Chapter 21: Radioactivity and Nuclear Chemistry

Chem 102
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Other radioactive dating applications

- ^{14}C dating works for organic objects < ~50,000 yrs old
- Age of rocks can be determined by measuring:

  $^{238}U \longrightarrow {}^{206}Pb$ ($t_{1/2} = 4.5 \times 10^9$ years)

  This ratio is set when rock forms from magma.

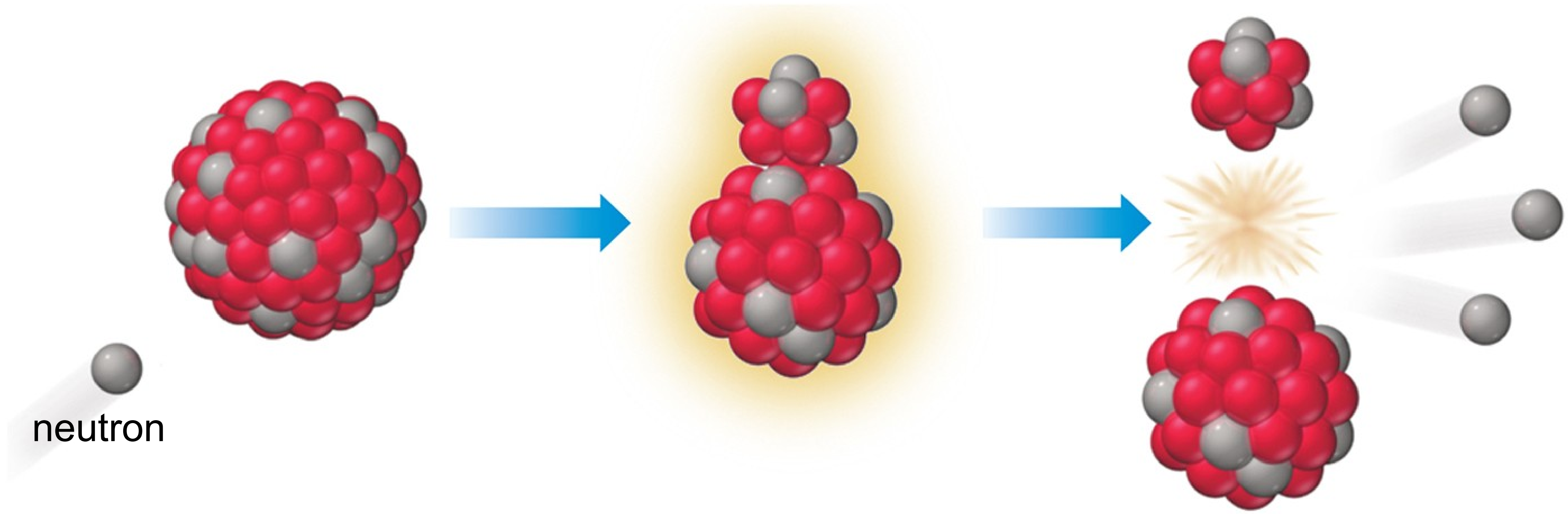
- Oldest rocks on Earth are ~4.0 billion years old
- Oldest meteorites are ~4.5 billion years old;
  roughly the age of our solar system

Nuclear fission

- Lise Meitner, Fritz Strassmann, Otto Hahn in 1939:

  The bombardment of uranium-235 with neutrons produces elements lighter than uranium:

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{140}_{56}\mathrm{Ba} + {}^{93}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n} + \text{energy}$$

