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Chapter 19

Nuclear Chemistry

1

Review

Atomic number (Z) = number of protons in nucleus

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

= atomic number (Z) + number of neutrons

$$\text{Mass Number} \rightarrow A \quad \text{Atomic Number} \rightarrow Z \quad {}^{A}_{Z}\mathbf{X} \leftarrow \text{Element Symbol}$$

	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

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2

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.

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

$$235 + 1 = 138 + 96 + 2 \times 1$$

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.

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

$$92 + 0 = 55 + 37 + 2 \times 0$$

Comparing Nuclear and Chemical Equations

Table 19.1 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.

Example 19.1 1

Balance the following nuclear equations (that is, identify the product X):

(a) $^{212}_{84}\text{Po} \rightarrow ^{208}_{82}\text{Pb} + \text{X}$

(b) $^{137}_{55}\text{Cs} \rightarrow ^{137}_{56}\text{Ba} + \text{X}$

Example 19.1 2

Strategy

In balancing nuclear equations, note that the sum of atomic numbers and that of mass numbers must match on both sides of the equation.

Solution

a) The mass number and atomic number are 212 and 84, respectively, on the left-hand side and 208 and 82, respectively, on the right-hand side. Thus, X must have a mass number of 4 and an atomic number of 2, which means that it is an α particle. The balanced equation is

$$^{212}_{84}\text{Po} \rightarrow ^{208}_{82}\text{Pb} + ^{4}_{2}\alpha$$

Example 19.1 3

b) In this case, the mass number is the same on both sides of the equation, but the atomic number of the product is 1 more than that of the reactant. Thus, X must have a mass number of 0 and an atomic number of −1, which means that it is a β particle. The only way this change can come about is to have a neutron in the Cs nucleus transformed into a proton and an electron; that is, ${}^{1}_{0}\text{n} \rightarrow {}^{1}_{1}\text{p} + {}^{0}_{-1}\beta$
(note that this process does not alter the mass number). Thus, the balanced equation is

$${}^{137}_{55}\text{Cs} \rightarrow {}^{137}_{56}\text{Ba} + {}^{0}_{-1}\beta$$

Example 19.1 4

Check

Note that the equation in (a) and (b) are balanced for nuclear particles but not for electrical charges. To balance the charges, we would need to add two electrons on the right-hand side of (a) and express barium as a cation (Ba^{+}) in (b).

Nuclear Stability

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 $\left(e^{-}=2,10,18,54,\text{and}\,86\right)$

Nuclei with even numbers of both protons and neutrons are more stable than those with odd numbers of neutrons and protons

All isotopes of the elements with atomic numbers higher than 83 are radioactive

All isotopes of Tc and Pm are radioactive

 9

9

Stable Isotopes

Table 19.2 Number of Stable Isotopes with Even and Odd Numbers of Protons and Neutrons

Protons	Neutrons	Number of Stable Isotopes
Odd	Odd	4
Odd	Even	50
Even	Odd	53
Even	Even	164

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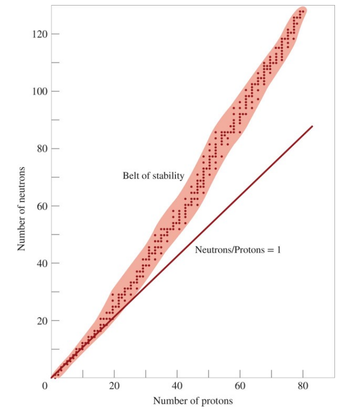
10

Ratio of Neutrons to Protons



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11

Nuclear Stability and Radioactive Decay 1

<u>Beta decay</u>

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

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

$^{1}_{0}n \rightarrow ^{1}_{1}p + ^{0}_{-1}\beta$

Decrease # of neutrons by 1

Increase # of protons by 1

<u>Positron decay</u>

$^{11}_{6}C \rightarrow ^{11}_{5}N + ^{0}_{+1}\beta$

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

$^{1}_{1}p \rightarrow ^{1}_{0}n + ^{0}_{+1}\beta$

Increase # of neutrons by 1

Decrease # of protons by 1

 12

12

Nuclear Stability and Radioactive Decay 2

Electron capture decay

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

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

$^{1}_{1}\text{p} + ^{0}_{-1}e \rightarrow ^{1}_{0}\text{n}$

Increase number of neutrons by 1

Decrease number of protons by 1

Alpha decay

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

Decrease number of neutrons by 2

Increase number of protons by 2

Spontaneous fission

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

13

13

Nuclear Binding Energy 1

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

$$\text{Nuclear binding energy} + ^{19}_{9}\text{F} \rightarrow 9\,^{1}_{1}\text{p} + 10\,^{1}_{0}\text{n}$$

