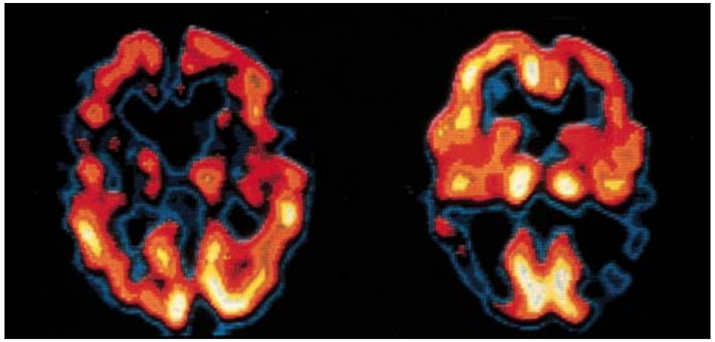


Chapter 18

The Nucleus: A Chemist’s View

Chapter 17 Preview

A Nucleus: A Chemist's View

- Nuclear Stability and Radioactive Decay
  - Types of radioactive decay, kinetics of radioactive decay, half-life
- Nuclear Transformations and uses of Radioactivity
  - Dating by radioactivity, Medical applications,…
- Thermodynamic Stability of the Nucleus
  - Nuclear Fission, Nuclear Reactors, Breeder Reactors, Fusion
- Effect of Radiation

Introduction

- The properties of the nucleus are not of primary importance to chemists, but because of their impact on our life some aspects about nucleus behavior should be introduced.
- After Rutherford experiments (1911), the atomic composition is

Mass Number → A; Atomic Number → Z; Element Symbol ← X

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

Atomic number (Z) = number of protons in nucleus

Mass number (A) = number of protons + number of neutrons

= atomic number (Z) + number of neutrons

	proton	neutron	electron	positron	α particle
	${}^{1}_{1}p$ or ${}^{1}_{1}H$	${}^{1}_{0}n$	${}^{0}_{-1}e$ or ${}^{0}_{-1}\beta$	${}^{0}_{+1}e$ or ${}^{0}_{+1}\beta$	${}^{4}_{2}He$ or ${}^{4}_{2}\alpha$
A	1	1	0	0	4
Z	1	0	-1	+1	2

Introduction

Comparison of Chemical Reactions and Nuclear Reactions

Chemical Reactions	Nuclear Reactions
1. Atoms are rearranged by the breaking and forming of chemical bonds.	1. Elements (or isotopes of the same elements) are converted from one to another.
2. Only electrons in atomic or molecular orbitals are involved in the breaking and forming of bonds.	2. Protons, neutrons, electrons, and other elementary particles may be involved.
3. Reactions are accompanied by absorption or release of relatively small amounts of energy.	3. Reactions are accompanied by absorption or release of tremendous amounts of energy.
4. Rates of reaction are influenced by temperature, pressure, concentration, and catalysts.	4. Rates of reaction normally are not affected by temperature, pressure, and catalysts.

18.1 Nuclear Stability and Radioactive Decay

Nuclear stability will be considered from both a kinetic and thermodynamic point of view:

- ***Thermodynamic Stability.***

  Potential energy of nucleus compared to the sum of potential energies of its component (proton and neutrons)

- ***Kinetic Stability.***

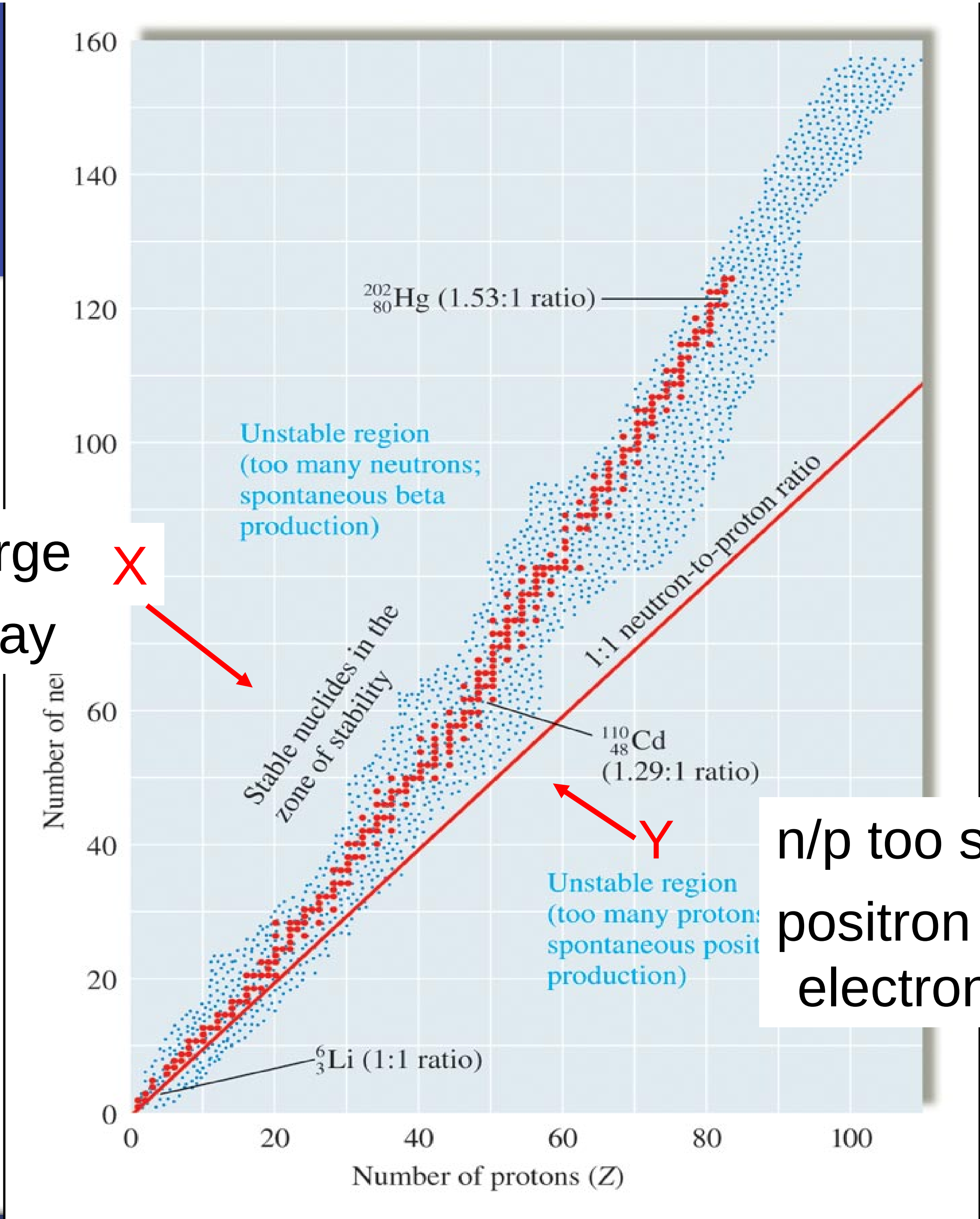
  Ability of the nucleus to decompose to form different nucleus, for Example:

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e$$

Beta, β, particle

- ***Type of particles***

	proton	neutron	electron	positron	α particle
	${}^{1}_{1}p$ or ${}^{1}_{1}H$	${}^{1}_{0}n$	${}^{0}_{-1}e$ or ${}^{0}_{-1}\beta$	${}^{0}_{+1}e$ or ${}^{0}_{+1}\beta$	${}^{4}_{2}He$ or ${}^{4}_{2}\alpha$
A	1	1	0	0	4
Z	1	0	-1	+1	2



n/p too large

beta decay

n/p too small

positron decay or electron capture

18.1 Nuclear Stability and Radioactive Decay

- Certain numbers of neutrons and protons are ***extra*** stable
  - n or p = 2, 8, 20, 50, 82 and 126
  - Like extra stable numbers of electrons in noble gases (e^- = 2, 10, 18, 36, 54 and 86)
- Nuclei with even numbers of both protons and neutrons are more stable than those with odd numbers of neutron and protons
- All isotopes of the elements with atomic numbers higher than 83 are radioactive
- All isotopes of Tc (TM) and Pm (La) are radioactive

Types of Radioactive Decay

Decays that does not involve a change in the mass number:

Beta decay (change a neutron to a proton) $\quad {}^{1}_{0}n \longrightarrow {}^{1}_{1}p + {}^{0}_{-1}\beta + \bar{\nu}$

$${}^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}\beta + \bar{\gamma}$$

Decrease # of neutrons by 1

$${}^{40}_{19}K \longrightarrow {}^{40}_{20}Ca + {}^{0}_{-1}\beta + \bar{\gamma}$$