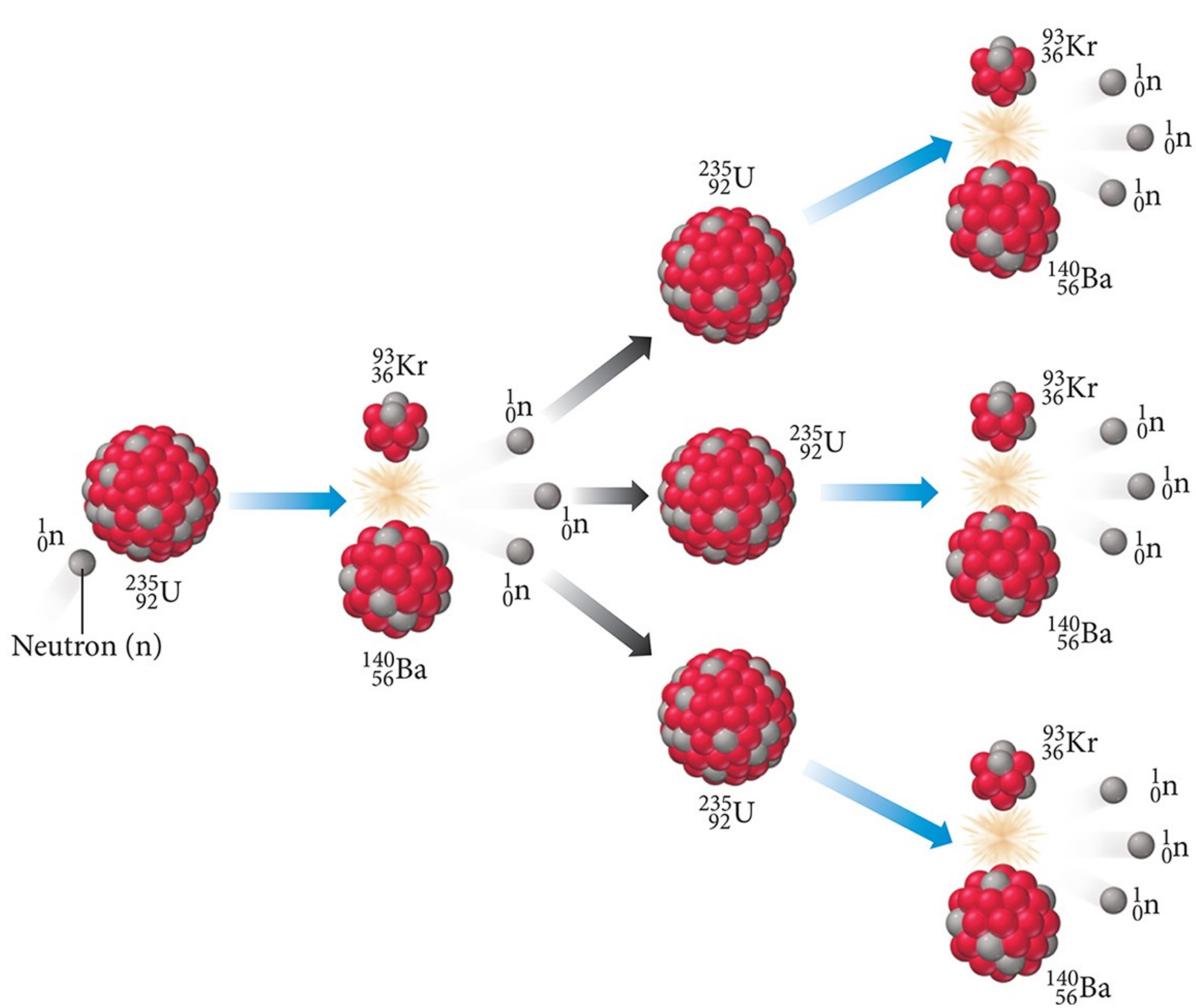


The nucleus is broken apart by neutron!

Chain reaction

- Initial decay produces more neutrons, so if more ^{235}U is present, the reaction can continue
- Can produce a lot of energy!
- Need a minimum amount of ^{235}U; critical mass
- ^{235}U is <1% of naturally occurring U. Needs to be refined (“**enriched**”).

Fission Chain Reaction

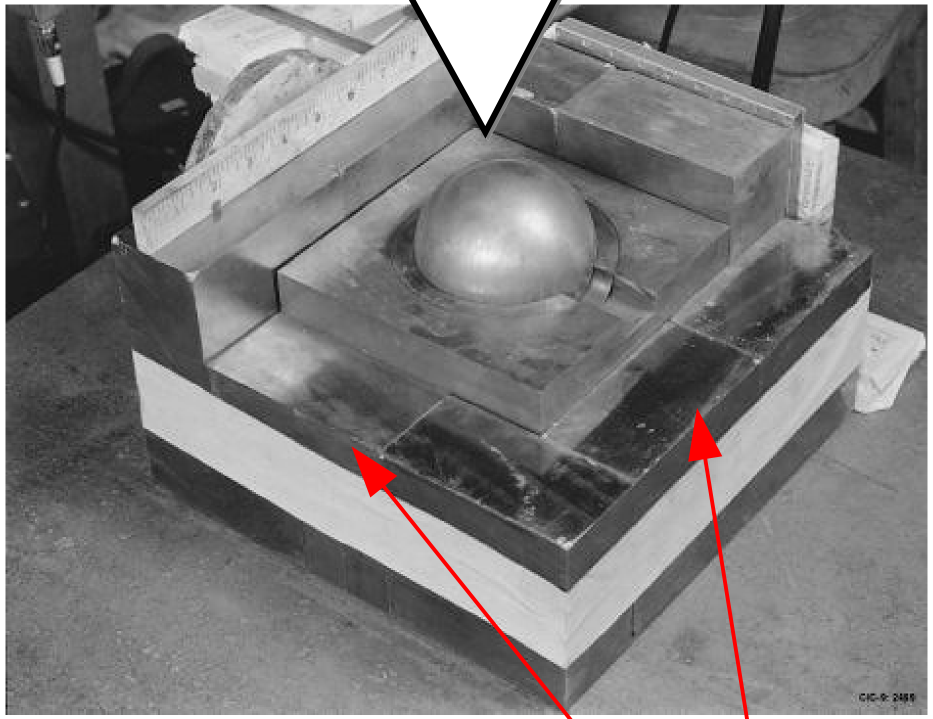


Accelerating chain reaction!

Critical mass

- A ‘runaway’ condition exists if enough neutrons strike enough U-235 atoms:
  - If the mass is small, neutrons escape from the surface without causing enough chain reactions (**subcritical**)
  - If the mass is large, neutrons remain inside and cause runaway (**supercritical**)
- **Critical mass** of U-235 is ~52 kg (17 cm diameter)

The ‘demon core’

