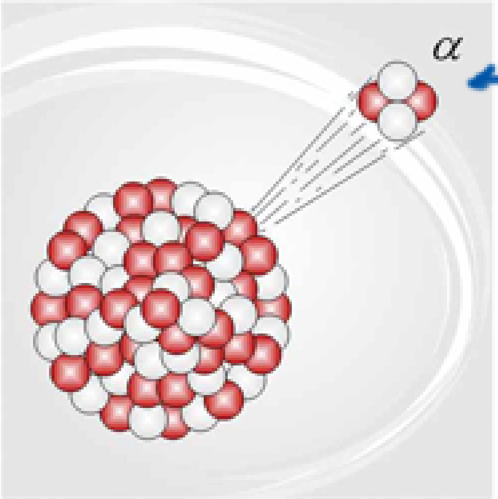


external field

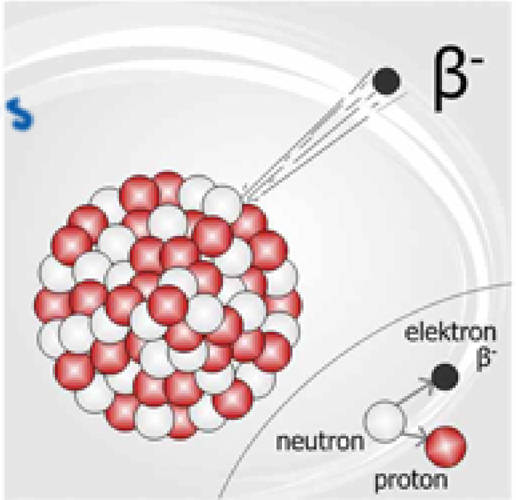
lower energy

An applied magnetic field splits the two spin states of a proton into states of unequal energy. Energy is lower for the state in which the spin magnetic moment is aligned with the external field.