Increase # of protons by 1

Positron decay (change a proton to a neutron) $\quad {}^{1}_{1}p \longrightarrow {}^{1}_{0}n + {}^{0}_{+1}\beta + \nu$

$${}^{11}_{6}C \longrightarrow {}^{11}_{5}B + {}^{0}_{+1}\beta + \gamma$$

Increase # of neutrons by 1

$${}^{38}_{19}K \longrightarrow {}^{38}_{18}Ar + {}^{0}_{+1}\beta + \gamma$$

Decrease # of protons by 1

Electron capture decay (e-captured by the nucleus) $\quad {}^{1}_{1}p + {}^{0}_{-1}e \longrightarrow {}^{1}_{0}n + \nu$

$${}^{37}_{18}Ar + {}^{0}_{-1}e \longrightarrow {}^{37}_{17}Cl + \gamma$$

Increase # of neutrons by 1

$${}^{55}_{26}Fe + {}^{0}_{-1}e \longrightarrow {}^{55}_{25}Mn + \gamma$$

Decrease # of protons by 1

Important → $${}^{201}_{80}Hg + {}^{0}_{-1}e \rightarrow {}^{201}_{79}Au + {}^{0}_{0}\gamma$$ ← **But not at acceptable rate**

Types of Radioactive Decay

Decays that involves a change in the mass number:

<u>Alpha decay</u> (involve a change in the mass number)

$$^{212}_{84}Po \longrightarrow\ ^{4}_{2}He +\ ^{208}_{82}Pb$$

Decrease # of neutrons by 2

Decrease # of protons by 2

<u>Spontaneous fission</u> (producing lighter nuclides)

$$^{252}_{98}Cf \longrightarrow 2\,^{125}_{49}In + 2\,^{1}_{0}n$$

<u>Gamma ray, or γ ray</u> (involve matter-energy interchange)

γ and $\bar{\gamma}$ have A = 0 and Z = 0

$$^{0}_{-1}e + ^{0}_{1}e \rightarrow 2\,^{0}_{0}\gamma$$

Balancing Nuclear Equations

1. Conserve mass number (A).

The sum of protons plus neutrons in the products must equal the sum of protons plus neutrons in the reactants.

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{138}_{55}Cs + ^{96}_{37}Rb + 2\,^{1}_{0}n$$

$$235 + 1 = 138 + 96 + 2x1$$

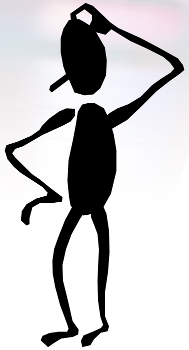
2. Conserve atomic number (Z) or nuclear charge.

The sum of nuclear charges in the products must equal the sum of nuclear charges in the reactants.

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{138}_{55}Cs + ^{96}_{37}Rb + 2\,^{1}_{0}n$$

$$92 + 0 = 55 + 37 + 2x0$$

Review Question



^{212}Po decays by alpha emission. Write the balanced nuclear equation for the decay of ^{212}Po.

alpha particle - $^{4}_{2}He$ or $^{4}_{2}\alpha$

$$^{212}_{84}Po \longrightarrow \, ^{4}_{2}He + \, ^{A}_{Z}X$$

$212 = 4 + A \qquad A = 208$

$84 = 2 + Z \qquad Z = 82$

$$^{212}_{84}Po \longrightarrow \, ^{4}_{2}He + \, ^{208}_{82}Pb$$

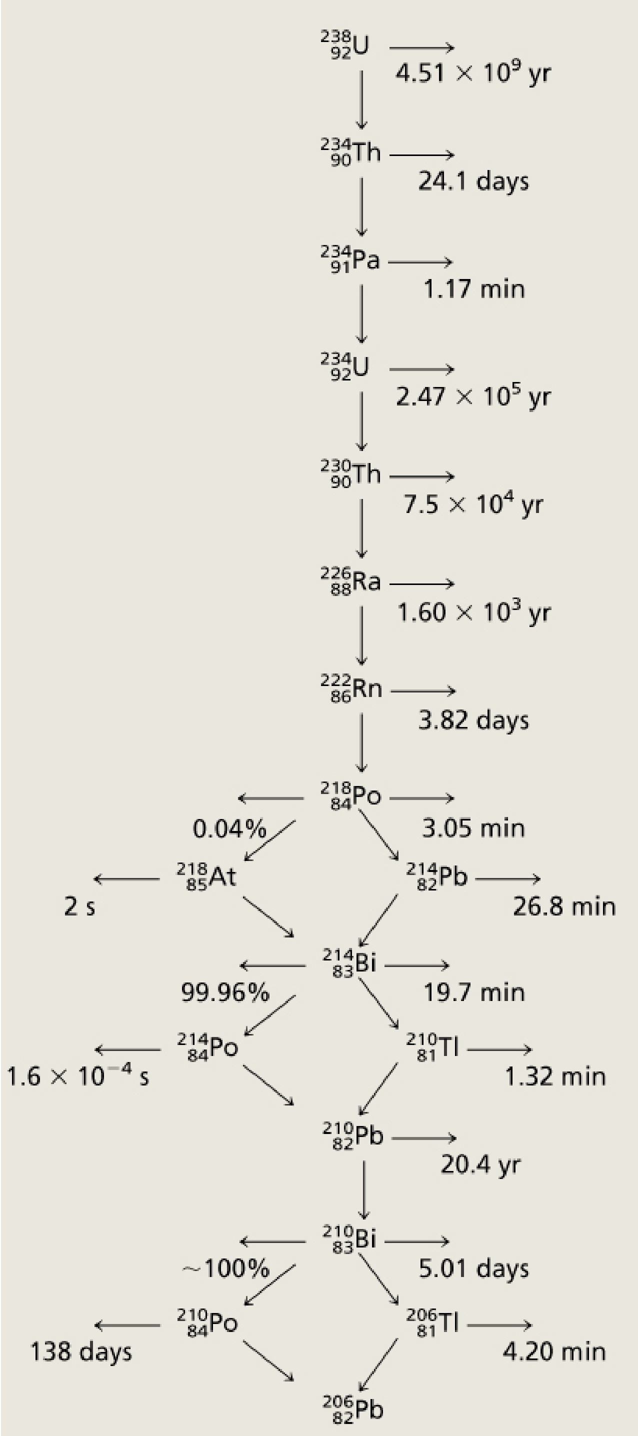
QUESTION

What should be placed in the blank to balance the following nuclear equation:

$$^{15}_{8}O \rightarrow ^{15}_{7}N + \_\_\_$$

1. Gamma ray
2. Alpha particle
3. Positron
4. B^{-}

Choice 3: A positron has a +1 change and the mass is considered to be zero for balancing the nuclear equation. When these are added to the right-side of the equation, both mass and charge are balanced .