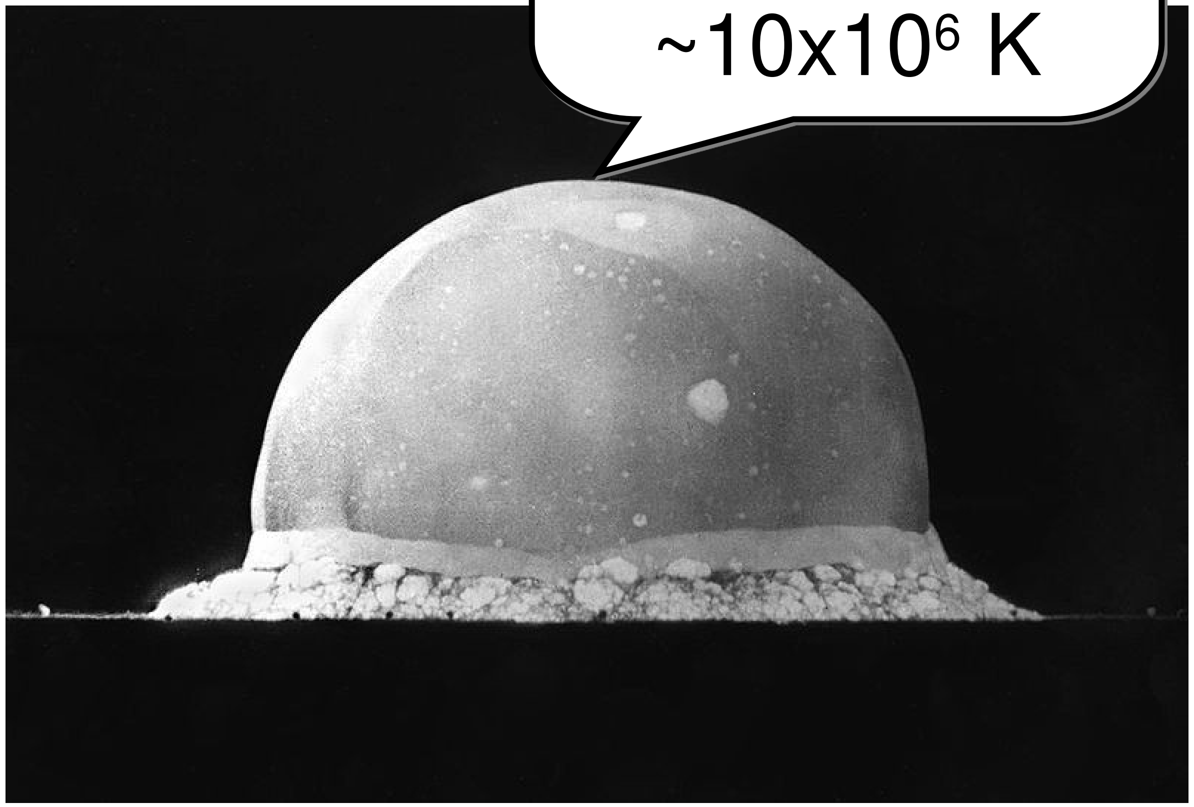


Pu sphere surrounded by neutron-reflective blocks goes supercritical if two additional blocks are added

Manhattan Project

- Development of atomic bomb during WW II (Oppenheimer *et al*.)
- Especially important: How to enrich enough uranium to produce a bomb? (Oak Ridge, TN)
- Bomb assembly at Los Alamos, NM
- In 1945 US dropped atomic bombs on Hiroshima and Nagasaki, Japan; end of WW II

16 ms after detonation, ~200 m wide, ~10×10^6 K



First atomic bomb test in New Mexico (Trinity test) in 1945 had the power of 18,000 tons of TNT

Nuclear power

- A huge amount of energy is released from nuclear fission. Uranium cylinder the size of a pencil could power an automobile for 20 years.
- If the energy of nuclear fission is released more slowly, it can be used to generate electricity (steam turbines).
- We can get energy from fission to generate electricity <u>without emitting CO_2</u>
- Nuclear fission provides ~20% of electricity in US

  France: 75%, Japan: ~30%
- Problems: Safety, waste disposal/storage (engineering)
- U is enriched only to 3.5% and cannot become bombs