nuclear decay



← helium nucleus

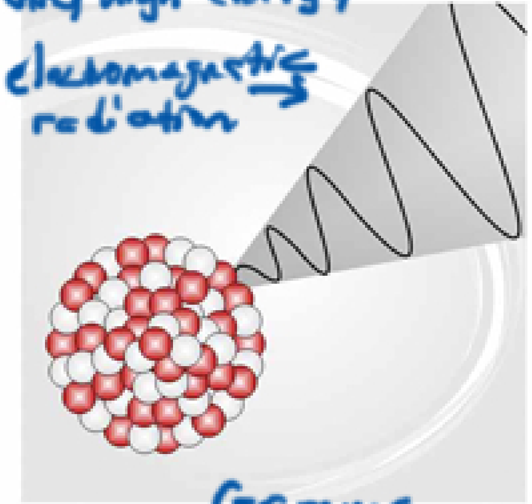


Beta Decay

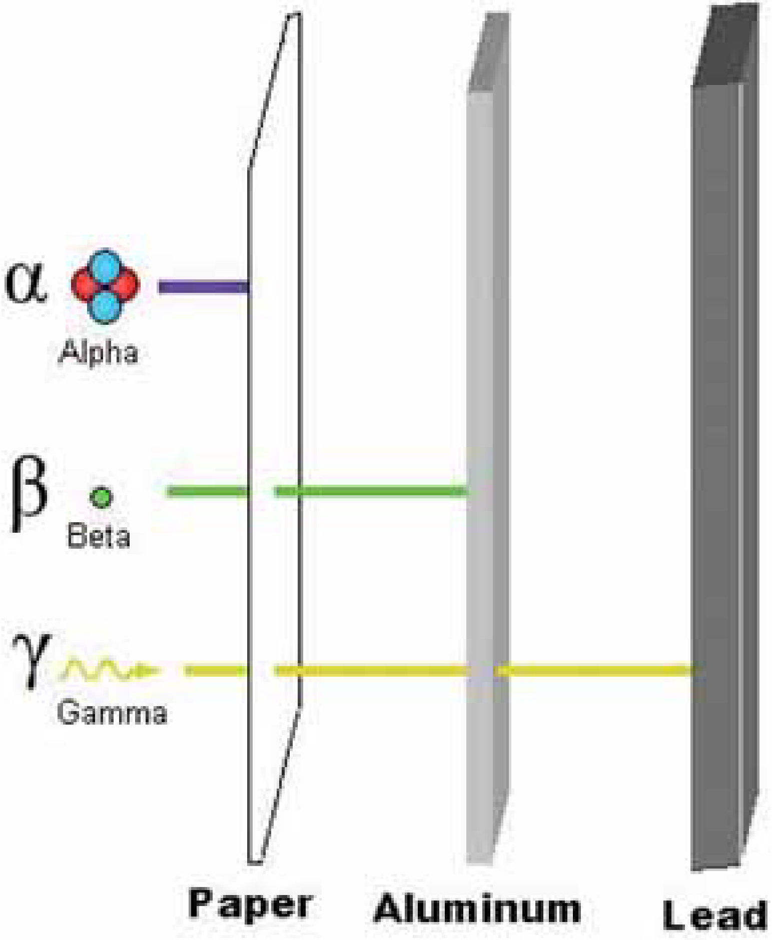
β^- electron

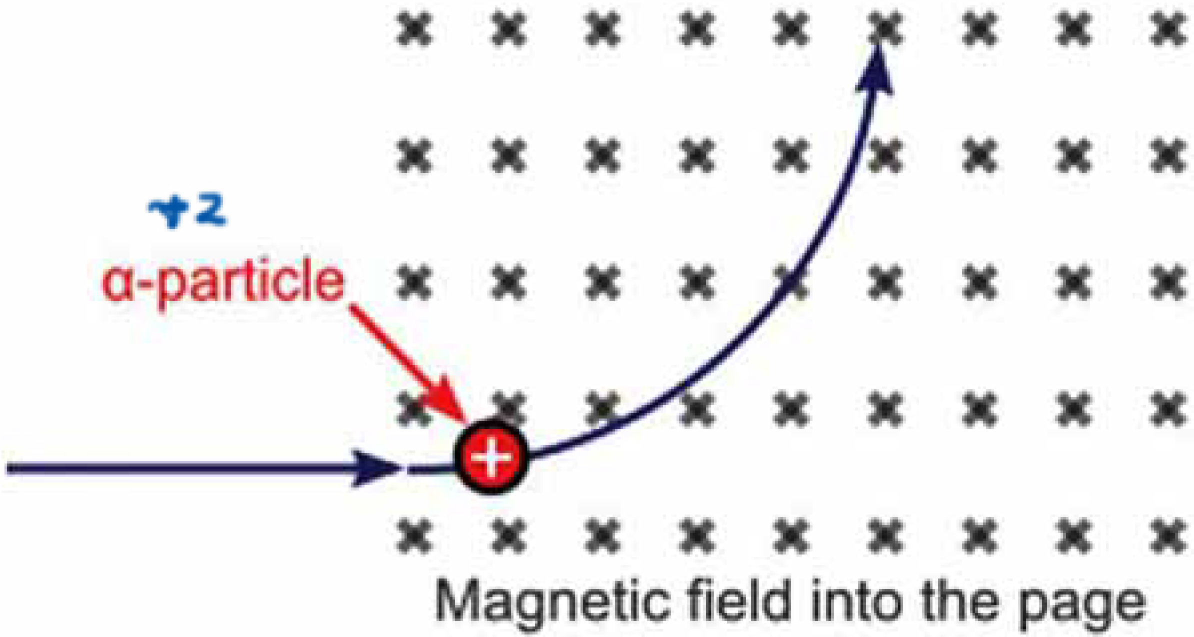
β^+ positron

very high energy electromagnetic radiation



Gamma


α
Alpha
β
Beta
γ
Gamma
Paper
Aluminum
Lead


+2
α-particle
Magnetic field into the page

Radioactive Decay

Alpha Decay

$$^{226}_{88}\mathrm{Ra} \longrightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}$$

A nuclei undergoes **alpha decay** by emitting an α **particle**, which is identical to a helium nucleus ($^{4}_{2}\mathrm{He}^{2+}$, two protons and two neutrons). *Z* decreases by 2 and *A* decreases by 4.

Beta Decay

$$^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\beta^{-} + \overset{\text{antineutrino}}{\bar{\nu}}$$

In β^- **decay**, a β^- **particle**, which is a high speed electron, and an **antineutrino**, $\bar{\nu}$, are emitted. A neutron changes into a proton in the nucleus (*Z* increases by 1 with *A* unchanged).

$$^{13}_{7}\mathrm{N} \longrightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{1}\beta^{+} + \underset{\text{neutrino}}{\nu}$$

In β^+ **decay**, a β^+ **particle**, (a **positron**, the anti-particle of the electron) and a **neutrino**, *ν*, are emitted. A proton changes into a neutron in the nucleus (*Z* decreases by 1 with *A* unchanged).

Electron Capture

$$^{7}_{4}\mathrm{Be} + {}^{0}_{-1}\mathrm{e} \longrightarrow {}^{7}_{3}\mathrm{Li} + \nu$$

In **electron capture**, a nucleus captures one of the atom's own electrons, changing a proton to a neutron (*Z* decreases by 1 with *A* unchanged), and a **neutrino**, *ν*, is emitted.

Gamma Decay

$$^{125}_{53}\mathrm{I}^{*} \longrightarrow {}^{125}_{53}\mathrm{I} + \gamma$$

Gamma decay occurs when a nucleus in an excited energy state (very often as the result of a prior decay event) emits a very high energy photon, a **gamma ray**, as it transitions to a lower energy state.