18.2 Kinetics of Radioactive Decay

N (no of nuclides) $\longrightarrow$ daughter

$$\text{rate} = -\frac{\Delta N}{\Delta t} \qquad \text{rate} = kN$$

$$-\frac{\Delta N}{\Delta t} = kN$$

$$N = N_0 \exp(-kt) \qquad \ln N = \ln N_0 - kt$$

N = the number of atoms at time t

N_0 = the number of atoms at time $t = 0$

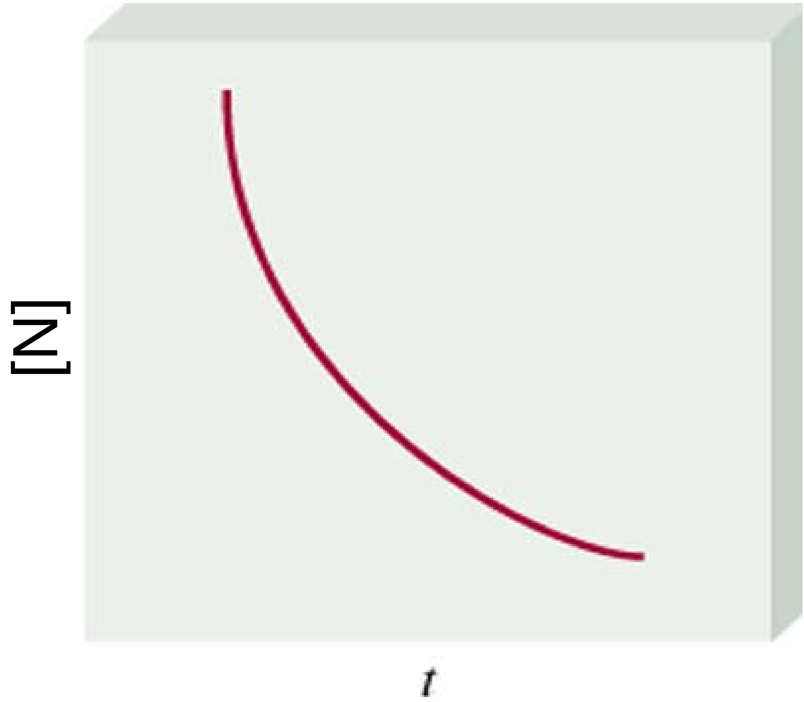
k is the decay constant

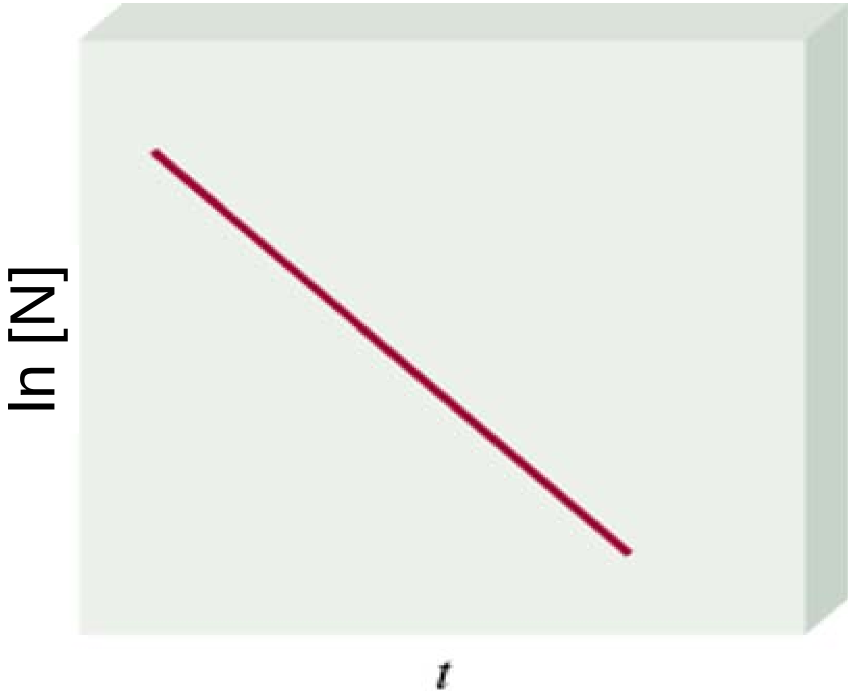
$$k = \frac{\ln 2}{t_{1/2}}$$

Kinetics of Radioactive Decay

$[N] = [N]_0 \exp(-\lambda t)$

$\ln[N] = \ln[N]_0 - \lambda t$





QUESTION

Iron is found in human blood; so using iron–59 (a beta emitter) can be used in several studies of red blood cells. The half-life of the nuclide is approximately 45.1 days. If a patient received a dose of iron–59 what percent would remain in their system after 30.0 days?

1. 35.3% remains
2. 63.1% remains
3. 66.5% remains
4. 158% (but this does not seem possible, what am I missing?)

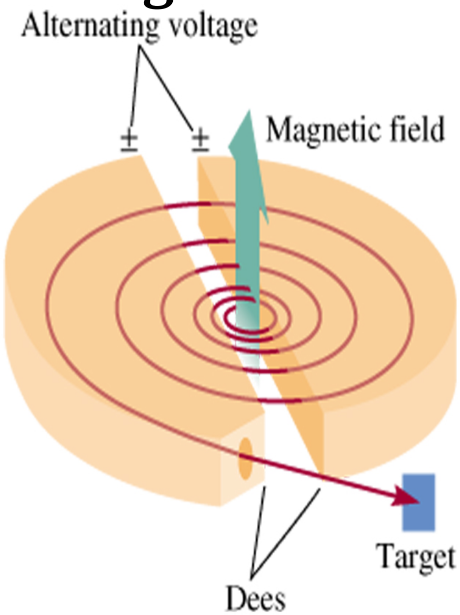
Choice 2 is the correct result. The decay kinetics of the nuclear process is first order.

$$\ln(N/N_0) = -(0.693/t_{1/2})\ t$$

In this case N_0 = 100.0 % so with proper substitution of the given values N = 63.1%

18.3 Nuclear Transformations

By bombarding an element with a-particle it will change to another



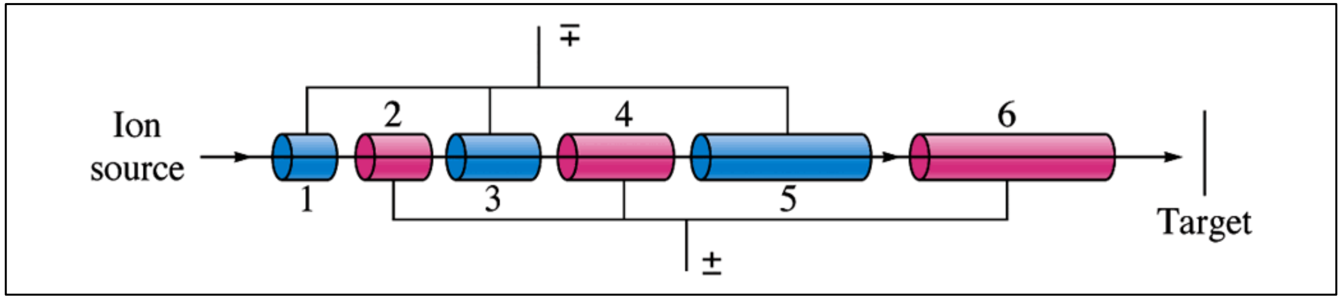
$$^{14}_{7}N + ^{4}_{2}\alpha \longrightarrow ^{17}_{8}O + ^{1}_{1}p$$

$$^{27}_{13}Al + ^{4}_{2}\alpha \longrightarrow ^{30}_{15}P + ^{1}_{0}n$$

$$^{14}_{7}N + ^{1}_{1}p \longrightarrow ^{11}_{6}C + ^{4}_{2}\alpha$$

Cyclotron Particle Accelerator

Linear particle accelerator



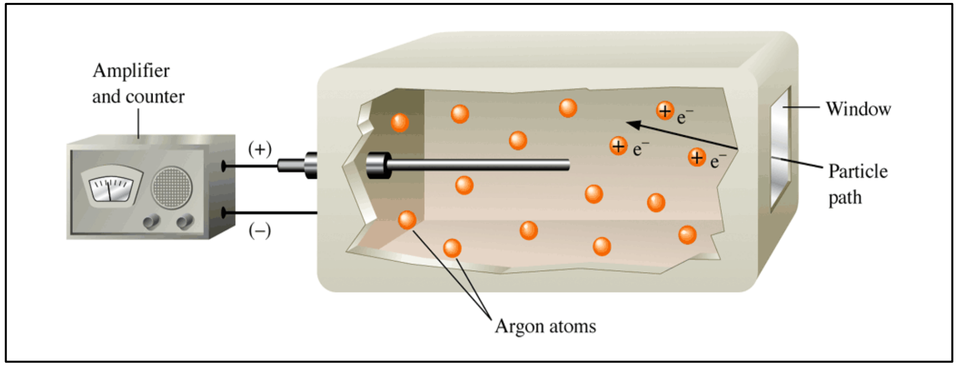
Nuclear Transmutation

The Transuranium Elements

Atomic Number	Name	Symbol	Preparation
93	Neptunium	Np	${}^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \longrightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}\beta$
94	Plutonium	Pu	${}^{239}_{93}\text{Np} \longrightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}\beta$
95	Americium	Am	${}^{239}_{94}\text{Pu} + {}^{1}_{0}\text{n} \longrightarrow {}^{240}_{95}\text{Am} + {}^{0}_{-1}\beta$
96	Curium	Cm	${}^{239}_{94}\text{Pu} + {}^{4}_{2}\alpha \longrightarrow {}^{242}_{96}\text{Cm} + {}^{1}_{0}\text{n}$
97	Berkelium	Bk	${}^{241}_{95}\text{Am} + {}^{4}_{2}\alpha \longrightarrow {}^{243}_{97}\text{Bk} + 2{}^{1}_{0}\text{n}$
98	Californium	Cf	${}^{242}_{96}\text{Cm} + {}^{4}_{2}\alpha \longrightarrow {}^{245}_{98}\text{Cf} + {}^{1}_{0}\text{n}$
99	Einsteinium	Es	${}^{238}_{92}\text{U} + 15{}^{1}_{0}\text{n} \longrightarrow {}^{253}_{99}\text{Es} + 7{}^{0}_{-1}\beta$
100	Fermium	Fm	${}^{238}_{92}\text{U} + 17{}^{1}_{0}\text{n} \longrightarrow {}^{255}_{100}\text{Fm} + 8{}^{0}_{-1}\beta$
101	Mendelevium	Md	${}^{253}_{99}\text{Es} + {}^{4}_{2}\alpha \longrightarrow {}^{256}_{101}\text{Md} + {}^{1}_{0}\text{n}$
102	Nobelium	No	${}^{246}_{96}\text{Cm} + {}^{12}_{6}\text{C} \longrightarrow {}^{254}_{102}\text{No} + 4{}^{1}_{0}\text{n}$
103	Lawrencium	Lr	${}^{252}_{98}\text{Cf} + {}^{10}_{5}\text{B} \longrightarrow {}^{257}_{103}\text{Lr} + 5{}^{1}_{0}\text{n}$
104	Rutherfordium	Rf	${}^{249}_{98}\text{Cf} + {}^{12}_{6}\text{C} \longrightarrow {}^{257}_{104}\text{Rf} + 4{}^{1}_{0}\text{n}$
105	Dubnium	Db	${}^{249}_{98}\text{Cf} + {}^{15}_{7}\text{N} \longrightarrow {}^{260}_{105}\text{Db} + 4{}^{1}_{0}\text{n}$
106	Seaborgium	Sg	${}^{249}_{98}\text{Cf} + {}^{18}_{8}\text{O} \longrightarrow {}^{263}_{106}\text{Sg} + 4{}^{1}_{0}\text{n}$
107	Bohrium	Bh	${}^{209}_{83}\text{Bi} + {}^{54}_{24}\text{Cr} \longrightarrow {}^{262}_{107}\text{Bh} + {}^{1}_{0}\text{n}$
108	Hassium	Hs	${}^{208}_{82}\text{Pb} + {}^{58}_{26}\text{Fe} \longrightarrow {}^{265}_{108}\text{Hs} + {}^{1}_{0}\text{n}$
109	Meitnerium	Mt	${}^{209}_{83}\text{Bi} + {}^{58}_{26}\text{Fe} \longrightarrow {}^{266}_{109}\text{Mt} + {}^{1}_{0}\text{n}$