$$E = (\Delta m)\,c^2$$

$$9 \times (\text{p mass}) + 10 \times (\text{n mass}) = 19.15708 \text{ amu}$$

$$\Delta m = 18.9984 \text{ amu} - 19.15708 \text{ amu}$$

$$\Delta m = -0.1587 \text{ amu}$$

$$\Delta E = -0.1587 \text{ amu} \times \left(3.00 \times 10^{8} \text{ m/s}\right)^2 = -1.43 \times 10^{16} \text{ amu m}^2/\text{s}^2$$

Using conversion factors:

$$1 \text{ kg} = 6.022 \times 10^{26} \text{ amu} \qquad 1 \text{ J} = \text{kg m}^2/\text{s}^2$$

$$\Delta \text{E} = -2.37 \times 10^{-11} \text{J}$$

14

14

Nuclear Binding Energy 2

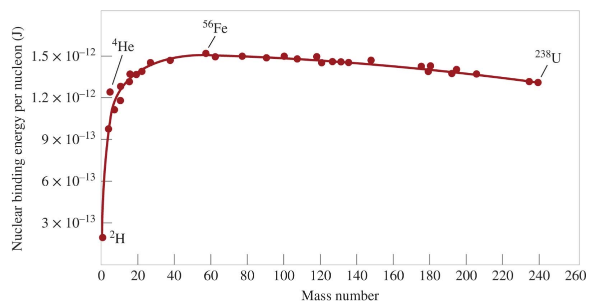
$$\Delta E = (-\,2.37 \times 10^{-11}\,\text{J}) \times (6.022 \times 10^{23}\,/\,\text{mol})$$
$$\Delta E = -1.43 \times 10^{13}\ \text{J/mol}$$
$$\Delta E = -1.43 \times 10^{10}\ \text{kJ/mol}$$

$$\text{Nuclear binding energy} = 1.43 \times 10^{10}\,\text{kJ/mol}$$
$$\text{binding energy per nucleon} = \frac{\text{binding energy}}{\text{number of nucleons}}$$
$$= \frac{2.37 \times 10^{-11}\ \text{J}}{19\ \text{nucleons}}$$
$$= 1.25 \times 10^{-12}\,\text{J/nucleon}$$

 15

15

Nuclear Binding Energy per Nucleon vs. Mass Number



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

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 16

16

Example 19.2 1

The atomic mass of $^{127}_{53}I$ is 126.9004 amu.
Calculate the nuclear binding energy of this nucleus and the corresponding nuclear binding per nucleon.

Example 19.2 2

Strategy

To calculate the nuclear binding energy, we first determine the difference between the mass of the nucleus and the mass of all the protons and neutrons, which gives us the mass defect. Next , we apply Equation (19.2) $\left[\Delta E = (\Delta m)\,c^2\right]$.

Solution

There are 53 protons and 74 neutrons in the iodine nucleus.

The mass of 53 $^{1}_{1}H$ atom is

$$53 \times 1.007825 \text{ amu} = 53.41473 \text{ amu}$$

The mass of 74 neutrons is

$$74 \times 1.008665 \text{ amu} = 74.64121 \text{ amu}$$

Example 19.2 3

Therefore, the predicted mass for $^{123}_{57}\text{I}$
is 53.41473 + 74.64121 = 128.05594 amu, and the mass defect is

$$\Delta m = 126.9004 \text{ amu} - 128.05594 \text{ amu}$$
$$= -1.1555 \text{ amu}$$

The energy released is

$$\Delta E = (\Delta m)\, c^2$$
$$= (-1.1555 \text{ amu})\ (3.00 \times 10^8 \text{ m/s})^2$$
$$= -1.04 \times 10^{17} \text{amu m}^2/\text{s}^2$$

