NUCLEAR CHEMISTRY

Nuclear reactions

reactions involve atomic nuclei
lead to changes in atoms

conversion of an atom into another

Isotopes

atoms having same atomic number
but different mass number

oxygen-17

Nuclear reactions

reactions involve atomic nuclei
lead to changes in atoms

conversion of an atom into another

Isotopes

atoms having same atomic number
but different mass number

oxygen-17 $^{17}_{8}\mathrm{O}$

Two sources of radioactivity

Natural radioactivity

isotopes present sincethe earth formed eg uranium-238 or 235
or produced by cosmic rays from the sun eg carbon-14

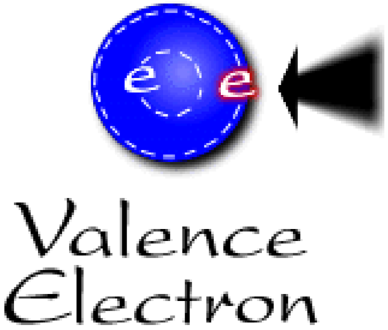
Synthetic radioactivity

isotopes made in nuclear reactors when atoms are split (fission).
Cyclotrons, particle accelerators

What is radioactivity?

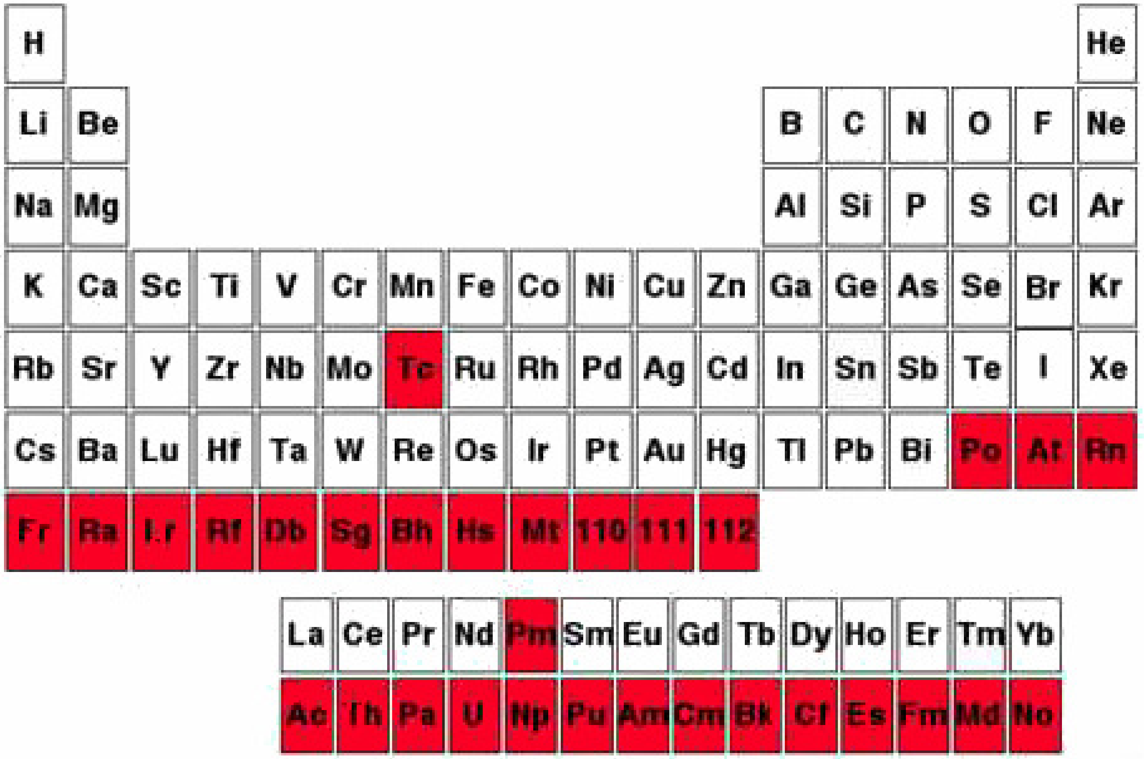
- Normal chemical reactions involve electrons

Valence electrons



What is radioactivity?