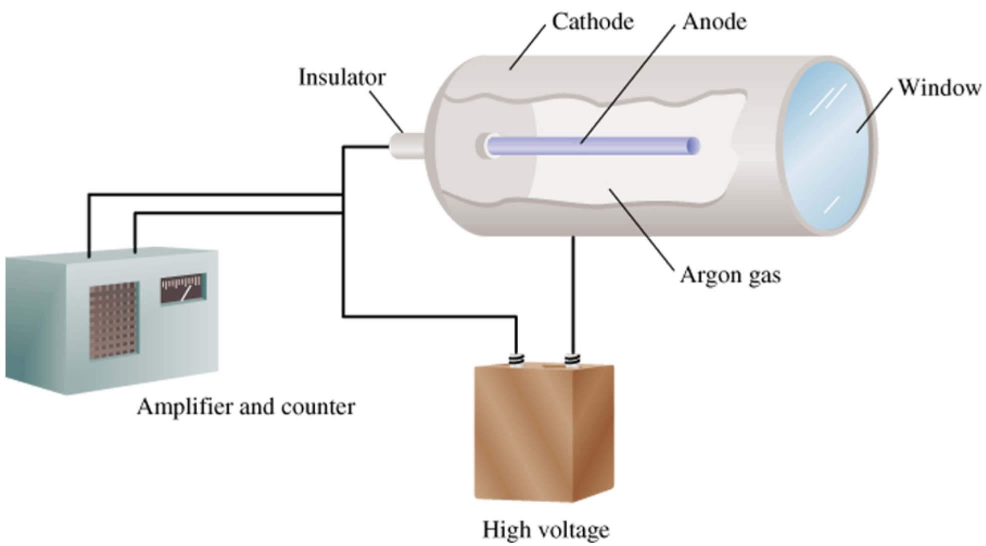
18.4 Detection and use of Radioactivity

Geiger-Müller Counter



$$Ar(g) \xrightarrow[\text{Particle}]{\text{High-energy}} Ar^{+}(g) + e^{-}$$

Scintillation Counter



Based on photocell senses

Dating by Radioactivity

- Archeologists and geologists rely heavily on radioactivities to provide accurate dates for artifacts and roks.
- C-14 dating method is used for dating ancient articles made from wood or cloth (1940, Willard Libby, Amer. Chemist).
  - Formation of C-14: $^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}H$
  - Decomposition of C-14: $^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e$
- As long as the plant lives, the $^{14}C/^{12}C$ ratio is the same. However, as soon as the tree is cut the ratio begins to decrease because of radioactive decay of C-14.
- Since the $t_{1/2}$ of C-14 is 5730 years, it is possible to identify the date of any carbon contained articles by using kinetic equation of C-14.

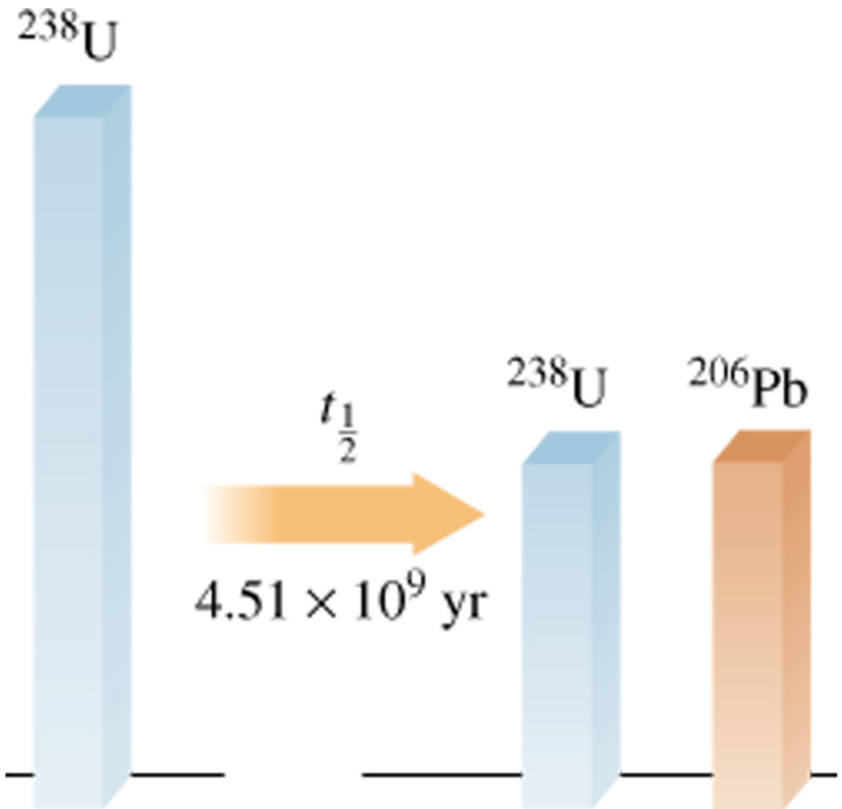
Dating by Radioactivity

Radiocarbon Dating

$$^{14}_{7}N + ^{1}_{0}n \longrightarrow ^{14}_{6}C + ^{1}_{1}H$$

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

$t_{½}$ = 5730 years



Uranium-238 Dating

$$^{238}_{92}U \longrightarrow ^{206}_{82}Pb + 8\,^{4}_{2}\alpha + 6\,^{0}_{-1}\beta$$

$t_{½}$ = 4.51 x 10^{9} years

QUESTION

In an archeological dig an ancient looking wood fragment arrangement is thought to be the remains of a campfire. A small sample is dated using radiocarbon techniques. How radioactive (in counts per minute per gram, CPM/g) would the sample be if it were 7 500 years old? [half-life of C–14 is 5 730 years and current carbon samples typically average 13.6 CPM/g]

1. 34 CPM/g
2. 4.7 CPM/g
3. 5.5 CPM/g
4. Less than 1 CPM/g

Choice 3: The first order kinetics rate law applies here:

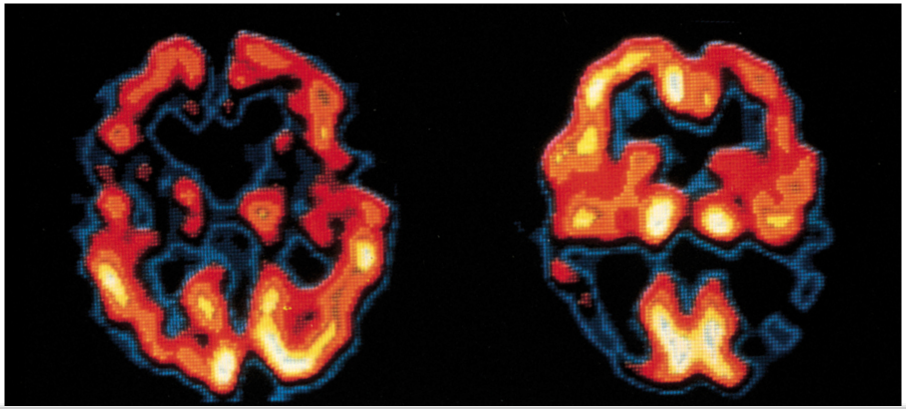
$$\ln (N/N_0) = (-\ .693/t_{1/2})t$$

Medical Applications

Using radiotracers

1 out of 3 hospital patients undergo a nuclear medicine procedure

- ^{24}Na, $t_{1/2}$ = 14.8 hr, β emitter, blood-flow tracer
- ^{131}I, $t_{1/2}$ = 14.8 hr, β emitter, thyroid gland activity
- ^{123}I, $t_{1/2}$ = 13.3 hr, γ–ray emitter, brain imaging
- ^{18}F, $t_{1/2}$ = 1.8 hr, β^+ emitter, positron emission tomography
- ^{99m}Tc, $t_{1/2}$ = 6 hr, γ–ray emitter, imaging agent



Brain images with ^{123}I-labeled compound

18.5 Thermodynamic Stability of Nucleus

Thermodynamic Stability is presented as energy released per nucleon. For example;

$$8\,{}^{1}_{1}p + 8\,{}^{1}_{0}n \longrightarrow {}^{16}_{8}O$$

Δ in mass of oxygen formation

= O-16 Mass – {8 [proton mass] + 8 [neutron mass]}

= 2.65535×10^{-23} g – {8 [1.67493 + 1.67262] x 10^{-24} g}

= **-2.269×10^{-25}** g

= **-0.1366 g/mol**

$E = mc^2$ (Einstein)

$\Delta E = \Delta mc^2$ = $(-1.366 \times 10^{-4}$ kg/mol) x $(3.00 \times 10^{8}$ m/s$)^2$