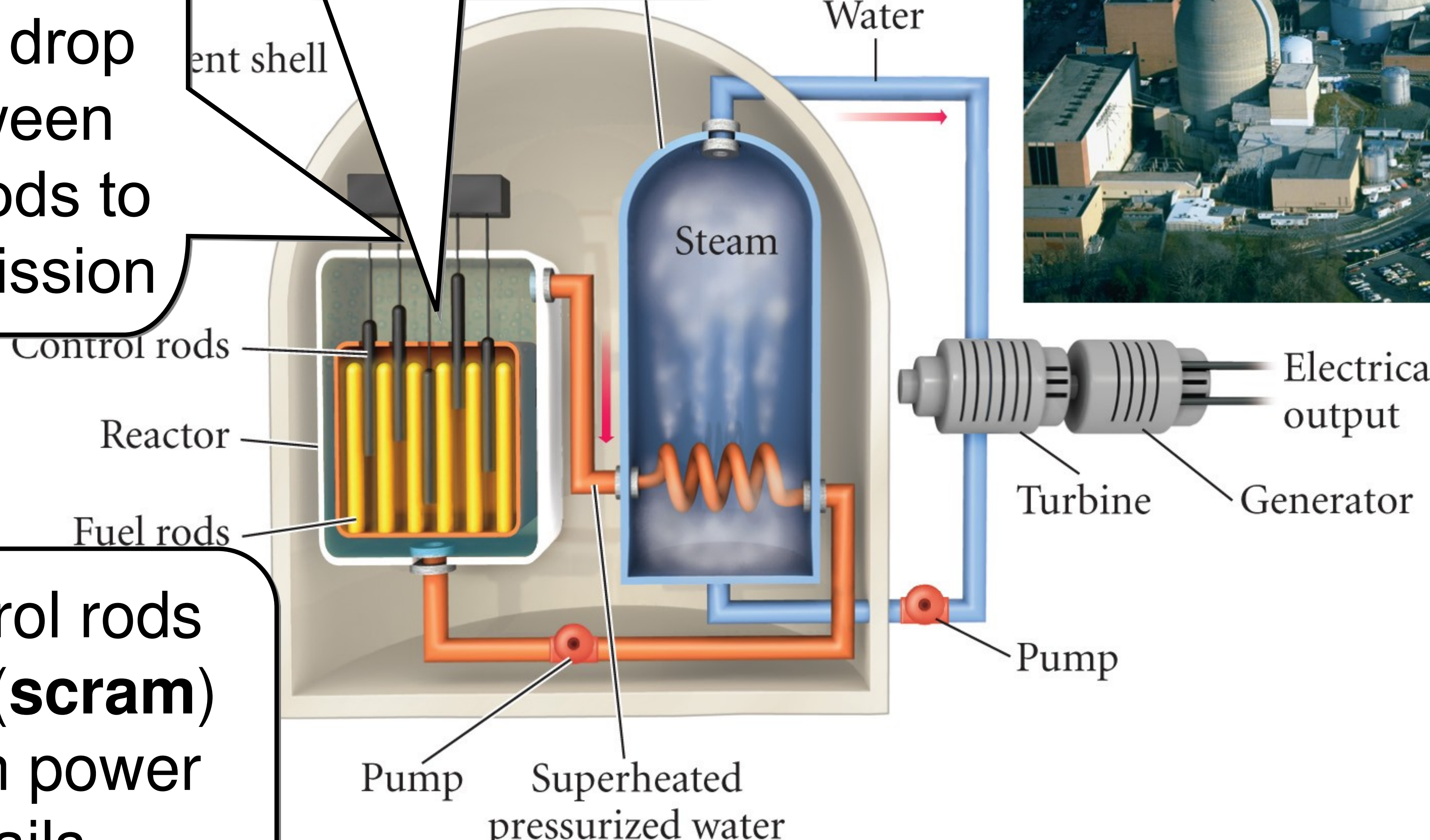
Nuclear power

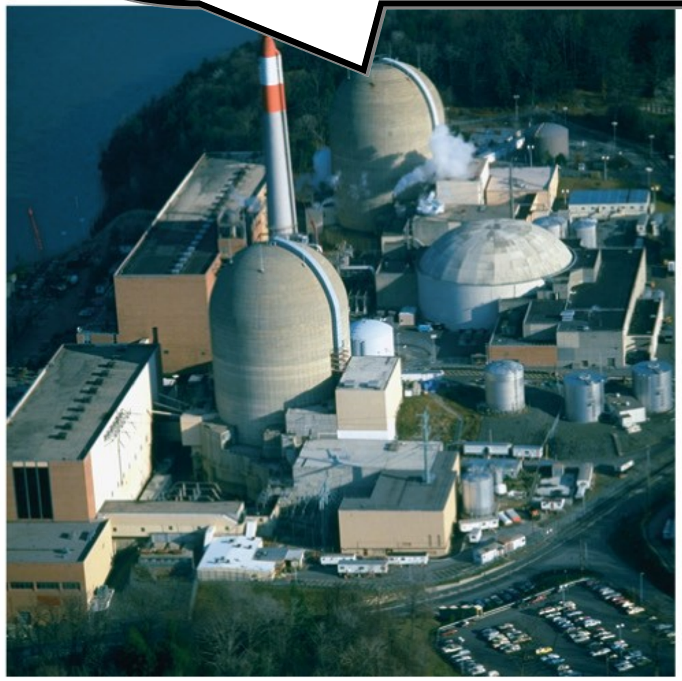
Neutron-absorbing **control rods** drop between fuel rods to slow fission

Water circulates around core

Concrete shell contains core

Control rods drop (**scram**) when power fails

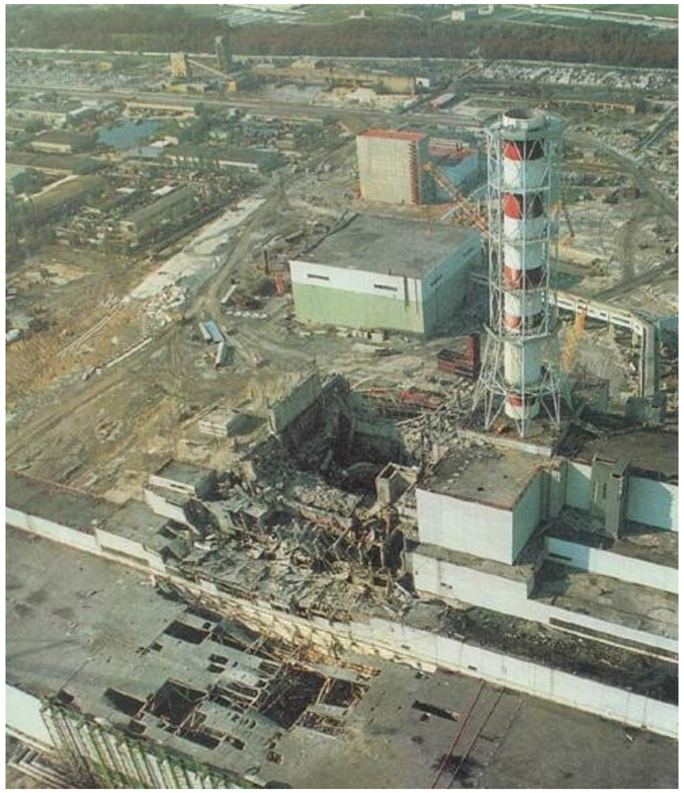




Nuclear power safety

Graphite rods are used to absorb neutrons to control the fission. Otherwise, an uncontrolled reaction could occur:

“Meltdown” (not a nuclear explosion)



Chernobyl (Soviet Union), 1986
(design fault, negligence)

Fukushima Daiichi (Japan), 2011
(earthquake & tsunami)

Nuclear power

Waste disposal:

- Products are produced in small quantities but they are intensely radioactive with long half-lives
- All US nuclear waste is stored at the nuclear power plant
- Central storage being developed at Yucca Mountain, NV
- Reprocessing the waste possible but relatively expensive

Mass defect and energy

- Where does the energy come from in nuclear fission?
- It turns out that mass is not conserved during the nuclear reaction!

proton

neutron

For example:

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

- Mass of reactants = 2 p^{+} + 2 n^{0} = (2 x 1.00783 amu) + (2 x 1.00866 amu) = 4.03298 amu
- Mass of products = 4.00260 amu

Mass is lost!