- unstable atoms ⇨ stable atoms

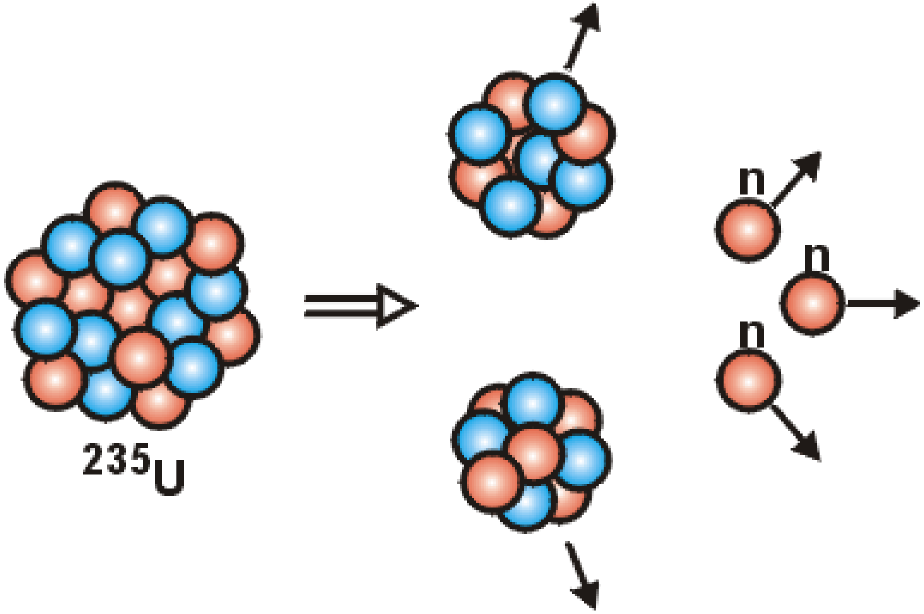


H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	110	111	112						
				La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
				Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

Elements that are naturally radioactive

What is radioactivity?

- unstable atoms ⇨ stable atoms



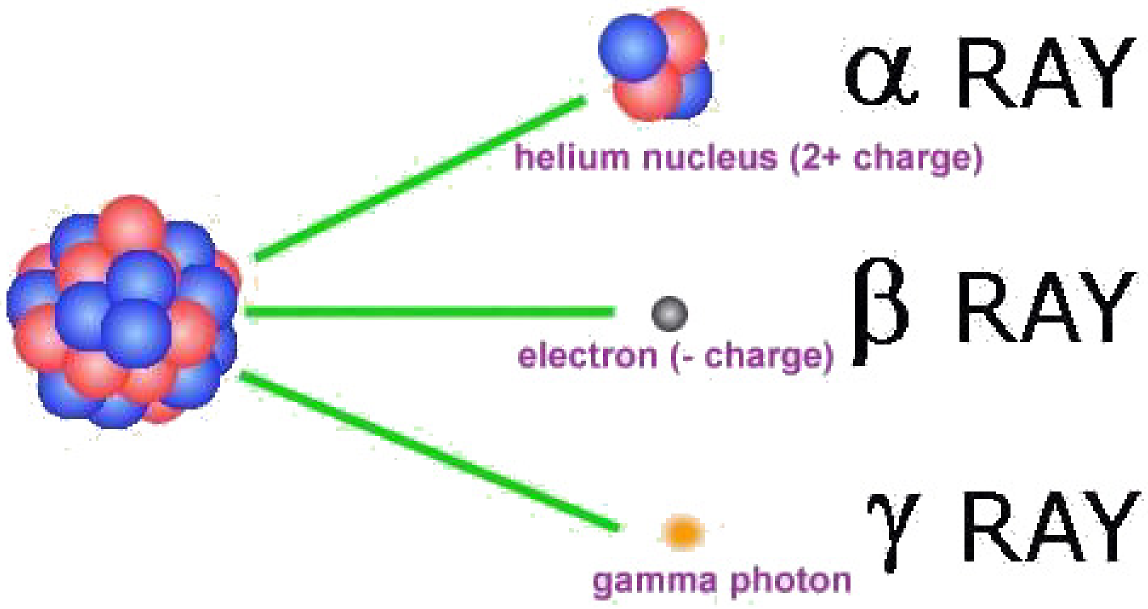
What is radioactivity?

Our understanding of atomic structure came from studies of radioactive elements

What is radioactivity?

the process by which atoms spontaneously emit high energy particles or rays from their nucleus

What is radioactivity?



Radioactivity unknown before 20th century

Discovered by Röntgen and Becquerel

Röntgen discovered X-rays in cathode ray tubes in 1895

Wilhelm Röntgen (1845-1923)