= -1.23×10^{13} J/mol

= -1.23×10^{13} J/mol /N_A = -2.04×10^{-11} J/nucleus

= -2.04×10^{-11} J/16 nucleon = **-1.275×10^{-12} J/nucleon**

This is the required energy to form O-16 atom from nuclear components

18.5 Thermodynamic Stability of Nucleus

Nuclear binding energy (BE) is the energy required to break up a nucleus into its component protons and neutrons.

$$BE + {}^{19}_{9}F \longrightarrow 9\,{}^{1}_{1}p + 10\,{}^{1}_{0}n$$

$$E = mc^2$$

$$BE = 9 \times (\text{p mass}) + 10 \times (\text{n mass}) - {}^{19}F \text{ mass}$$

$$BE\ (\text{amu}) = 9 \times 1.007825 + 10 \times 1.008665 - 18.9984$$

$$BE = 0.1587 \text{ amu} \qquad 1 \text{ amu} = 1.49 \times 10^{-10}\ J$$

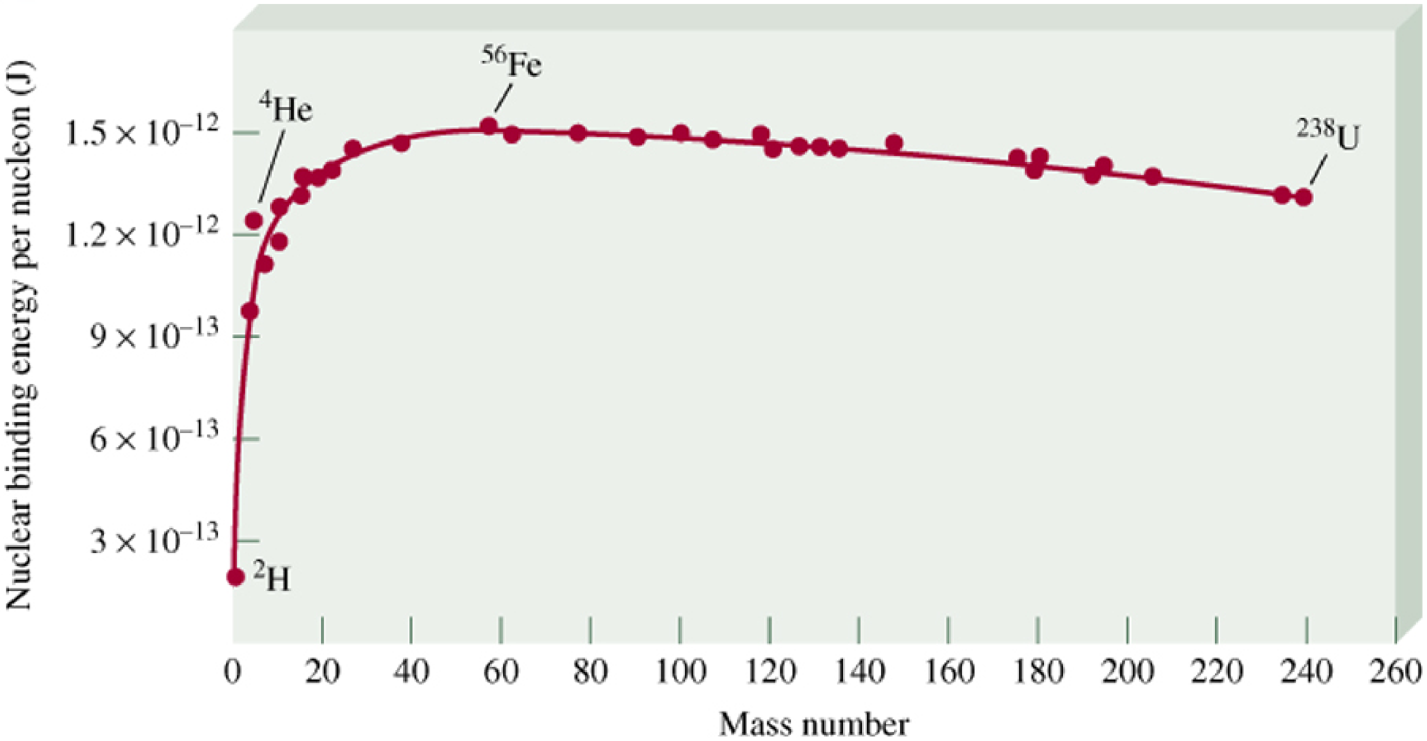
$$BE = 2.37 \times 10^{-11} J$$

$$\text{binding energy per nucleon} = \frac{\text{binding energy}}{\text{number of nucleons}}$$

$$= \frac{2.37 \times 10^{-11}\ J}{19 \text{ nucleons}} = 1.25 \times 10^{-12}\ J$$

Nuclear binding energy (BE)

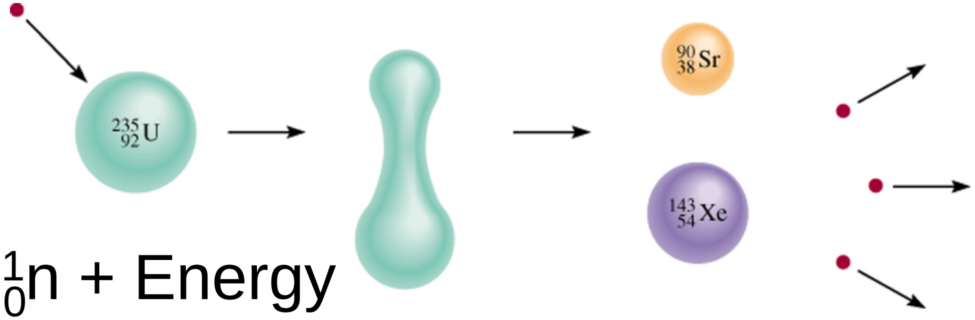
Nuclear binding energy per nucleon vs Mass number



$$\frac{\text{nuclear binding energy}}{\text{nucleon}} \uparrow \qquad \text{nuclear stability} \uparrow$$

18.6 Nuclear Fission and Nuclear Fusion

Nuclear Fission is the process at which heavy nucleus will be spitted into two or more nuclei with smaller number.



$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{90}_{38}Sr + ^{143}_{54}Xe + 3^{1}_{0}n + \text{Energy}$$

Energy = [mass ^{235}U + mass n – (mass ^{90}Sr + mass ^{143}Xe + 3 x mass n)] x c^2

Energy = 3.3×10^{-11} J per ^{235}U

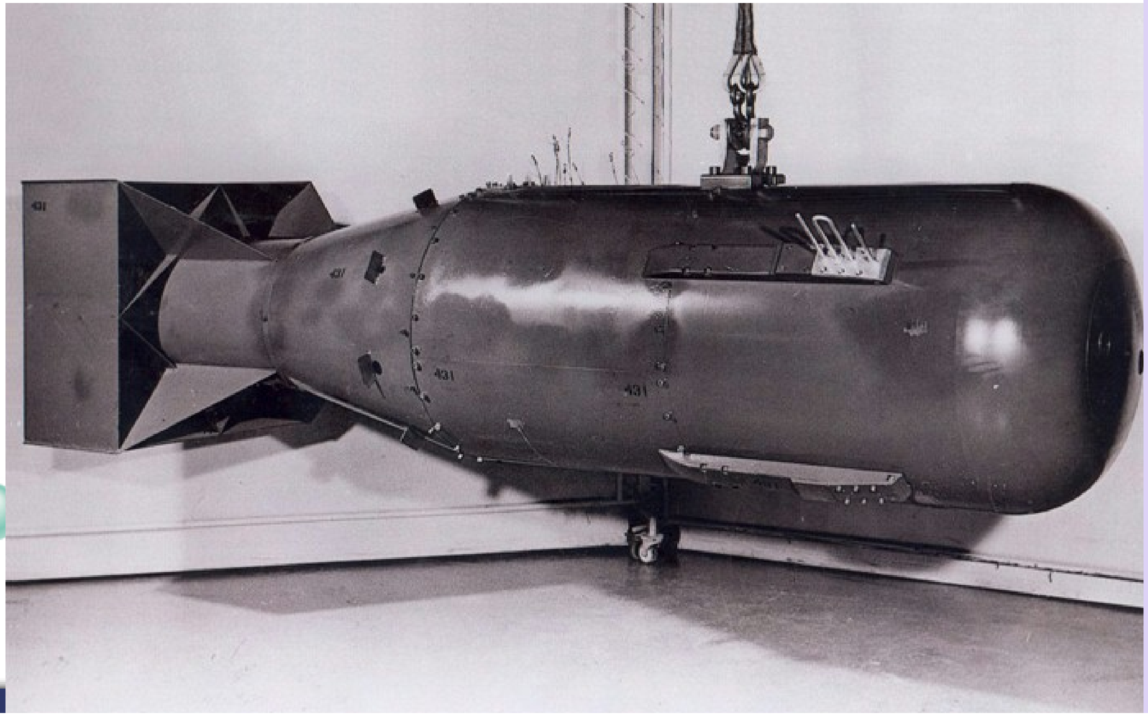
= 2.0×10^{13} J per mole ^{235}U

Combustion of 1 ton of coal = 5×10^{7} J

Nuclear Fission

Nuclear chain reaction is a self-sustaining sequence of nuclear fission reactions.