 19

19

Example 19.2 4

Let's convert to a more familiar energy unit of joules. Recall that $1 \text{ J} = 1 \text{ kg} \cdot \text{m}^2/\text{s}^2$. Therefore, we need to convert amu to kg:

$$\Delta E = -1.04 \times 10^{17} \frac{\cancel{\text{amu}} \cdot \text{m}^2}{\text{s}^2} \times \frac{1.00 \cancel{\text{g}}}{6.022 \times 10^{23} \cancel{\text{amu}}} \times \frac{1 \text{ kg}}{1000 \cancel{\text{g}}}$$
$$= -1.73 \times 10^{-10} \frac{\text{kg} \cdot \text{m}^2}{\text{s}^2} = -1.73 \times 10^{-10} \text{ J}$$

Thus the nuclear binding energy is $\mathbf{1.73 \times 10^{10}}$ **J.** The nuclear binding energy per nucleon is obtained as follows:

$$= \frac{1.73 \times 10^{-10} \text{ J}}{127 \text{ nucleons}} = 1.36 \times 10^{-12} \text{ J/ nucleon}$$

 20

20

Kinetics of Radioactive Decay

N → daughter

rate = λN

$$\ln \frac{N_t}{N_0} = -\lambda t$$

N = the number of atoms at time t

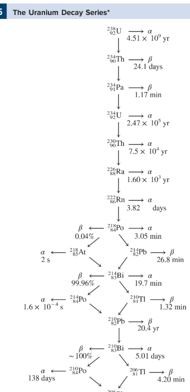
N_0 = the number of atoms at time $t = 0$

λ is the decay constant

$$t_{\frac{1}{2}} = \frac{0.693}{\lambda}$$

Uranium Decay Series

Table 19.5 The Uranium Decay Series*



*The times denote the half-lives.

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Dating

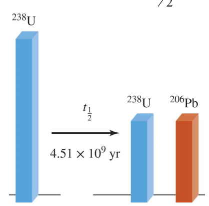
Radiocarbon Dating

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

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}\beta + \bar{\nu} \qquad t_{1/2} = 5730 \text{ years}$$

Uranium – 238 Dating

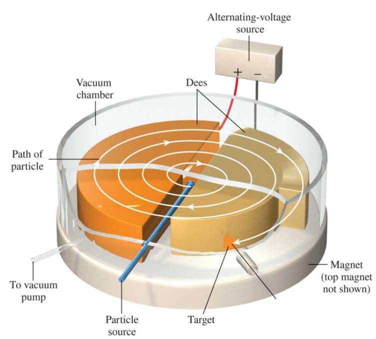
$$^{238}_{92}U \rightarrow ^{206}_{82}Pb + 8\,^{4}_{2}\alpha + 6\,^{0}_{-1}\beta \qquad t_{1/2} = 4.51\times10^{9} \text{ years}$$