Mass defect and energy

The mass is not conserved either when U-235 is bombarded by neutrons:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \longrightarrow ^{140}_{56}\mathrm{Ba} + ^{93}_{36}\mathrm{Kr} + 3\,^{1}_{0}\mathrm{n}$$

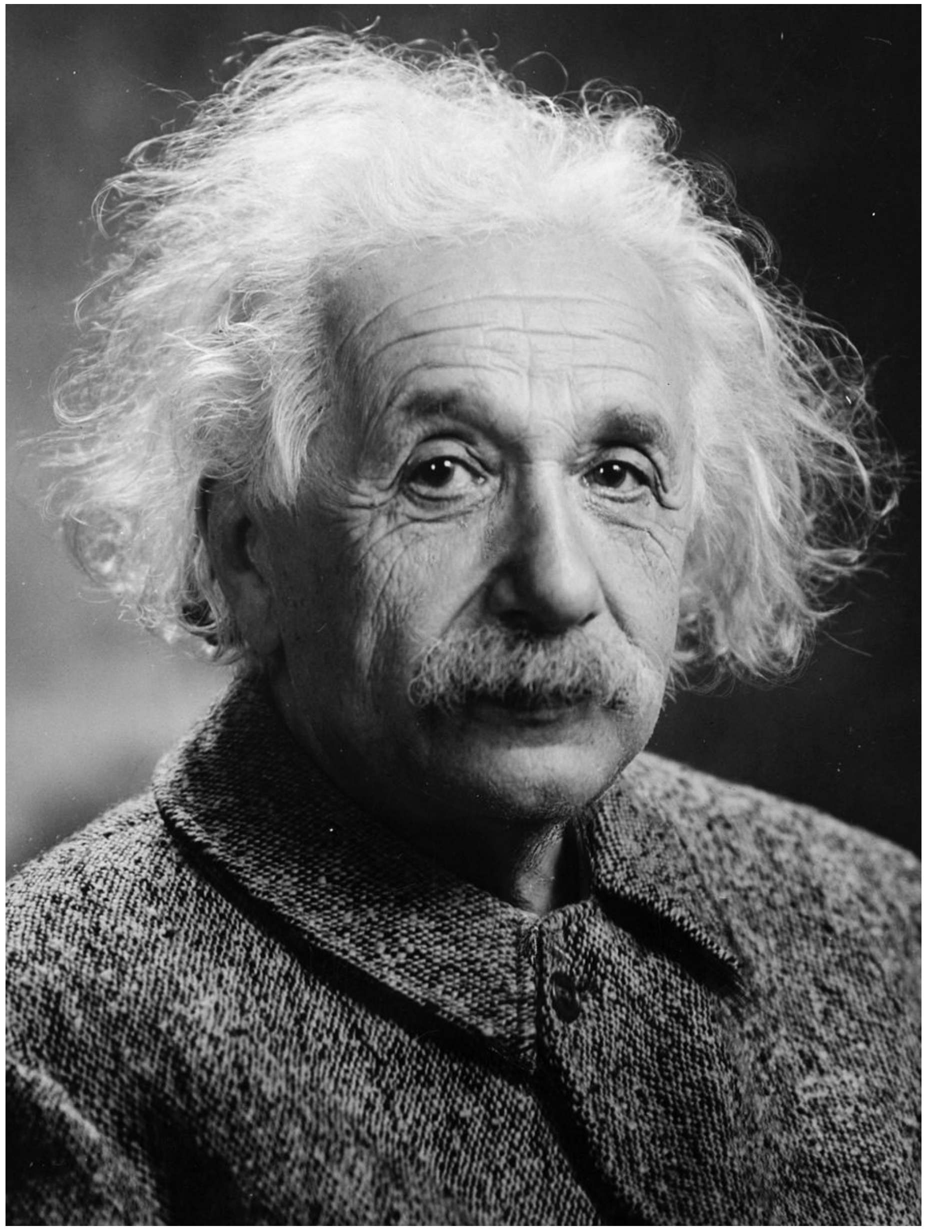
Mass Reactants		Mass Products	
$^{235}_{92}\mathrm{U}$	235.04392 amu	$^{140}_{56}\mathrm{Ba}$	139.910581 amu
$^{1}_{0}\mathrm{n}$	1.00866 amu	$^{93}_{36}\mathrm{Kr}$	92.931130 amu
		$3\,^{1}_{0}\mathrm{n}$	3(1.00866) amu
Total	**236.05258 amu**		**235.86769 amu**

Matter conversion to energy

- Matter to energy: $E = mc^2$

  $= 1.6617 \times 10^{13}$ J / mol of U-235

- "nuclear binding energy" (E):
  - Amount of energy required to break apart a nucleus into its component nucleons (protons and neutrons)
  - Usually expressed in MeV (1 amu = 931.5 MeV)