The minimum mass of fissionable material required to generate a self-sustaining nuclear chain reaction is the ***critical mass***.



Little boy

4000 Kg

3 m

0.7 m

64 kg of U-235

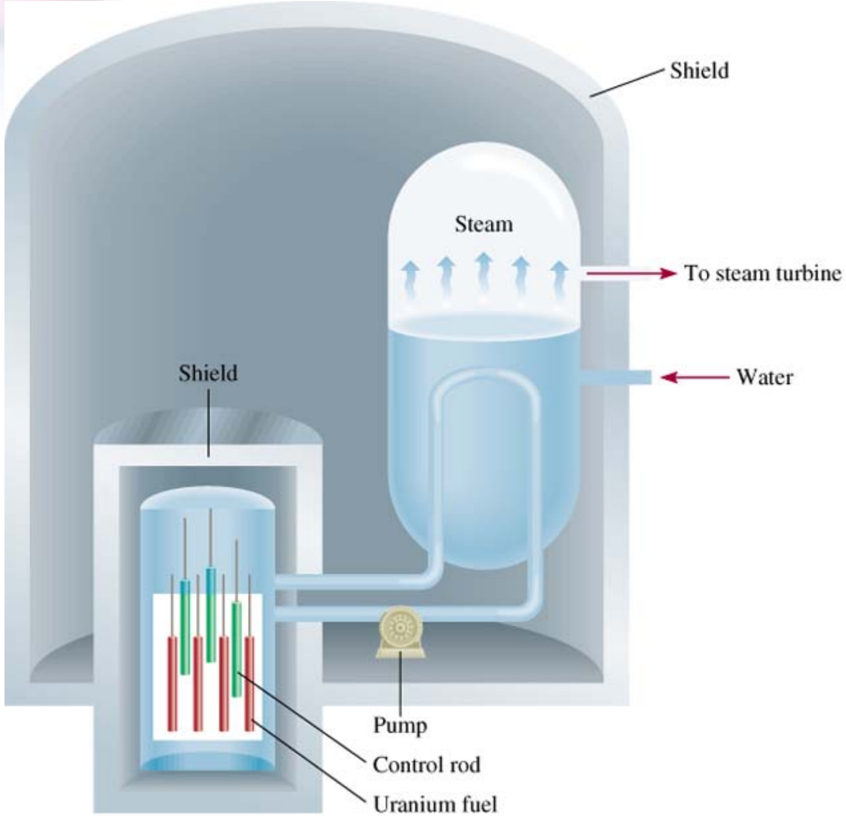
0.7 kg fission

0.6 kg Energy transfer

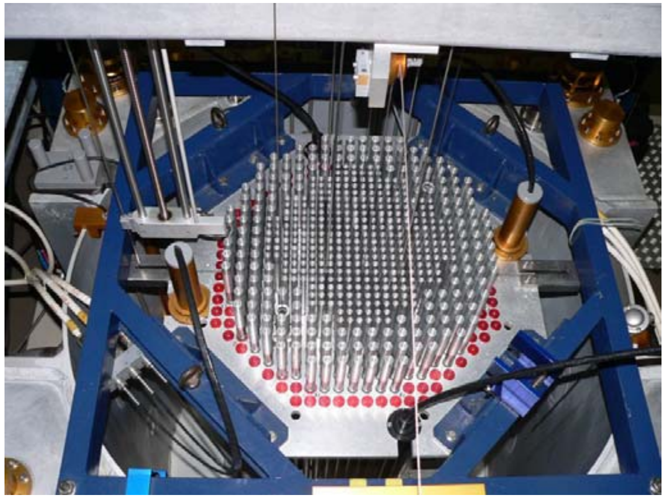
15 kton of TNT

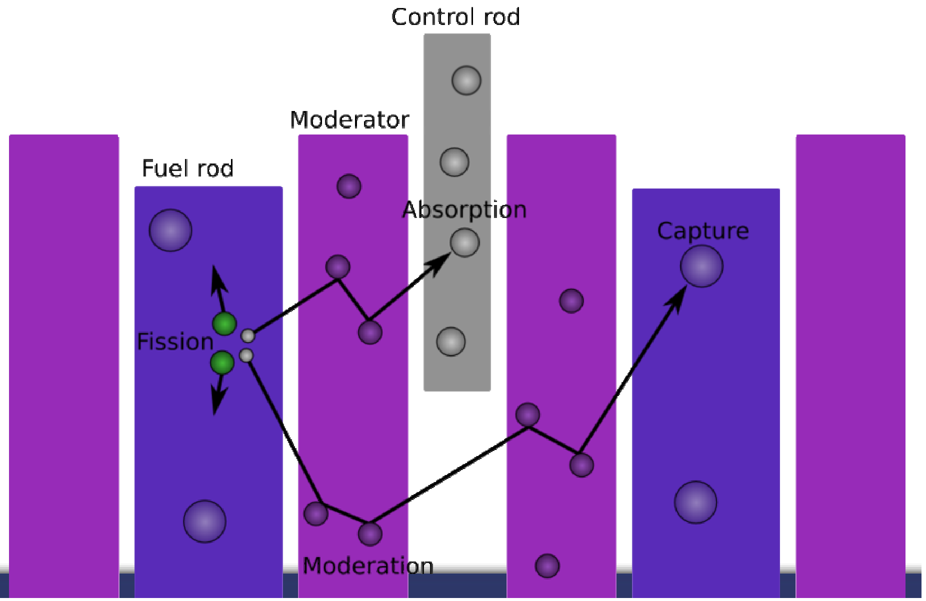
63 x 10^{12} J (TJ)

Nuclear Fission
Nuclear Reactors



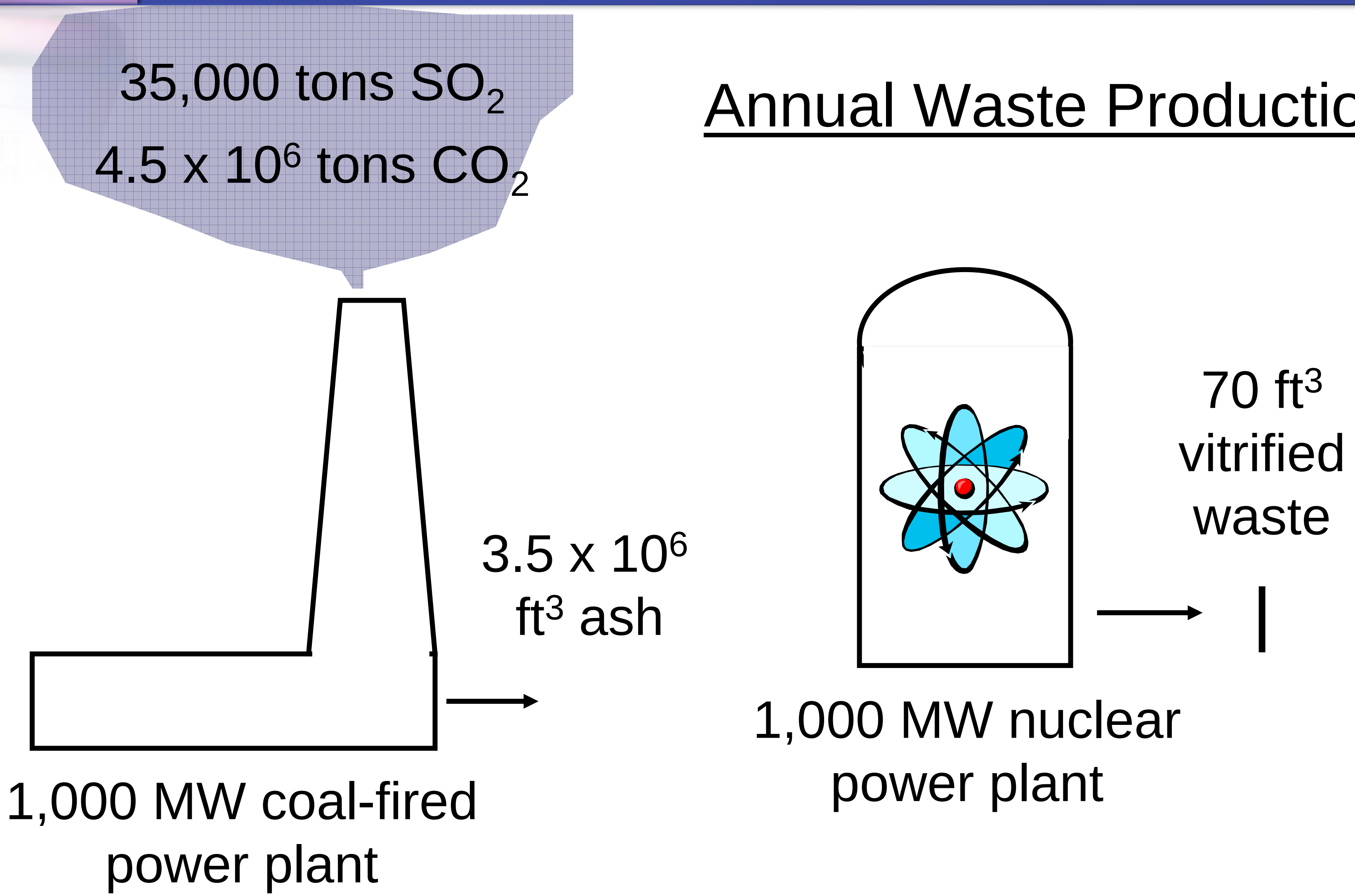
Schematic diagram of a nuclear fission reactor