 23

23

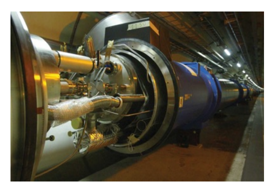
Nuclear Transmutation 1



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

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

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



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24

Nuclear Transmutation 2

Table 19.6 The Transuranium Elements

Atomic Number	Name	Symbol	Preparation
93	Neptunium	Np	${}^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{239}_{93}Np + {}^{0}_{-1}\beta$
94	Plutonium	Pu	${}^{239}_{93}Np \longrightarrow {}^{239}_{94}Pu + {}^{0}_{-1}\beta$
95	Americium	Am	${}^{239}_{94}Pu + {}^{1}_{0}n \longrightarrow {}^{240}_{95}Am + {}^{0}_{-1}\beta$
96	Curium	Cm	${}^{239}_{94}Pu + {}^{4}_{2}\alpha \longrightarrow {}^{242}_{96}Cm + {}^{1}_{0}n$
97	Berkelium	Bk	${}^{241}_{95}Am + {}^{4}_{2}\alpha \longrightarrow {}^{243}_{97}Bk + 2{}^{1}_{0}n$
98	Californium	Cf	${}^{242}_{96}Cm + {}^{4}_{2}\alpha \longrightarrow {}^{245}_{98}Cf + {}^{1}_{0}n$
99	Einsteinium	Es	${}^{238}_{92}U + 15{}^{1}_{0}n \longrightarrow {}^{253}_{99}Es + 7{}^{0}_{-1}\beta$
100	Fermium	Fm	${}^{238}_{92}U + 17{}^{1}_{0}n \longrightarrow {}^{255}_{100}Fm + 8{}^{0}_{-1}\beta$
101	Mendelevium	Md	${}^{253}_{99}Es + {}^{4}_{2}\alpha \longrightarrow {}^{256}_{101}Md + {}^{1}_{0}n$
102	Nobelium	No	${}^{246}_{96}Cm + {}^{12}_{6}C \longrightarrow {}^{254}_{102}No + 4{}^{1}_{0}n$
103	Lawrencium	Lr	${}^{252}_{98}Cf + {}^{10}_{5}B \longrightarrow {}^{257}_{103}Lr + 5{}^{1}_{0}n$
104	Rutherfordium	Rf	${}^{249}_{98}Cf + {}^{12}_{6}C \longrightarrow {}^{257}_{104}Rf + 4{}^{1}_{0}n$
105	Dubnium	Db	${}^{249}_{98}Cf + {}^{15}_{7}N \longrightarrow {}^{260}_{105}Db + 4{}^{1}_{0}n$
106	Seaborgium	Sg	${}^{249}_{98}Cf + {}^{18}_{8}O \longrightarrow {}^{263}_{106}Sg + 4{}^{1}_{0}n$
107	Bohrium	Bh	${}^{209}_{83}Bi + {}^{54}_{24}Cr \longrightarrow {}^{262}_{107}Bh + {}^{1}_{0}n$
108	Hassium	Hs	${}^{208}_{82}Pb + {}^{58}_{26}Fe \longrightarrow {}^{265}_{108}Hs + {}^{1}_{0}n$
109	Meitnerium	Mt	${}^{209}_{83}Bi + {}^{58}_{26}Fe \longrightarrow {}^{266}_{109}Mt + {}^{1}_{0}n$
110	Darmstadtium	Ds	${}^{208}_{82}Pb + {}^{62}_{28}Ni \longrightarrow {}^{269}_{110}Ds + {}^{1}_{0}n$
111	Roentgenium	Rg	${}^{209}_{83}Bi + {}^{64}_{28}Ni \longrightarrow {}^{272}_{111}Rg + {}^{1}_{0}n$
112	Copernicium	Cn	${}^{208}_{82}Pb + {}^{70}_{30}Zn \longrightarrow {}^{277}_{112}Cn + {}^{1}_{0}n$
113	Nihonium	Nh	${}^{228}_{115}Mc \longrightarrow {}^{284}_{113}Nh + {}^{4}_{2}\alpha$
114	Flerovium	Fl	${}^{244}_{94}Pu + {}^{48}_{20}Ca \longrightarrow {}^{289}_{114}Fl + 3{}^{1}_{0}n$
115	Moscovium	Mc	${}^{243}_{95}Am + {}^{48}_{20}Ca \longrightarrow {}^{288}_{115}Mc + 3{}^{1}_{0}n$
116	Livermorium	Lv	${}^{248}_{96}Cm + {}^{48}_{20}Ca \longrightarrow {}^{293}_{116}Lv + 3{}^{1}_{0}n$
117	Tennessine	Ts	${}^{249}_{97}Bk + {}^{48}_{20}Ca \longrightarrow {}^{297}_{117}Ts + 4{}^{1}_{0}n$
118	Oganesson	Og	${}^{249}_{98}Cf + {}^{48}_{20}Ca \longrightarrow {}^{294}_{118}Og + 3{}^{1}_{0}n$

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 25

25

Example 19.3 1

Write the balanced equation for the nuclear reaction

${}^{56}_{26}Fe\,(d, \alpha)\,{}^{25}_{54}Mn$

where d represents the deuterium nucleus $\left(\text{that is } {}^{1}_{2}H\right)$.

 26

26

Example 19.3 2

To write the balanced nuclear equation, remember that the first isotope $^{56}_{26}Fe$ is the reactant and the second isotope $^{54}_{25}Mn$ is the product. The first symbol in parentheses (d) is the bombarding particle and the second symbol in parentheses (α) is the particle emitted as a result of nuclear transmutation.