β emitters

^{32}P ^{35}S ^{14}C

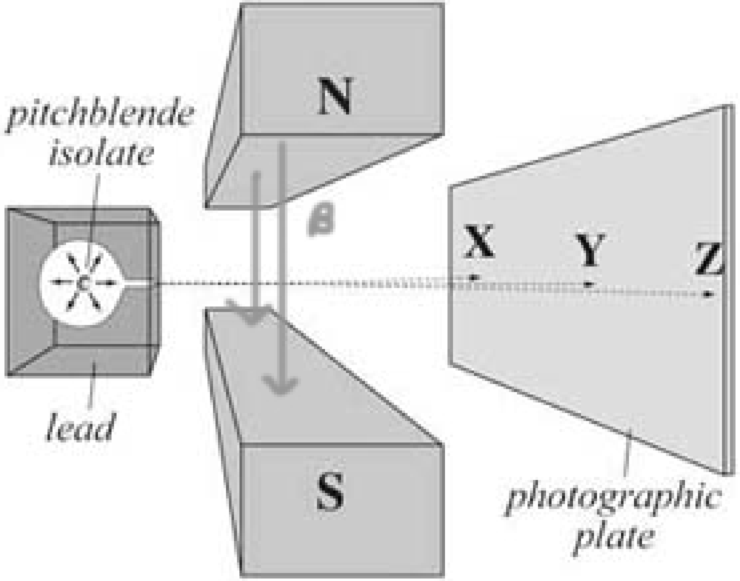
^{3}H ↖↑ radiolabels

PET scanning

$$^{18}_{9}F \longrightarrow {}^{18}_{8}O + \beta^{+} + \nu$$

$$\beta^{+} + \beta^{-} \longrightarrow \gamma$$

An isolate of the ore, pitchblende, is significantly radioactive. When the radiation is deflected by the magnetic field at right and detected photographically, one component of the radiation, **X**, is found to bend into the plane of the figure, and another component, **Z**, bends out of the plane. The third component, **Y**, is not affected by the magnetic field. Which of the following describes the components?



a. **X** is composed of β^- rays; **Y** is γ rays; and **Z** is α rays

b. **X** is composed of α rays; **Y** is anti-neutrinos; and **Z** is β^- rays

c. **X** is composed of β^+ rays; **Y** is neutrinos; and **Z** is β^- rays

[✓ d.] **X** is composed of α rays; **Y** is γ rays; and **Z** is β^- rays

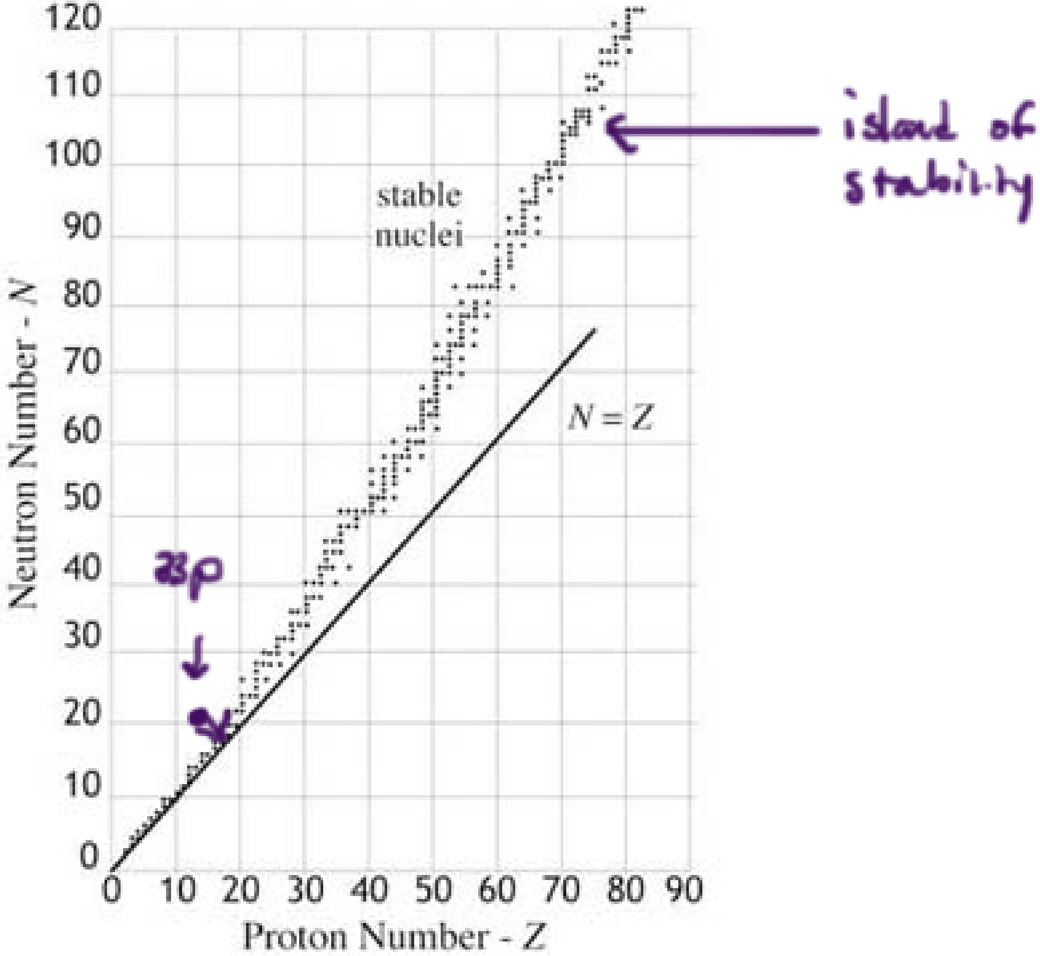
Stable nuclides are represented by a narrow band of proton-to-neutron ratios on the graph of neutron number vs. proton number. Nuclei falling outside this region are unstable and subject to radioactive decay. Unstable nuclei above the band are said to be neutron rich, and those below it are neutron poor. What type of decay would be expected for the isotope of phosphorus, $^{33}_{15}\mathrm{P}$?