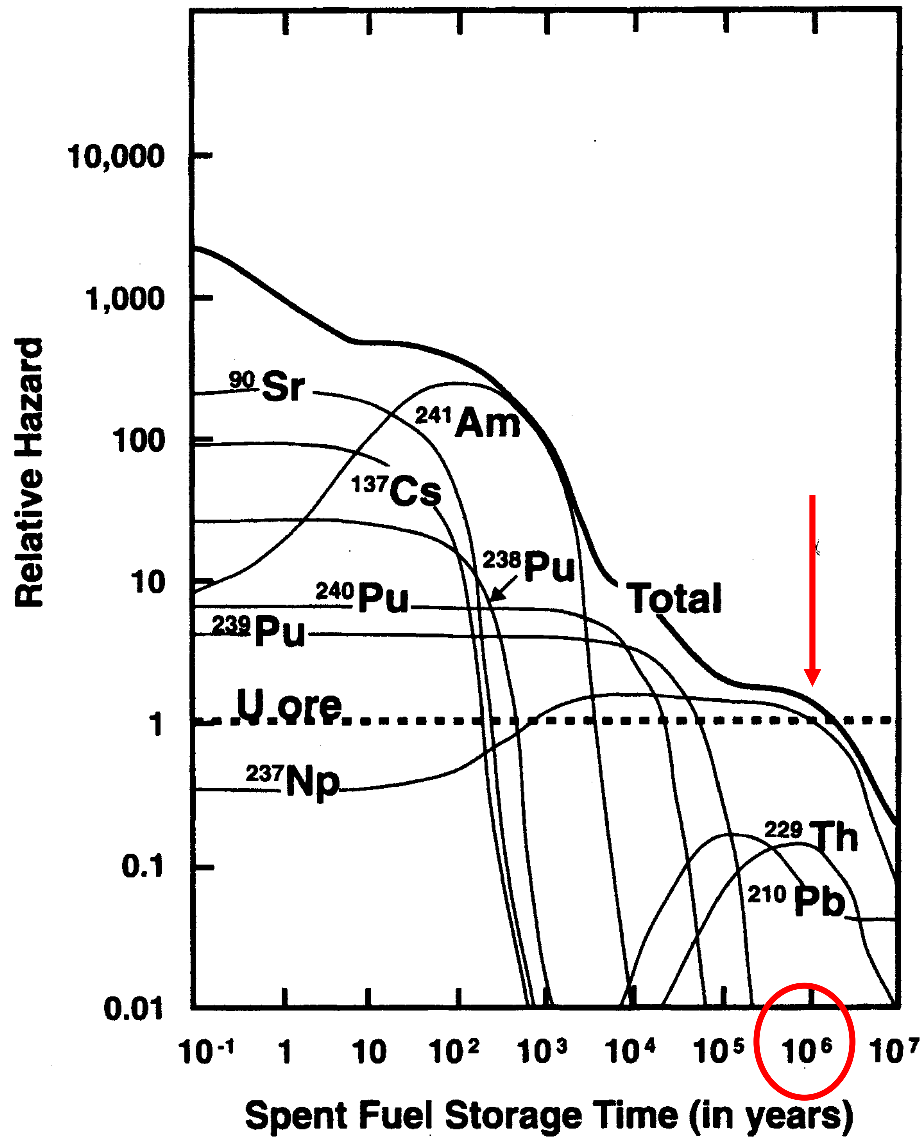
Nuclear Fission

Annual Waste Production



Nuclear Fission

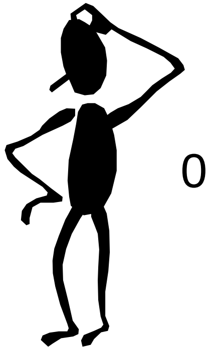
Hazards of the radioactivities in spent fuel compared to uranium ore



From “Science, Society and America’s Nuclear Waste,” DOE/RW-0361 TG

Nuclear Fission

Chemistry In Action: Nature's Own Fission Reactor

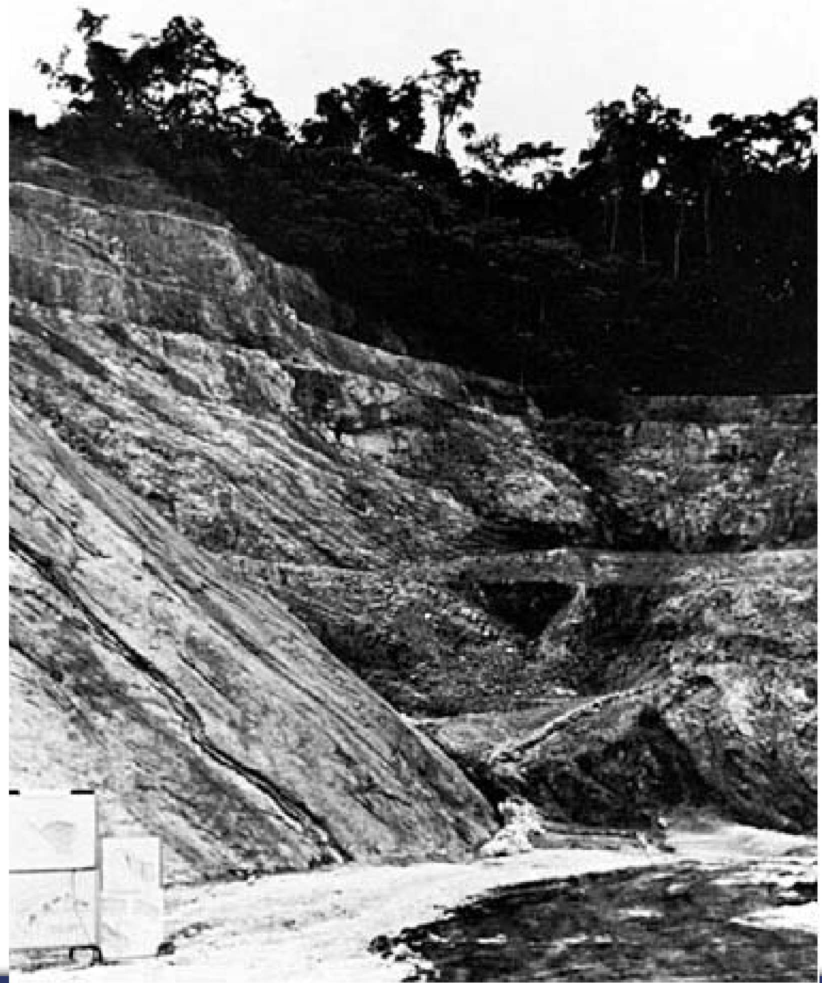


Natural Uranium

0.7202 % U-235 99.2798% U-238

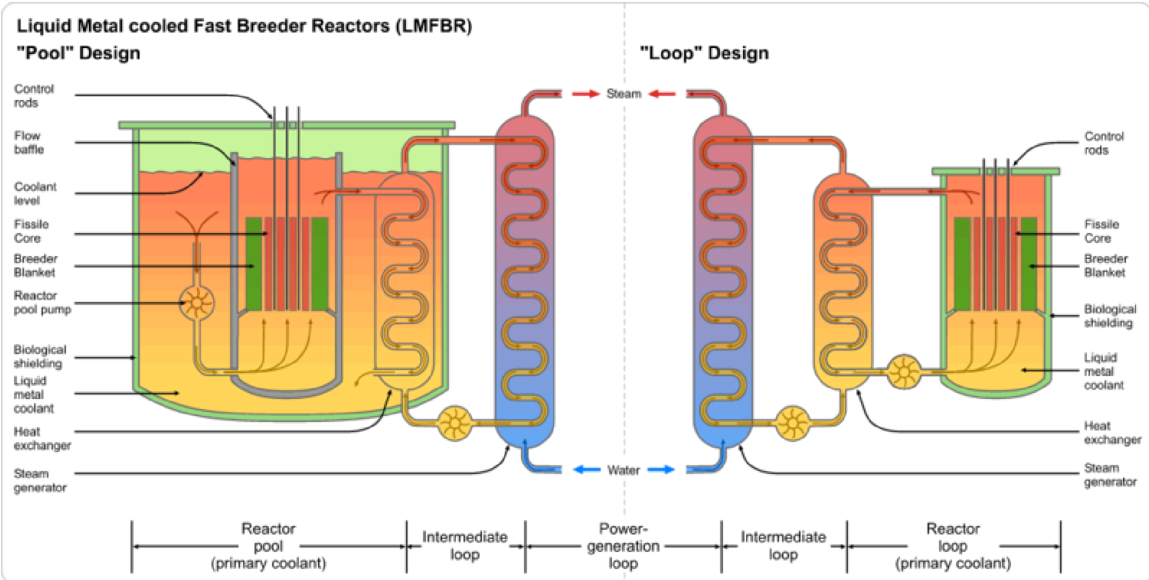
Measured at Oklo

0.7171 % U-235

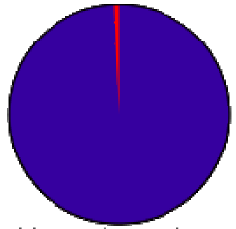


Nuclear Fission
Breeder Reactors

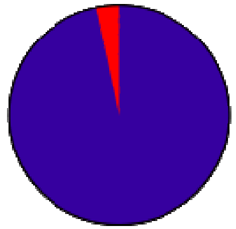
Using fissionable fuel that is rich enough in $^{235}_{92}U$ where the main component is natural uranium that will be fissionable to $^{239}_{93}Pu$