Röntgen:rays produced a fog on photographic plates

World’s first X-ray: Bertha Röntgen’s hand

Becquerel (1845-1923)
U compounds
produced fog on
photographic plates

Discovered (1896) it was
naturally radioactive

MARIE CURIE

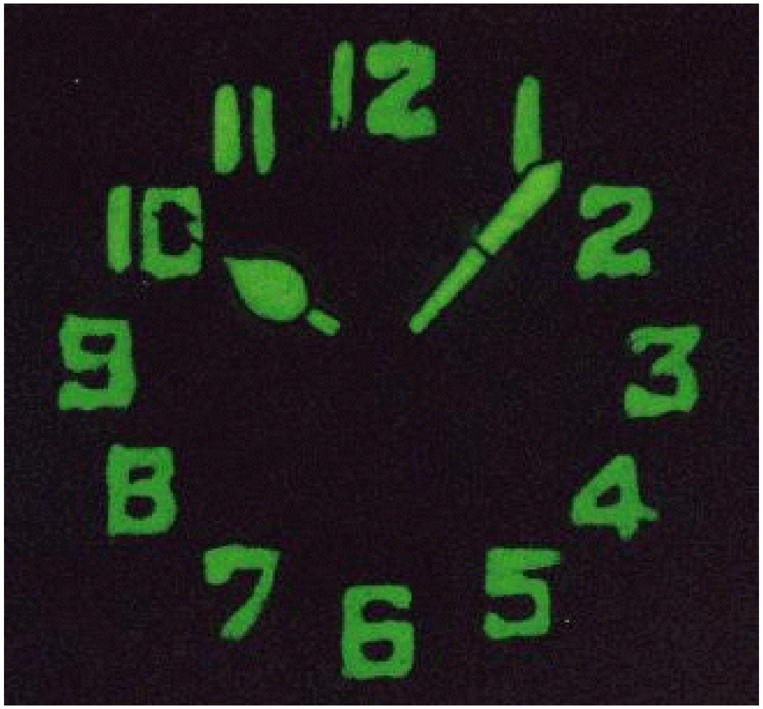
1867-1934

Showed other elements - thorium- were radioactive

With Pierre Curie, discovered and isolated new elements:
radium, polonium

Radium millions of times more active than uranium

Radium



Good for nervous disorders, insomnia, general debility, arthritis, and rheumatism.

This large pottery crock was lined with radium ore

Vita Radium Suppositories (ca.1930)

Common particles

$^{4}_{2}\mathrm{He}$

$^{0}_{-1}\mathrm{e}$

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

$^{1}_{0}\mathrm{n}$

$^{0}_{0}\gamma$

Types of Nuclear Reactions

1. **Radioactive decay:**
   unstable nucleus

2. **Transmutation:**
   Atoms change into new atoms

Types of Nuclear Reactions

3. **Fission:**
   Heavy into lighter nucleus
4. **Fusion**
   Light into heavier nucleus

Nuclear Equations

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

Atomic numbers must equal

Mass numbers must equal

Nuclear Equations

$$^{82}_{35}\mathrm{Br} \rightarrow \; ^{82}_{36}\mathrm{Kr} + \; ^{0}_{-1}\mathrm{e}$$

How can electrons come from nucleus?

Nuclear Equations

$$^{82}_{35}\mathrm{Br} \rightarrow \, ^{82}_{36}\mathrm{Kr} + \, ^{0}_{-1}\mathrm{e}$$

How can electrons come from nucleus?

$$^{1}_{0}\mathrm{n} \rightarrow \, ^{1}_{1}\mathrm{H} + \, ^{0}_{-1}\mathrm{e}$$

Nuclear Equations

$${}^{9}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C} + ?$$

Nuclear Equations

$$^{9}_{4}\mathrm{Be} + ^{4}_{2}\mathrm{He} \rightarrow ^{12}_{6}\mathrm{C} + ^{1}_{0}?$$

Nuclear Equations

$$ {}^{9}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}\mathrm{n} $$

Nuclear Equations

$$^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \rightarrow \ ? \ + {}^{1}_{1}\mathrm{H}$$

Nuclear Equations

$$^{14}_{7}\mathrm{N} + ^{4}_{2}\mathrm{He} \rightarrow ^{17}_{8}\mathrm{O} + ^{1}_{1}\mathrm{H}$$

Energy released

$$\Delta E = \Delta m \times c^2$$

Convert:

Atomic Mass Units (amu) into kg

1 amu = 1.66×10^{-27} kg

Mass (kg) =

mass number × 1.66×10^{-27} kg

(amu)

Energy released

Compare predicted and experimental He masses

Predicted mass =
$2p^+ + 2n + 2e^- = 4.0320$ amu

Experiment mass = 4.0015 amu

Mass

= Δm

Energy released

$$\Delta E = \Delta m \times c^2$$

Mass → nuclear binding energy

$$E = 0.0305 \times 1.66 \times 10^{-27} \times (3 \times 10^{8})^{2}$$

$$= 4.5 \times 10^{-12} \text{ J per atom}$$

For 1 mole: $E = 2.7 \times 10^{9}$ kJ

Energy released

$$\Delta E = \Delta m \times c^2$$

Also used to find E released during any nuclear reaction

Energy released

$$\Delta E = \Delta m \times c^2$$

Also used to find E released during any nuclear reaction

$$^{210}_{84}\text{Po} \rightarrow \, ^{206}_{82}\text{Pb} + \, ^{4}_{2}\text{He}$$

209.9829 **205.9745** **4.0026**

Need Δm

Energy released

Δm = initial mass - final mass

= (mass Po) - (mass Pb + He)

= 209.9829 - (205.9745 + 4.0026)

$$^{210}_{84}\mathrm{Po} \rightarrow {}^{206}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$$

209.9829	205.9745	4.0026

Δm = 0.058 amu

Energy released

$\Delta E = \Delta m \times c^2$

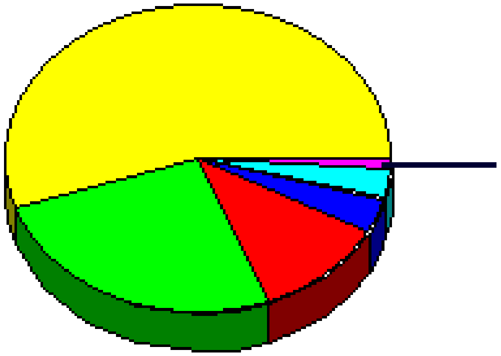
$= (0.0058 \times 1.66 \times 10^{-27}) \times (3 \times 10^8)^2$