a. α decay

b. β^+ decay

[✓ c.] β^- decay

d. electron capture



Activity and Half-Life

$$A = -\lambda N$$

just like $(\text{rate} = k[X])$

1st order kinetics

$$A = \frac{\Delta N}{\Delta t} = -\lambda N$$

A = activity (disintegrations per second)
N = number of radioactive nuclei
t = time
λ = decay constant

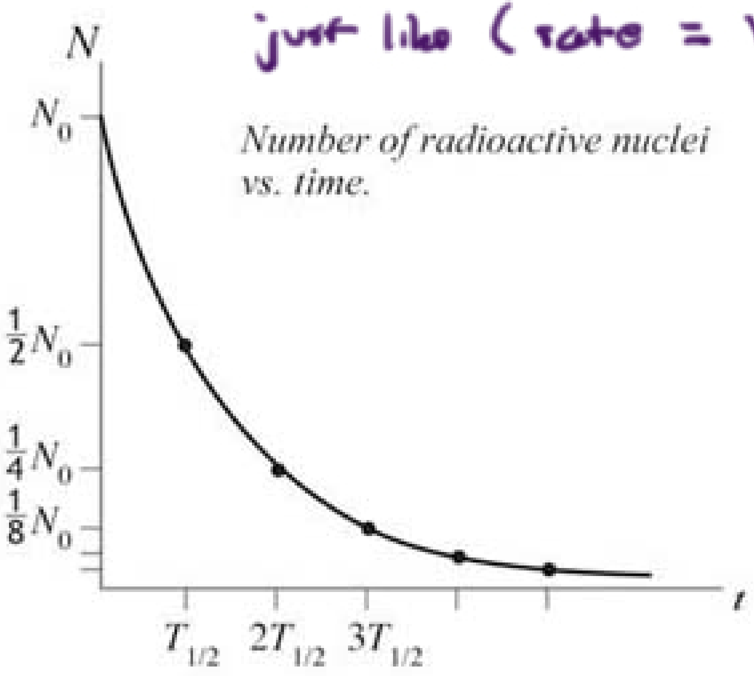
↙ exponential decay

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

N = number of radioactive nuclei
N_0 = number of nuclei initially present
λ = decay constant
t = time

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

$T_{1/2}$ = half-life
λ = decay constant



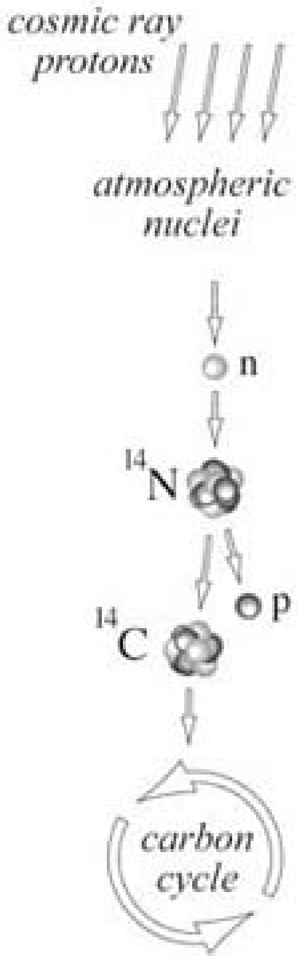
Number of radioactive nuclei vs. time.

The half-life is the time required for half of an amount of a given radionuclide to undergo decay.

half lives	1	2	3	4	5
# remaining	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{8}$	$\frac{1}{16}$	$\frac{1}{32}$

In the upper atmosphere, cosmic ray protons collide with nuclei causing reactions that produce neutrons. These neutrons in turn lead to the transformation of ^{14}N into ^{14}C. This is a continuous process which maintains a ratio of ^{14}C to ^{12}C in the atmosphere that is fairly constant through millenia. After an organism dies, it ceases exchanging carbon with the atmosphere, and the ratio ^{14}C to ^{12}C decreases through the beta decay of ^{14}C which has a half-life of 5730 years.

Measuring the level of radioactive decay of ^{14}C in the preserved epidermal tissue of a mummy, it was found to sustain 20% of the activity of living tissue. What is the approximate age of the mummy?



1 2 3

$\frac{1}{2}$ $\frac{1}{4}$ $\frac{1}{8}$

a. 1400 yrs [✓ b.] 13,500 yrs c. 25,000 yrs d. 30,000 yrs

Mass / Energy Equivalence in Nuclear Processes

Reaction Energy

$$Q = \Delta m c^2$$

Q = total energy released in a nuclear process
Δm = mass difference between products and reactants
c = speed of light (3×10^8 m/s)

The rest mass of nucleons in a stable nucleus is lower.