Example 19.3 3

Solution

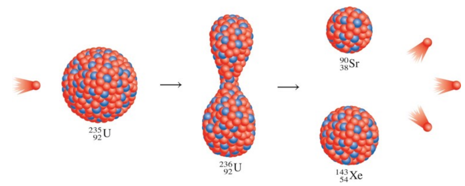
The abbreviation tells us that when iron-56 is bombarded with a deuterium nucleus, it produces the manganese-54 nucleus plus an α particle. Thus, the equation for this reaction is

$$^{56}_{26}Fe + ^{2}_{1}H \rightarrow ^{4}_{2}\alpha + ^{54}_{25}Mn$$

Check

Make sure that the sum of mass numbers and the sum of atomic numbers are the same on both sides of the equation.

Nuclear Fission 1



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

$$\text{Energy} = \left[\text{mass } ^{235}U + \text{mass n} - \left(\text{mass } ^{90}Sr + \text{mass } ^{143}Xe + 3 \times \text{mass n}\right)\right] \times c^2$$

$$\text{Energy} = 3.3\times10^{-11} \text{ J per } ^{235}U$$

$$= 2.0\times10^{13} \text{ J per mole } ^{235}U$$

$$\text{Combustion of 1 ton of coal} = 5\times10^{7} \text{ J}$$

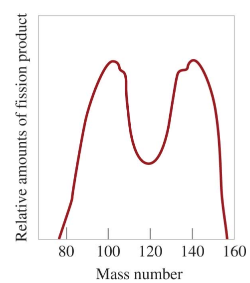
 29

29

Nuclear Fission 2

Representative fission reaction

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



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Nuclear Binding Energies

Table 19.5 Nuclear Binding Energies of ^{235}U and Its Fission Products

	Nuclear Binding Energy
^{235}U	2.83×10^{-10} J
^{90}Sr	1.23×10^{-10} J
^{143}Xe	1.92×10^{-10} J

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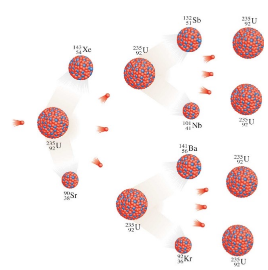
Nuclear Fission 3

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.***



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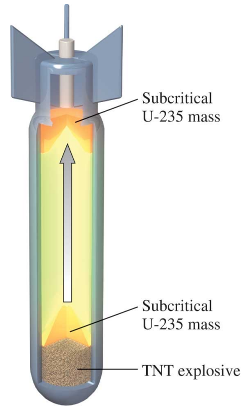
Schematic of an Atomic Bomb



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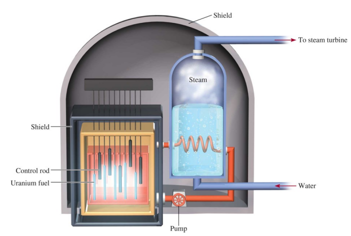
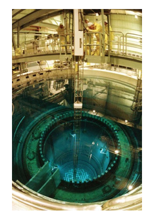
Schematic Diagram of a Nuclear Reactor



U_3O_8



refueling

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(Middle image): Marvin Lazarus/Science Source; (Right image): Toby Talbot/AP Images

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

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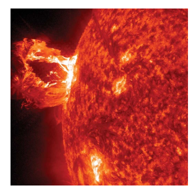
From Meshik, A.P., et.al.: The Workings of An Ancient Nuclear Reactor. Scientific American. November 2005; 293(5). Photo appeared on page 82-83. Photo by François Gauthier-Lafaye.

35

35

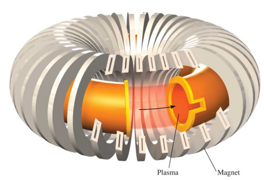
Nuclear Fusion

Fusion Reaction	Energy Released
${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{1}H + {}^{1}_{1}H$	4.9×10^{-13} J
${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$	2.8×10^{-12} J
${}^{6}_{3}Li + {}^{2}_{1}H \rightarrow 2\,{}^{4}_{2}He$	3.6×10^{-12} J