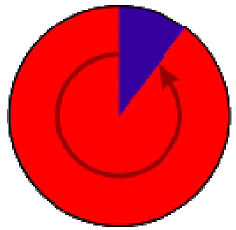
Schematic diagram of a nuclear breeder reactor



Natural uranium
> 99.2% U-238
0.72% U-235



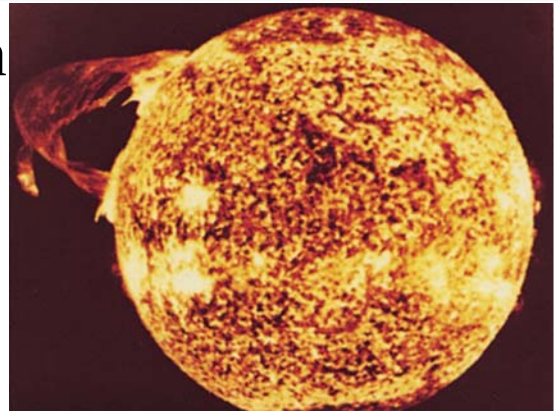
Low-enriched uranium
(reactor grade)
3-4% U-235



Highly enriched uranium
(weapons grade)
90% U-235

Nuclear Fusion

Stars produce their energy through nuclear fusion



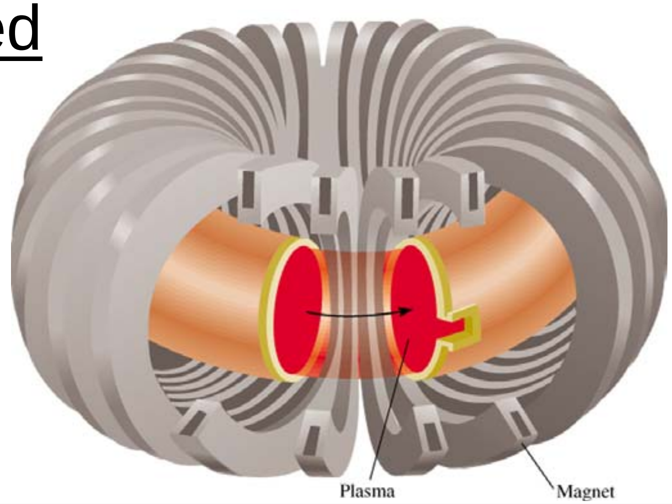
For example:

Sun consists of 73% Hydrogen
26% Helium
1% other elements

its vast quantities of energy is due to:

Fusion Reaction	Energy Released
$^{2}_{1}H + ^{2}_{1}H \longrightarrow ^{3}_{1}H + ^{1}_{1}H$	6.3×10^{-13} J
$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n$	2.8×10^{-12} J
$^{6}_{3}Li + ^{2}_{1}H \longrightarrow 2\ ^{4}_{2}He$	3.6×10^{-12} J

Tokamak magnetic plasma confinement



18.7 Effects of Radiation

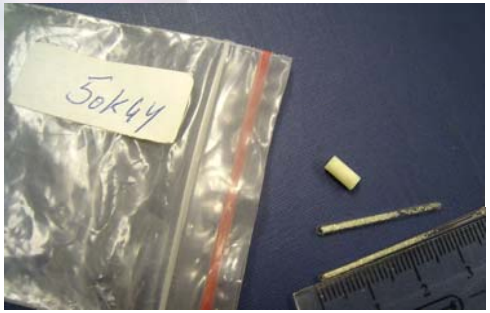
Radiation damage types:

1. Somatic damage: destroy organism resulting in sickness or death
2. Genetic damage: damage genetic machinery lead to cancer

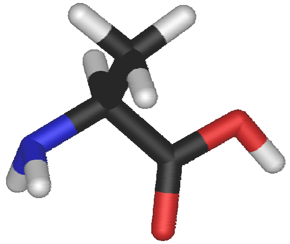
Damaging effect depends on:

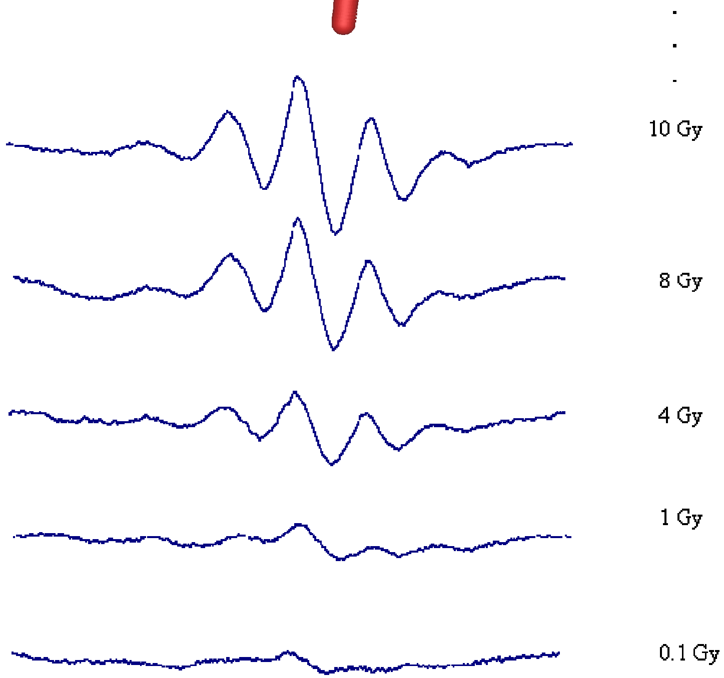
1. Energy of the radiation
   Higher energy more damage
2. Penetrating ability of rad.
   γ highly penetrate, β 1 cm, α stopped by the skin
3. Ionizing ability of rad.
   Extracting of electrons, g cause occasional ionization while a produce much ionizing damage
4. Chemical properties of radiation source
   The effectiveness of ingested radioactive materials in causing damage depend on its residence time in the human body, e.g., Kr no effect, Sr similar to Ca and may cause leukemia and bone cancer

Dosimeter Fabrication



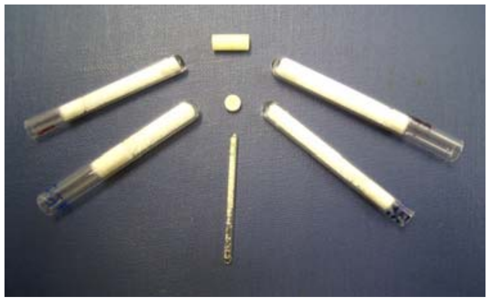
Representative samples of the home made alanine dosimeters





High Doses

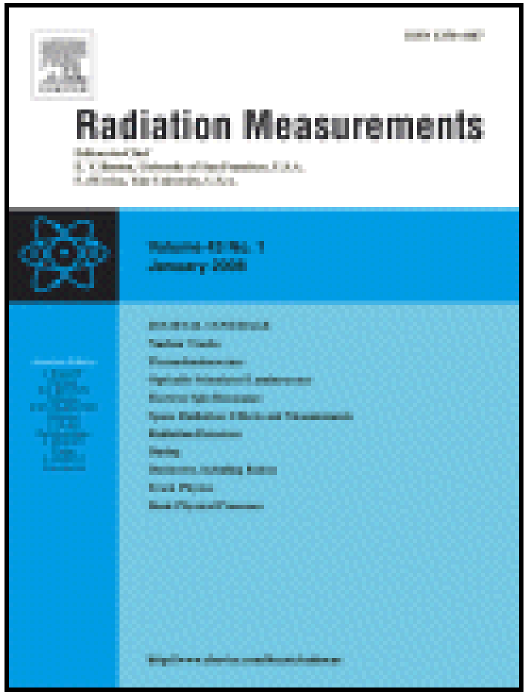
Low Doses



Disks,
Cylinders,
Alanine in glass,
Gassed, Degassed, or Open to air

Low Doses Irradiation

Relative P2P intensity of Alanine/Mn(II) samples at different doses



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EPR of gamma irradiated polycrystalline alanine-in-glass dosimeter

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Chemistry In Action: Food Irradiation

Dosage	Effect
Up to 100 kilorad	Inhibits sprouting of potatoes, onions, garlics. Inactivates trichinae in pork. Kills or prevents insects from reproducing in grains, fruits, and vegetables.
100 – 1000 kilorads	Delays spoilage of meat poultry and fish. Reduces salmonella. Extends shelf life of some fruit.
1000 to 10,000 kilorads	Sterilizes meat, poultry and fish. Kills insects and microorganisms in spices and seasoning.