Binding Energy

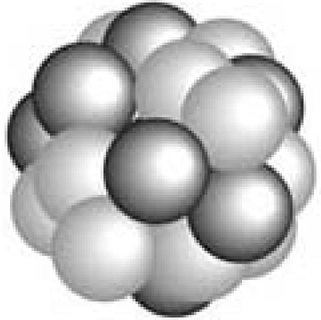
$$E_b = [\underbrace{\overset{\text{free protons}}{Zm_p} + \overset{\text{free neutrons}}{Nm_n} - \overset{\text{nucleus}}{M_{Nu}}}_{\text{mass defect}}] \times c^2$$

$$E_b = [Zm_p + Nm_n - M_{Nu}] \times 931.5 \text{ MeV/u}$$

E_b = nucleus binding energy
Z = atomic number
m_p = free proton mass
N = neutron number

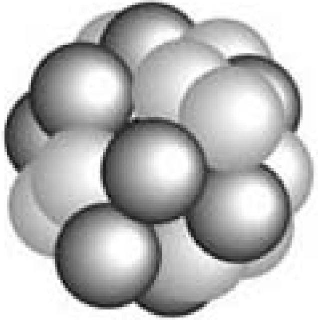
m_{Nu} = free neutron mass
M_{Nu} = atomic mass of combined nucleus
c = speed of light (3×10^8 m/s)

The rest mass of a free neutron is 1.008665, and the rest mass of a free proton is 1.007276 u. Which of these two nuclei is the most stable?



$^{23}_{11}\mathbf{Na}$

22.989770 u



$^{23}_{12}\mathbf{Mg}$

22.994127 u

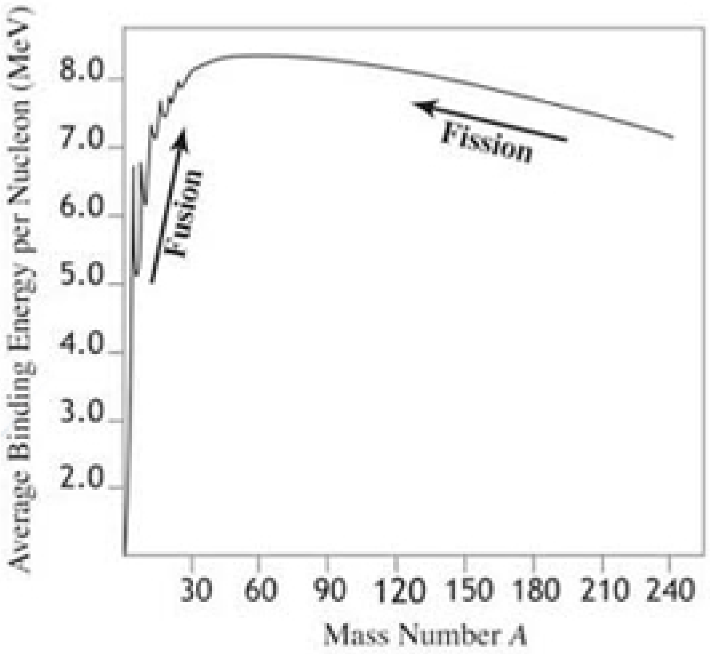
[✓ a.] $^{23}_{11}\mathbf{Na}$

b. $^{23}_{12}\mathbf{Mg}$

c. Their stabilities are equal.

d. $^{23}_{12}\mathbf{Mg}$ is more stable against α decay, while $^{23}_{11}\mathbf{Na}$ is more stable against β^- decay.

Fusion and Fission



Fusion combines two light nuclei to produce a heavier nuclei. It requires very high concentrations of reactants and high temperature conditions.

$$^{2}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \longrightarrow ^{3}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n}$$

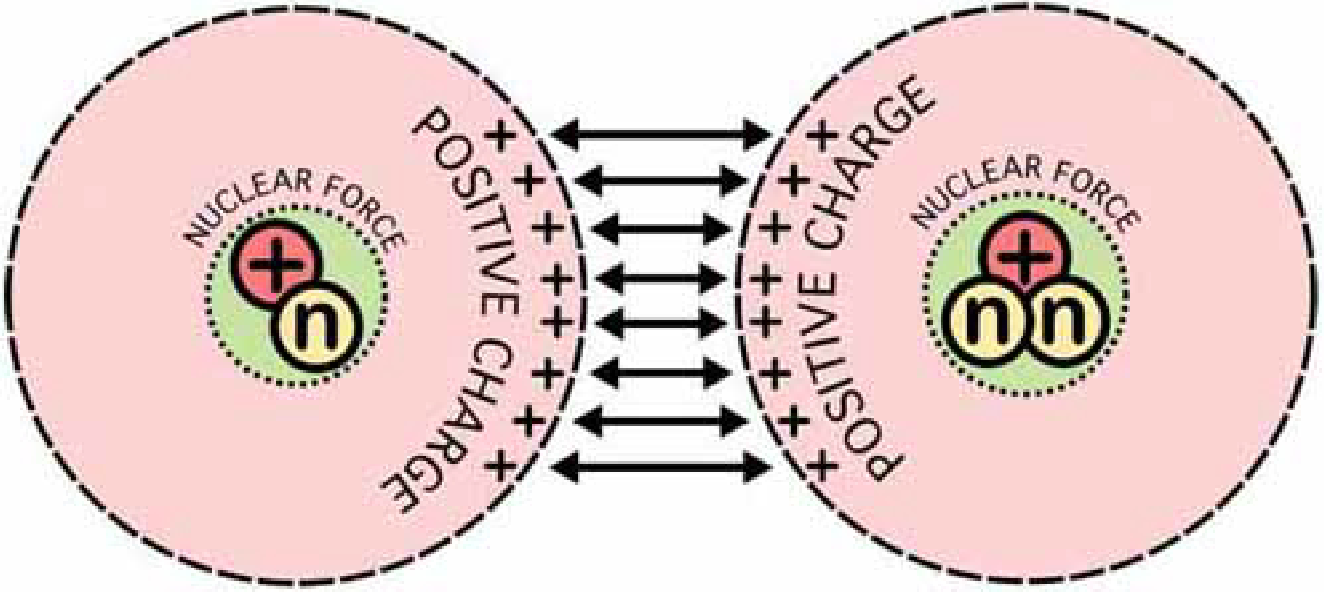
Fission is the splitting of a heavy nucleus into two lighter nuclei. In the reaction below, note that a neutron initiates fission and that more neutrons are produced by fission. Thus a nuclear *chain reaction* is possible if the mass of $^{235}_{92}\mathrm{U}$ is sufficiently concentrated (critical mass).