Solar Fusion

Tokamak magnetic plasma confinement



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NASA/SDO

36

36

Radioactive Isotopes in Medicine

Table 19.6 Some Radioactive Isotopes Used in Medicine

Isotope	Half-Life	Uses
^{18}F	1.8 h	Brain imaging, bone scan
^{24}Na	1.5 h	Monitoring blood circulation
^{32}P	14.3 d	Location of ocular, brain, and skin tumors
^{43}K	22.4 h	Myocardial scan
^{47}Ca	4.5 d	Study of calcium metabolism
^{51}Cr	27.8 d	Determination of red blood cell volume, spleen imaging, placenta localization
^{60}Co	5.3 yr	Sterilization of medical equipment, cancer treatment
99mTc	6 h	Imaging of various organs, bones, placenta location
^{125}I	60 d	Study of pancreatic function, thyroid imaging, liver function
^{131}I	8 d	Brain imaging, liver function, thyroid activity

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 37

37

Radioisotopes in Medicine

Research production of ^{99}Mo

$$^{98}_{42}Mo + ^{1}_{0}n \rightarrow ^{99}_{42}Mo$$

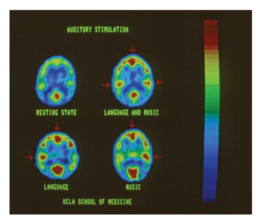
Commercial production of ^{99}Mo

$$^{235}_{95}U + ^{1}_{0}n \rightarrow ^{99}_{42}Mo + \text{other fission products}$$

$$^{99}_{42}Mo \rightarrow ^{99m}_{43}Tc + ^{0}_{-1}\beta \qquad t_{1/2} = 66 \text{ hours}$$

$$^{99m}_{43}Tc \rightarrow ^{99}_{43}Tc + \gamma - \text{ray} \qquad t_{1/2} = 6 \text{ hours}$$

Bone Scan with ^{99m}Tc

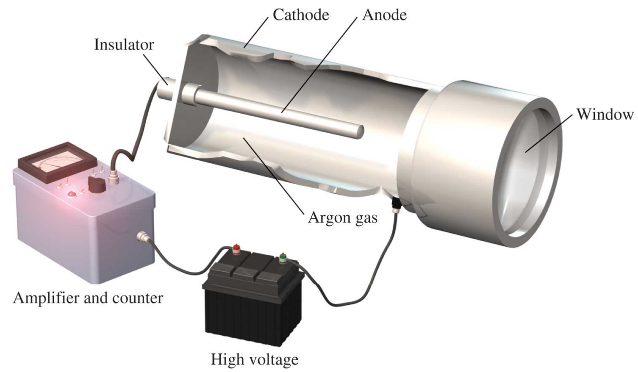


Dr. John Mazziotta et al./Neurology/Science Source

 38

38

Geiger-Müller Counter



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 39

39

Biological Effects of Radiation

Radiation absorbed dose (rad)

$$1 \text{ rad} = 1\times10^{-5} \text{ J/g of material}$$

Roentgen equivalent for man (rem)

$$1 \text{ rem} = 1 \text{ rad} \times \text{Q}$$

Quality Factor

γ- ray $= 1$

$\beta = 1$

$\alpha = 20$

Table 19.7 Average Yearly Radiation Doses for Americans

Source	Dose (mrem/yr)*
Cosmic rays	20-50
Ground and surroundings	25
Human body†	26
Medical and dental X rays	50-75
Air travel	5
Fallout from weapons tests	5
Nuclear waste	2
Total	133-188

*1 mrem = 1 millirem = 1×10^{-3} rem

†The radioactivity in the body comes from food and air.

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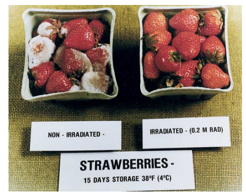
Chemistry In Action: Food Irradiation

Food Irradiation Dosages and Their Effects*

Dosage	Effect
Low dose (Up to 100 kilorads)	Inhibits sprouting of potatoes, onions, garlics. Inactivates trichinae in pork. Kills or prevents insects from reproducing in grains, fruits, and vegetables after harvest.
Medium dose (100 to 1000 kilorads)	Delays spoilage of meat, poultry, and fish by killing spoilage microorganism. Reduces salmonella and other food-borne pathogens in meat, fish, and poultry. Extends shelf life by delaying mold growth on strawberries and some other fruits.
High dose (1000 to 10,000 kilorads)	Sterilizes meat, poultry, fish, and some other foods. Kills microorganisms and insects in spices and seasoning.

*Source: *Chemical & Engineering News*, May 5 (1986).



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