$= 2.89 \times 10^{-13}$ J

$${}^{210}_{84}\mathrm{Po} \rightarrow {}^{206}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$$

209.9829	205.9745	4.0026

Sources of Radiation Exposure



Other
- Occupation 0.3%
- Fallout < 0.3%
- Nuclear Fuel Cycle 0.1%
- Misc. 0.1%

🟨 Radon (55%)
🟩 Natural Sources (excluding Radon) (26%)
🟥 Medical X-rays (11%)
🟦 Nuclear Medicine (4%)
▢ Consumer Products (3%)
🟪 Other (<1%)

Radon

Second leading cause of lung cancer in the US.

Causes 1000's of lung cancer deaths per year.

Radon:
What Is It?

86
Rn
222

Colorless, odorless and tasteless radioactive gas
In most rocks and soil

Released by decay of uranium

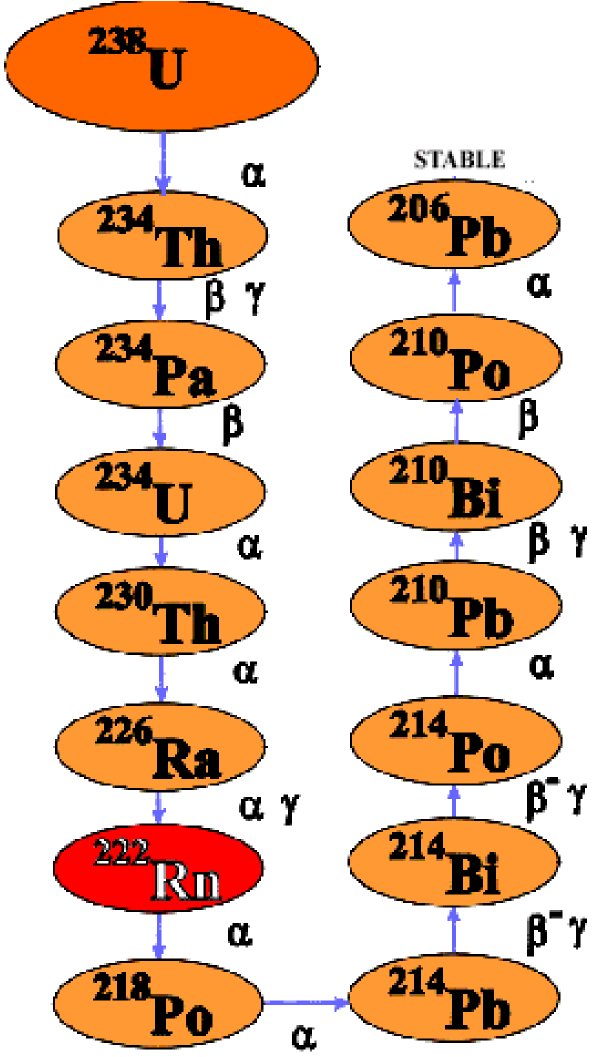
Dispersed outdoors
Possible high levels indoors

RADON
IN ALABAMA

High levels in15 counties

Madison and Colbert greatest

Where does radon come from ?
Why is radon dangerous ?



Radon: gas

Polonium: solid

Shielding

Alpha particles

blocked by: 1 cm of air
sheet of paper
human skin

If α-emitting isotopes inhaled or ingested → harmful.

Shielding

Beta particles
requires 1 mm of Al to block

If β-emitting isotopes inhaled or ingested → absorbed by bones

Shielding

Gamma and X-rays

need thick concrete or lead to block

most penetrating
severe damage to internal organs

Measuring Radiation

Geiger counter:
radiation ionizes argon ⇨ current

Units of radiation

Becquerel (Bq)

SI unit = 1 disintegration/sec

Curie (Ci)

amount of radioactive material decaying at same rate as 1 g of Ra

= 3.7×10^{10} dis/sec

1 Ci = 3.7×10^{10} Bq

Measure radioactive decay

Units of radiation

Gray (Gy)