$$^{1}_{0}\mathrm{n} + ^{235}_{92}\mathrm{U} \longrightarrow ^{140}_{54}\mathrm{Xe} + ^{94}_{38}\mathrm{Sr} + 2\,^{1}_{0}\mathrm{n}$$

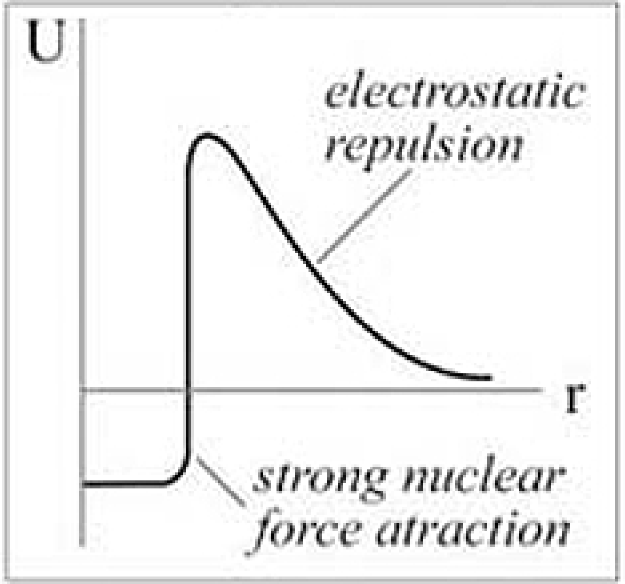
↑

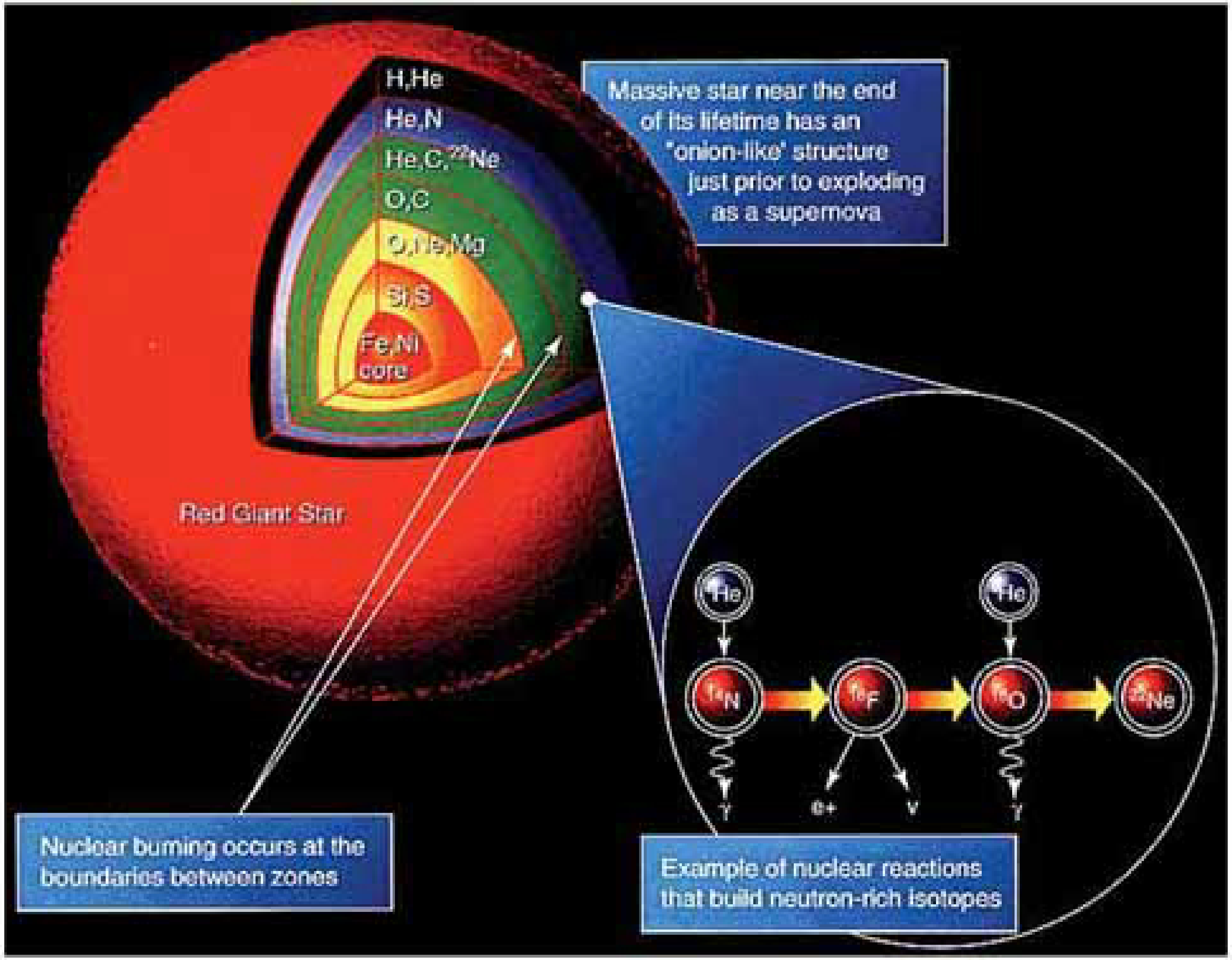
thermal (slow)