Albert Einstein

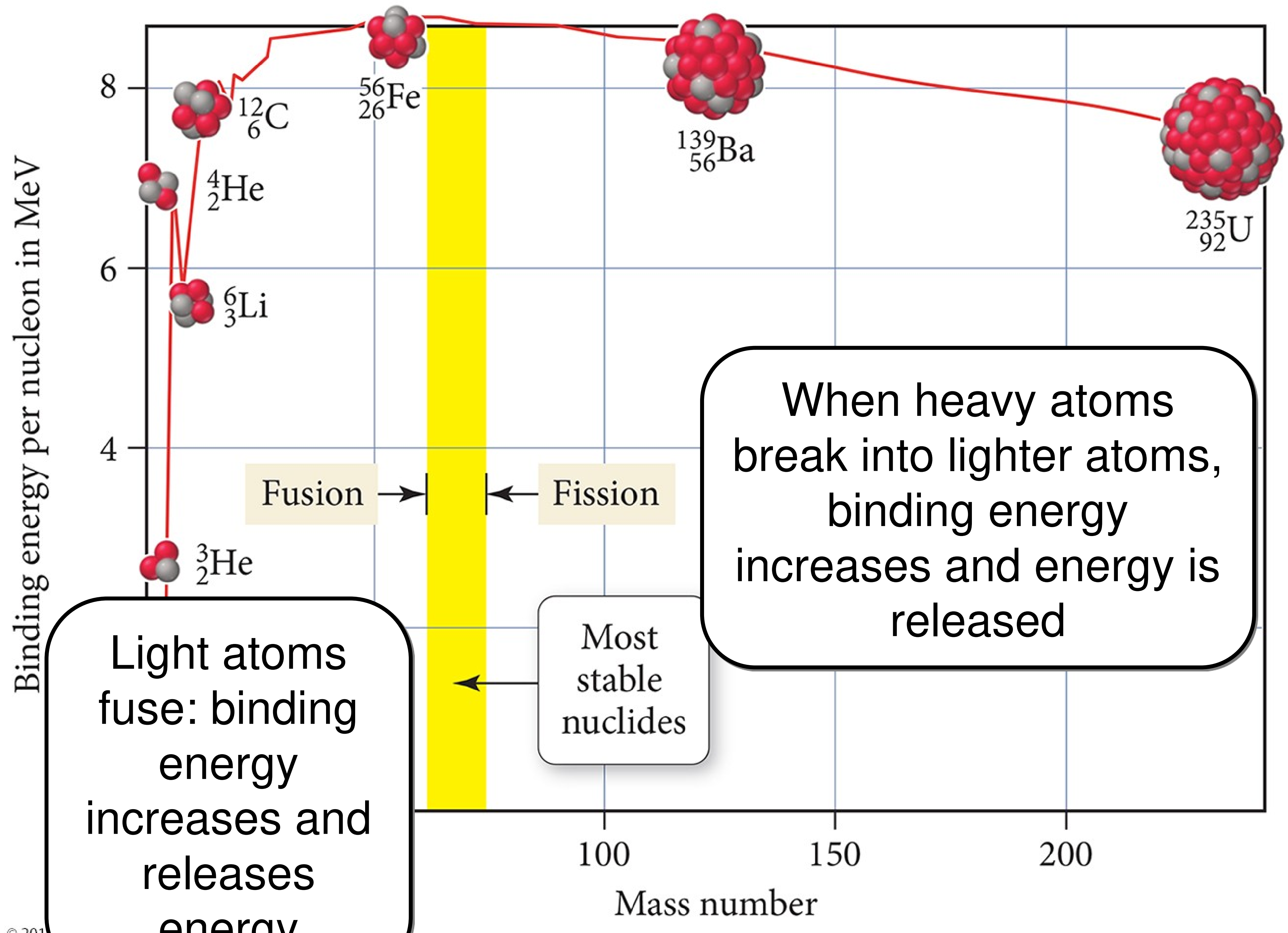
Example

What is the binding energy per nucleon for He-4 atom?

Based on the previous example (slide 11), the mass defect is 0.03038 amu or 28.30 MeV. This element has four nuclides, so the binding energy is 28.30 MeV / 4 = 7.08 MeV.

Note that: 1 MeV = 9.65×10^{10} J/mol and 28.30 MeV = 2.73×10^{12} J/mol of He.

The Curve of Binding Energy



When heavy atoms break into lighter atoms, binding energy increases and energy is released

Light atoms fuse: binding energy increases and releases energy

Example

How much energy per gram is released from U-235 fission?

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{142}_{54}\mathrm{Xe} + {}^{90}_{38}\mathrm{Sr} + 4\ {}^{1}_{0}\mathrm{n}$$

We calculate Δm = -0.18050 g/mol. This gives $\Delta E = \Delta m \cdot c^2$ = $-1.622\mathrm{x}10^{13}$ kJ/mol (or $-6.34\mathrm{x}10^{10}$ kJ for each 1 g of U-235).

One gram is enough energy to heat 250 million liters of water from 25 °C to 100 °C. It would take 1650 kg of octane to release the same amount of energy!

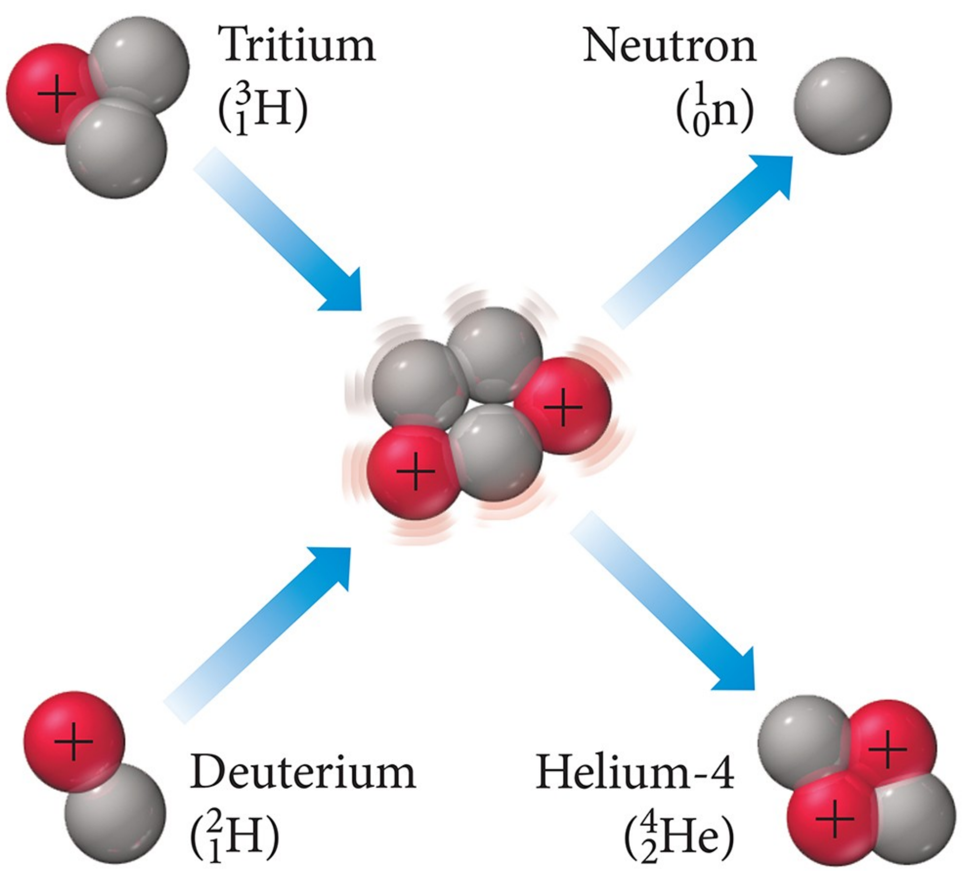
Nuclear fusion

- Combining two lighter nuclei to form a heavier one
- Requires very high temperature but releases a huge amount of energy!
- Hydrogen bomb:

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

  1000x stronger than fusion bomb
- Solar fusion (powers the sun)
- “cold” fusion (***nonsense!***)

Deuterium-Tritium Fusion Reaction



Example

What is the energy release in the following fusion reaction:

$$^{2}_{1}\mathrm{H} + ^{3}_{2}\mathrm{He} \rightarrow ^{4}_{2}\mathrm{He} + ^{1}_{1}\mathrm{H}$$

2.01345 amu	3.01493 amu	4.00150 amu	1.00728 amu

The change in mass (Δm) *is:*

$$\Delta m = (4.00150 + 1.00728) - (2.01345 + 3.01493)\ \text{amu}$$
$$= -0.01960\ \text{amu}$$
$$= -0.01960\ \text{g/mol}$$
$$= -1.960\text{x}10^{-5}\ \text{kg/mol}$$

(per mole of reactions)

Example (continued)

Let’s convert this to energy

$$\begin{aligned}\Delta E &= \Delta m \cdot c^2 \\ &= -1.960\text{x}10^{-5}\ \text{kg}/\text{mol} \times (2.998\text{x}10^{8}\ \text{m}/\text{s})^2 \\ &= -1.76\text{x}10^{12}\ \text{kg}\cdot\text{m}^2/\text{s}^2\cdot\text{mol} \\ &= -1.76\text{x}10^{12}\ \text{J}/\text{mol}\end{aligned}$$

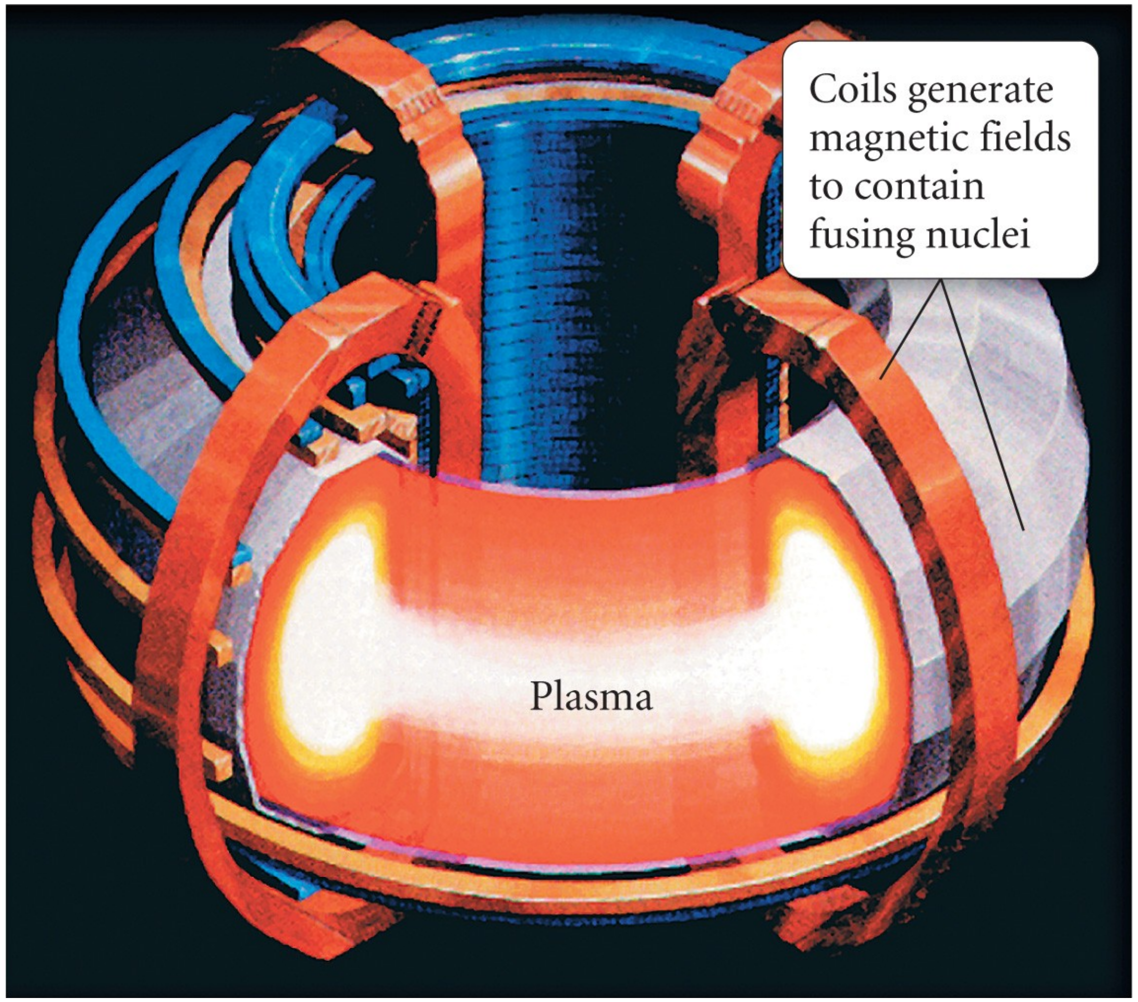
1.76 *billion* kJ of energy / mol!!!