1 Gy of radiation deposits 1 J of energy per kg of matter (SI unit)

Rad **1 Rad = 0.01 Gy**

Measure equivalent dose

Units of radiation

Sievert (Sv) 1 Sv = 100 rem

Rem
rad equivalent for humans, used to describe biological damage

Measure absorbed dose

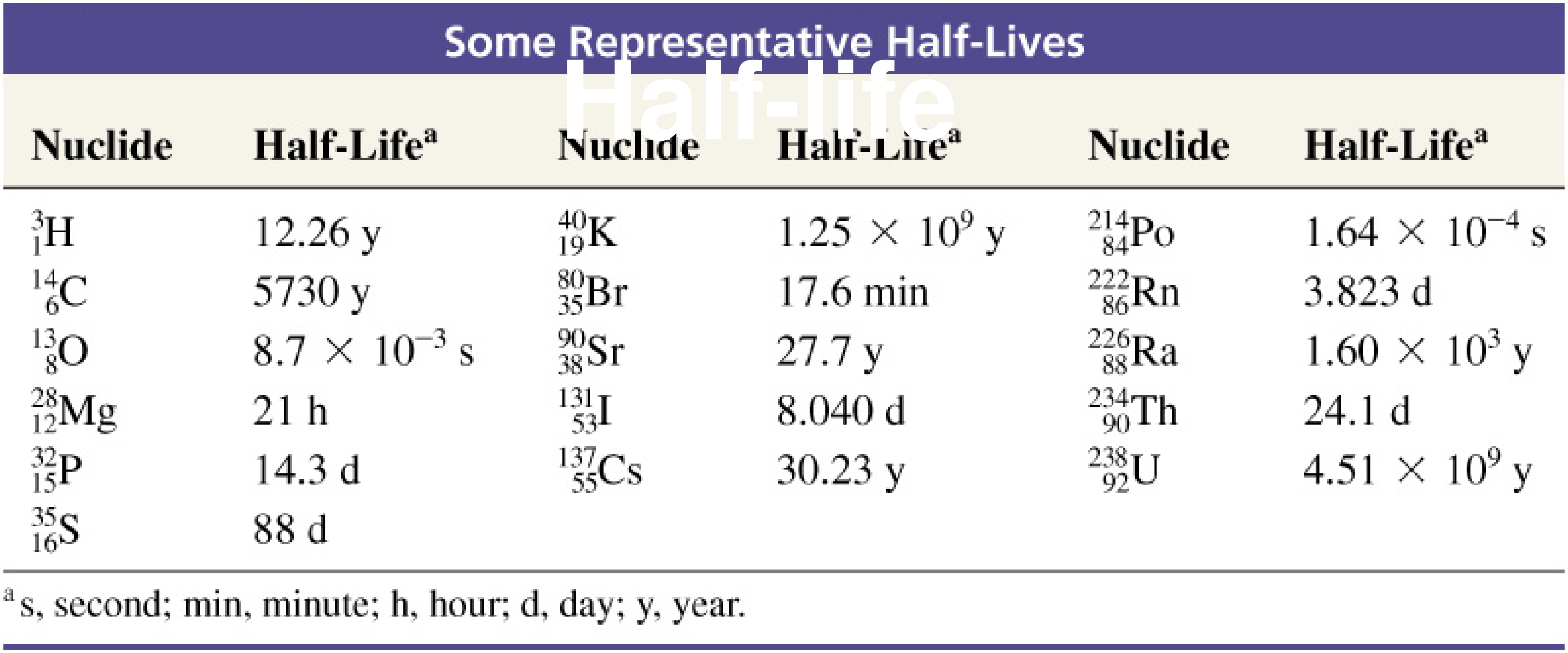
Everything is radioactive to some extent

One loaf of bread 70Bq

One adult person 3,000Bq

Half-life

Time for 50% of an isotope to decay



Some Representative Half-Lives

Nuclide	Half-Life[a]	Nuclide	Half-Life[a]	Nuclide	Half-Life[a]
$^{3}_{1}\mathrm{H}$	12.26 y	$^{40}_{19}\mathrm{K}$	1.25×10^{9} y	$^{214}_{84}\mathrm{Po}$	1.64×10^{-4} s
$^{14}_{6}\mathrm{C}$	5730 y	$^{80}_{35}\mathrm{Br}$	17.6 min	$^{222}_{86}\mathrm{Rn}$	3.823 d
$^{13}_{8}\mathrm{O}$	8.7×10^{-3} s	$^{90}_{38}\mathrm{Sr}$	27.7 y	$^{226}_{88}\mathrm{Ra}$	1.60×10^{3} y
$^{28}_{12}\mathrm{Mg}$	21 h	$^{131}_{53}\mathrm{I}$	8.040 d	$^{234}_{90}\mathrm{Th}$	24.1 d
$^{32}_{15}\mathrm{P}$	14.3 d	$^{137}_{55}\mathrm{Cs}$	30.23 y	$^{238}_{92}\mathrm{U}$	4.51×10^{9} y
$^{35}_{16}\mathrm{S}$	88 d				

[a] s, second; min, minute; h, hour; d, day; y, year.