neutron


NUCLEAR FORCE
POSITIVE CHARGE
NUCLEAR FORCE
POSITIVE CHARGE
+
n
+
n n

The graph at right shows potential energy vs. distance between a deuteron and a tritium nucleus. Before fusion can occur, the electrostatic force of repulsion between the two nuclei must be overcome by their kinetic energy. This allows the colliding nuclei to approach within a few femtometers (fm) (1 fm = 10^{-15} m) of each other where the strong nuclear force prevails and fusion can occur.



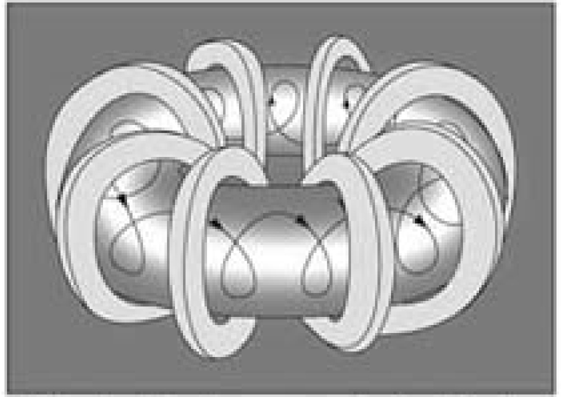


Massive star near the end of its lifetime has an "onion-like" structure just prior to exploding as a supernova

Nuclear burning occurs at the boundaries between zones

Example of nuclear reactions that build neutron-rich isotopes

Most nuclear fusion reactions achieved in the laboratory require the reactant atoms to be in the form of a plasma. Plasma is a very high temperature form of matter in which the atoms are completely ionized. Which of the following best describes the required plasma temperature for the sustained fusion of deuterium and tritium?



The helical magnetic field of a tokamak fusion reactor traps the high temperature plasma, preventing it from contacting the container walls.

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} $$

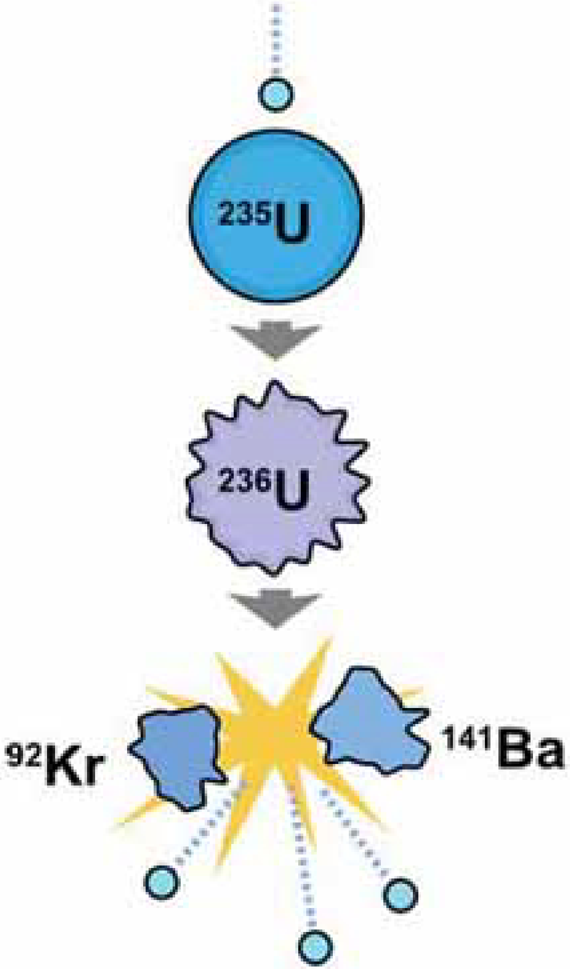
a. the temperature necessary to fully ionize deuterium and tritium

[✓ b.] a temperature great enough for the kinetic energy of two typical colliding nuclei to exceed their electrostatic potential energy barrier

c. the core temperature of the sun

d. the temperature where the average particle speed produces a magnetic force greater than the electrostatic repulsion between nuclei