Radioactive Decay

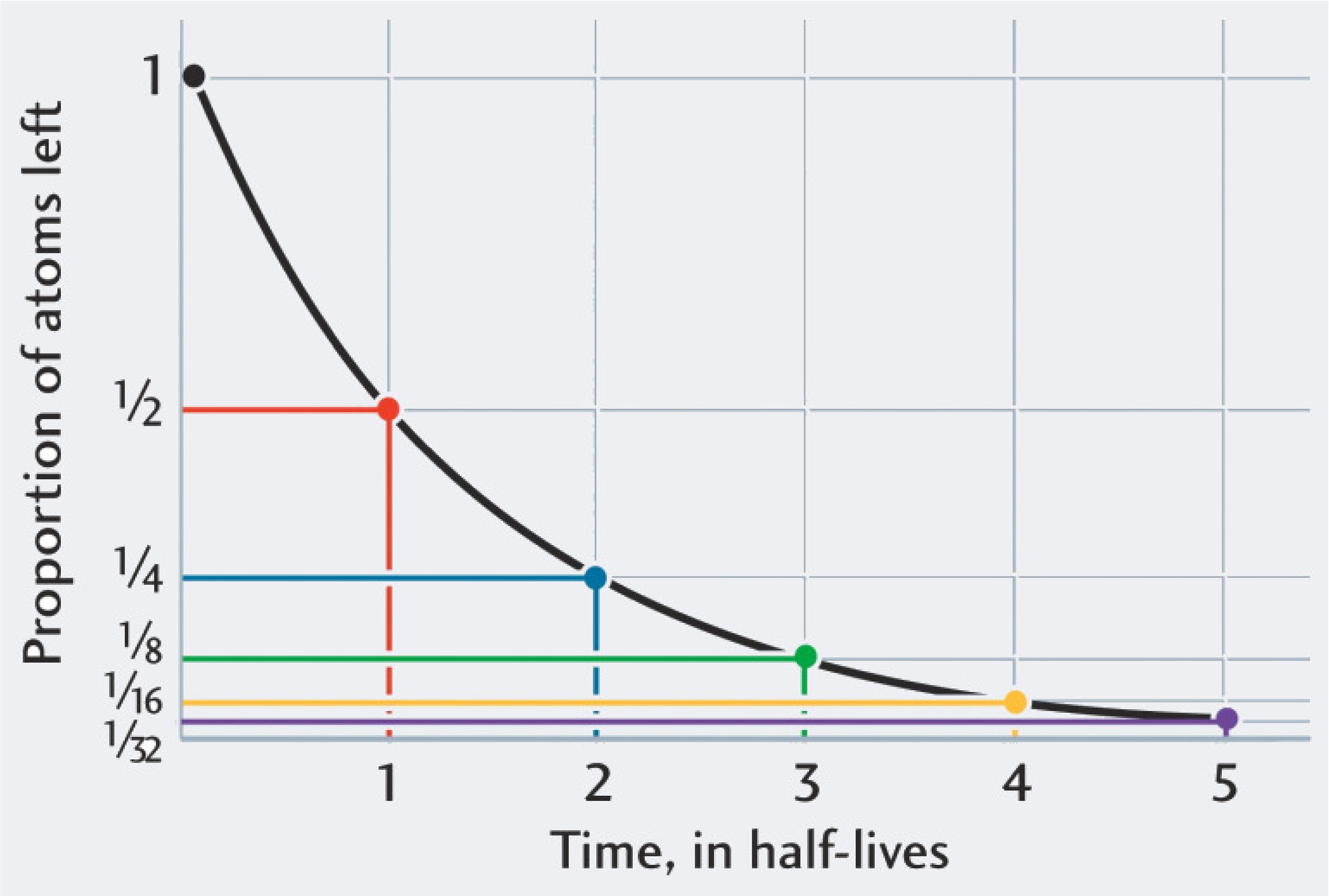
Half Life

● parent isotope

○ daughter isotope

Decay of ^{14}C

$$100\% \xrightarrow[\text{1st half life}]{\text{5,730 years}} 50\% \xrightarrow[\text{2nd half life}]{\text{5,730 years}} 25\%$$


Proportion of atoms left
1
1/2
1/4
1/8
1/16
1/32
1
2
3
4
5
Time, in half-lives

Half-life

First-order reaction

$$t_{1/2} = \frac{0.693}{k}$$

$$\log \frac{C_0}{C_t} = \frac{kt}{2.303}$$

k = rate constant

C_0, C_t = initial, final amounts

$$\log \frac{C_0}{C_t} = \frac{kt}{2.303}$$

- how much isotope left after time, t
-

- time taken for % of isotope to decay

Example:

Half-life of ^{63}Ni is 100 years.
If you had 100 g of ^{63}Ni, how much would be left after 250 years?

$$\log \frac{C_0}{C_t} = \frac{kt}{2.303}$$

$$\log \frac{C_0}{C_t} = \frac{kt}{2.303}$$

$k = ?$

$C_0 = 100\ \text{g}$

$C_t = ?$

$t = 250\ \text{yr}$

$$\log \frac{C_0}{C_t} = \frac{kt}{2.303}$$

$k = ?$
$C_0 = 100\ \text{g}$
$C_t = ?$
$t = 250\ \text{yr}$

$$t_{1/2} = \frac{0.693}{k}$$

$k = 0.0693\ \text{yr}^{-1}$
$C_t = 17.7\ \text{g}$

Radiation and Health

Factors influencing degree of exposure

Half-life shorter half-life materials decay faster ⇨ greater damage

Type of radiation some worse than others

Distance from source Intensity $\propto$ 1/distance^2

Time of exposure cumulative

Uses of radiation

- Age determination (dating) of minerals/fossils
- Cancer treatment
- Tracers & Imaging
- Nuclear power
- Food irradiation

Radioactive Dating

two general types

geochronology
long half-life isotopes in minerals

carbon dating
radioactive C-14 in formerly living objects

Radiocarbon Dating

Two carbon isotopes found in nature:

carbon-12 non-radioactive
carbon-14 radioactive

Radiocarbon Dating

In living tissue ratio C-14 to C-12 is 1:10^{12}

After death, no more C-14 taken in; ratio changes

Decreases by 50% every 5,730 yrs

Good for fossils, wood, textiles

Nuclear Power

Energy obtained 2 ways

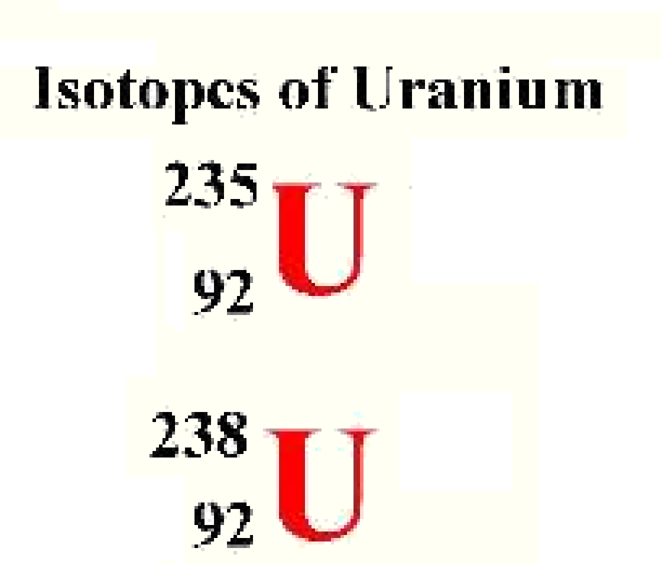
Fission: splitting large atoms
(power plants; bombs)

Fusion: joining small atoms (sun)

Nuclear energy provides about 20 % of US electricity

103 nuclear reactors with operating licences in 31 states

25 % of electricity in Alabama



Isotopes of Uranium

$^{235}_{92}\mathrm{U}$

$^{238}_{92}\mathrm{U}$

Pitchlend

Nuclear Power

Uranium-235 used as reactor fuel

Produces nuclear chain reaction by fission

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

Nuclear Power

Fisson generates heat

Heat boils water

steam

⇓

turbines

⇓

electricity

Two sections U-235
forced together

Creates
supercritical mass

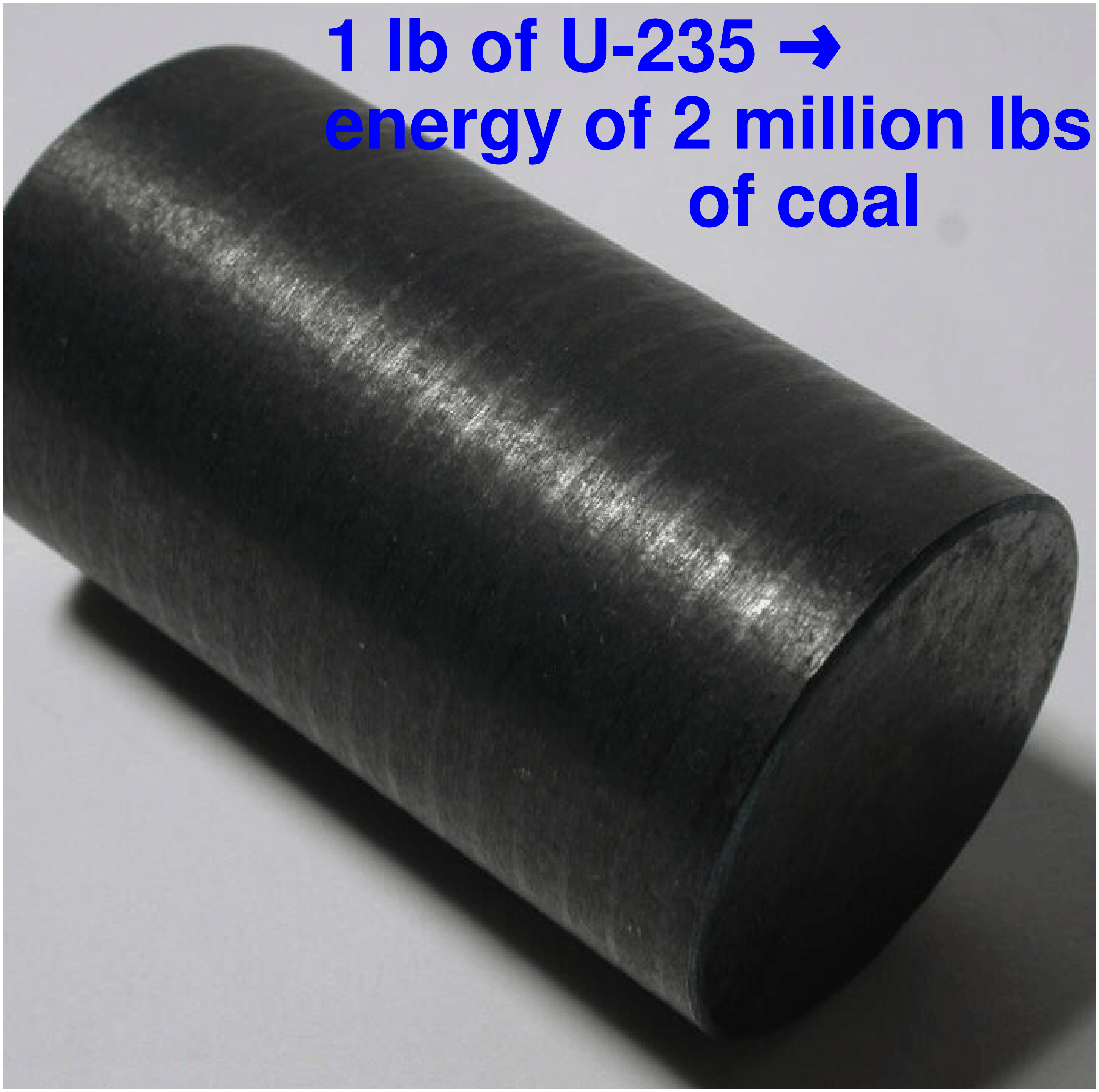
When just enough fissions occur to keep the chain reaction going ➜ critical reaction ➜ nuclear power