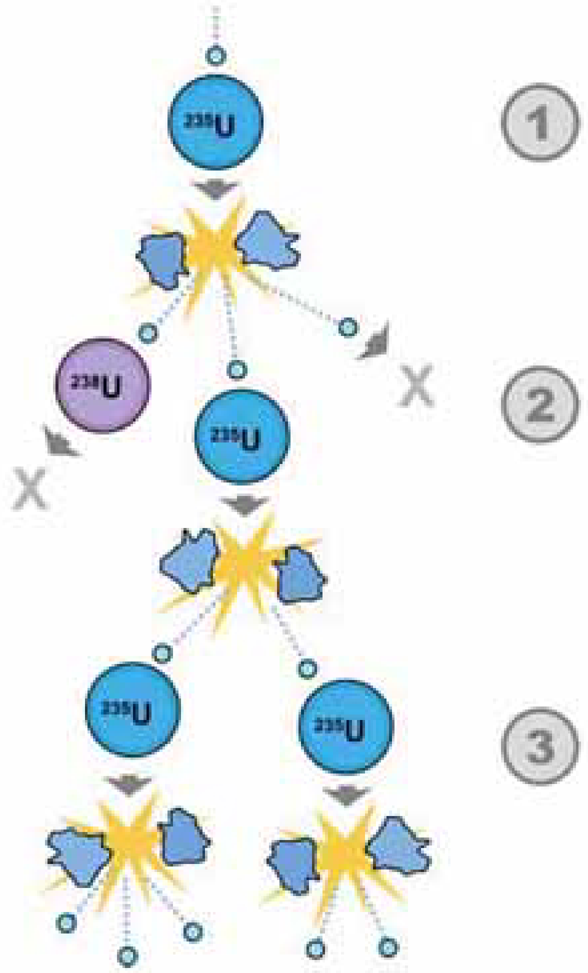
critical mass -
high enough ^{235}U %
to sustain chain
reaction



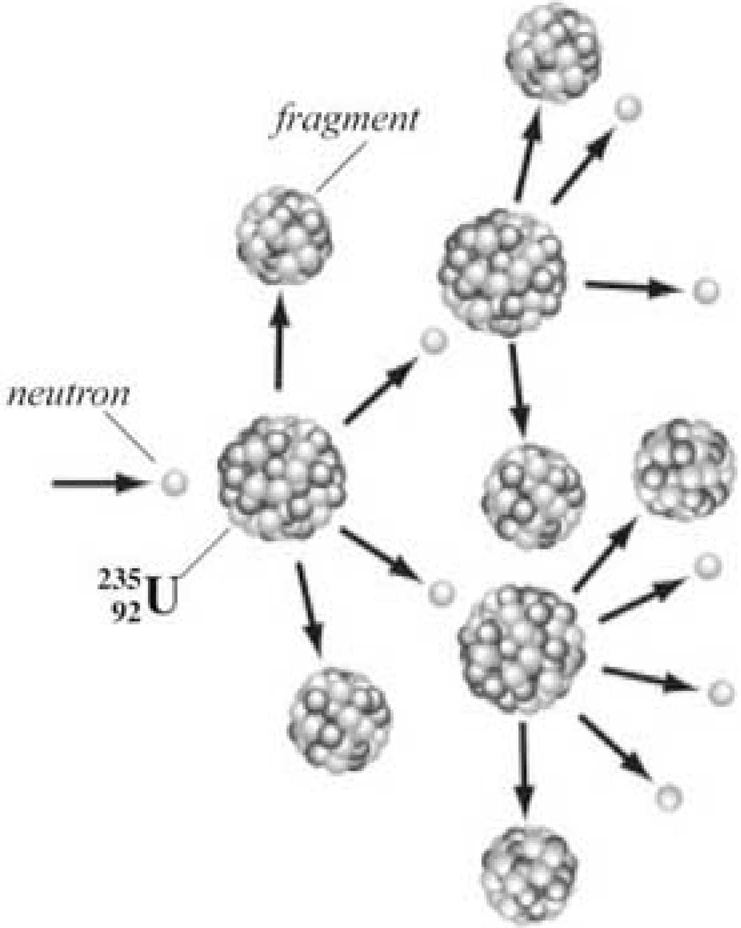
^{235}U

most uranium is
^{238}U

enriched uranium
high ^{235}U


^{235}U
1
^{238}U
^{235}U
X
X
2
^{235}U
^{235}U
3

Chain Reaction Fission of $^{235}_{92}\mathrm{U}$



The $^{235}_{92}\mathrm{U}$ nucleus undergoes fission after capturing a thermal neutron. The fission reaction produces two fission fragments and, depending upon the particalar daughter nuclei, two or three neutrons. These neutrons, in turn, can trigger the fission of other nuclei, leading to

Typical $^{235}_{92}\mathrm{U}$ Fission Reactions

$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + 2\,{}^{1}_{0}\mathrm{n}$$

$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$$

$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{132}_{50}\mathrm{Sn} + {}^{101}_{42}\mathrm{Mo} + 3\,{}^{1}_{0}\mathrm{n}$$