When excess neutrons produced fission rate keeps increasing ➜ supercritical reaction ➜ nuclear explosion

Little Boy and Fat Man

August 6th, 1945: 8:15am.
Enola Gay releases "Little Boy" at altitude 31,500'.
Preset to explode at altitude 2000' above Hiroshima.
75,000 people killed immediately.
48,000 buildings destroyed.

August 9th, 1945: 10:00am.
Bock’s Car releases "Fat Man" over Nagasaki.
35,000 people killed immediately.



1 lb of U-235 ➜ energy of 2 million lbs of coal

Uranium tipped tank penetrating munitions

Why use uranium?

1. Very, very dense
2. Very hard
3. Pyrophoric

Health Effects

Two classes

Somatic (whole body) damage

- Chronic (cancer)
- Acute (acute radiation syndrome)

Genetic damage

  - Alters genetic material
  - Mutations in offspring

Cadmium control rods absorb excess neutrons to keep reactor below supercritical

Fusion

Solar output =
E of burning 1500 lb coal/hour
for each sq^2 of solar surface

Fusion

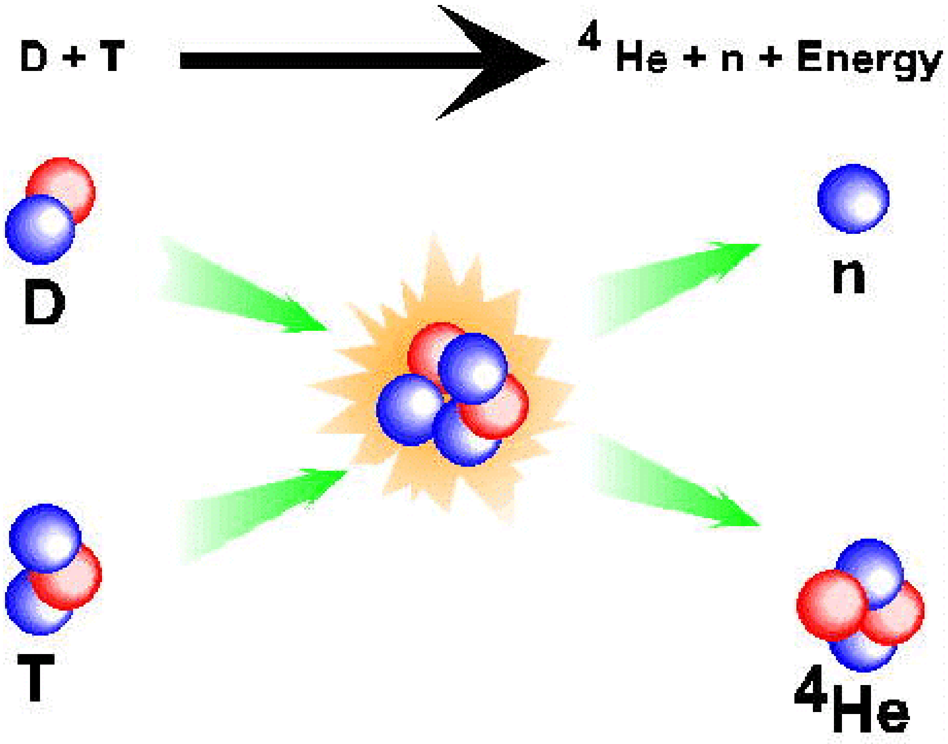
1919: Sir Arthur Eddington showed H → He provided Sun’s energy

Fusion

4 million metric tons H per sec

100 billion H-bombs each sec

Fusion



Deuterium & Tritium come from water


NUCLEAR WASTE
DISPOSAL SITE
IF YOU CAN READ THIS,
YOU'RE TOO CLOSE.
THE CHRISTIAN SCIENCE MONITOR
Bennett