Million times more than typical chemical reactions!

Ten times more than typical fission reactions

Nuclear fusion

- Very high temperatures are required (> 10,000 K) for fusing two positive nuclei
- Atoms must be contained by magnetic fields or lasers
- Fusion has been achieved for short times but much more energy required than produced

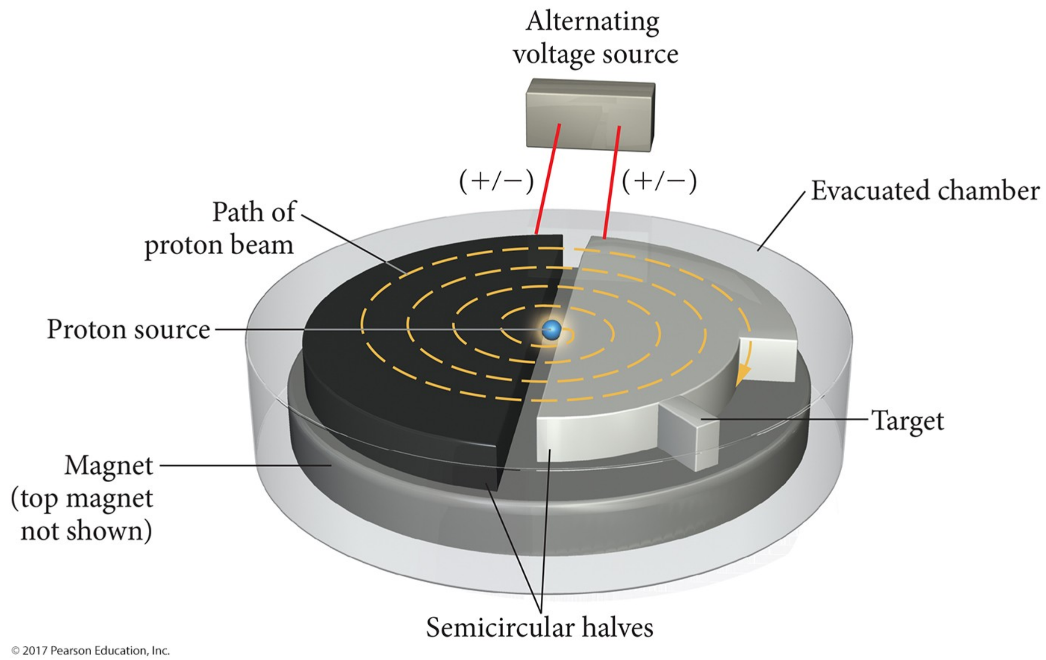


The 'Tokamak' fusion reactor is a 'wall-less' container

ITR Project, France

Nuclear transmutation and particle accelerators

- Can convert one element to another non-spontaneously by bombarding with high energy particles
- Cyclotron or linear accelerator



Effects of radiation on life

When α and β particles strike living cells considerable damage may occur.

1. Acute damage

- Large amount of radiation in a short period of time:
  Rapidly dividing cells are most susceptible (intestinal, reproductive and immune cells)
- Large numbers of ions created within the cell that react with and destroy important cell molecules leading to cell death

Effects of radiation on life

2. Chronic damage

- Large amount of radiation over a long period of time
- DNA is damaged at a faster rate than it can be repaired in the cell
- Cell may die or grow abnormally (cancer)
- If DNA of reproductive cells is damaged, it may be passed to offspring (genetic mutations)
- Genetic diseases in offspring may result

Measuring radiation exposure

- Major unit of radioactivity is the **Curie** (Ci) where 1 Ci = 3.7×10^{10} decay events / s
- But 1 Ci exposure to α particles will do more damage than 1 Ci exposure to β particles
- It is better to measure amount of energy deposited in the body

1 **Gray** (Gy) = 1 J / kg body tissue

1 **rad** = 0.01 Gy = 0.01 J / kg body tissue

But this does not account for the type of radiation.

Measuring radiation exposure

- The rad is multiplied by the **relative biological effectiveness** (RBE) factor to produce the **rem** unit

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

The RBE for α particles is much higher than γ rays

- Average person receives ~360 milli-rem per year
- Measurable physiological effects occur at ~20 rem

Measuring radiation exposure

TABLE 19.4 Exposure by Source for Persons Living in the United States

Source	Dose
Natural Radiation	
A 5-hour jet airplane ride	2.5 mrem/trip (0.5 mrem/hr at 39,000 feet) (Whole body dose)
Cosmic radiation from outer space	27 mrem/yr (whole body dose)
Terrestrial radiation	28 mrem/yr (whole body dose)
Natural radionuclides in the body	35 mrem/yr (whole body dose)
Radon gas	200 mrem/yr (lung dose)
Diagnostic Medical Procedures	
Chest X-ray	8 mrem (whole body dose)
Dental X-rays (panoramic)	30 mrem (skin dose)
Dental X-rays (two bitewings)	80 mrem (skin dose)
Mammogram	138 mrem per image
Barium enema (X-ray portion only)	406 mrem (bone marrow dose)
Upper gastrointestinal tract	244 mrem (X-ray portion only) (bone marrow dose)
Thallium heart scan	500 mrem (whole body dose)
Consumer Products	
Building materials	3.5 mrem/year (whole body dose)
Luminous watches (H-3 and Pm-147)	0.04–0.1 mrem/year (whole body dose)
Tobacco products (to smokers of 30 cigarettes per day)	16,000 mrem/year (bronchial epithelial dose)

Measuring radiation exposure

TABLE 19.5 Effects of Radiation Exposure

Approximate Dose (rem)	Probable Outcome
20–100	Decreased white blood cell count; possible increase in cancer risk
100–400	Radiation sickness including vomiting and diarrhea; skin lesions; increase in cancer risk
500	Death (often within 2 months)
1000	Death (often within 2 weeks)
2000	Death (within hours)

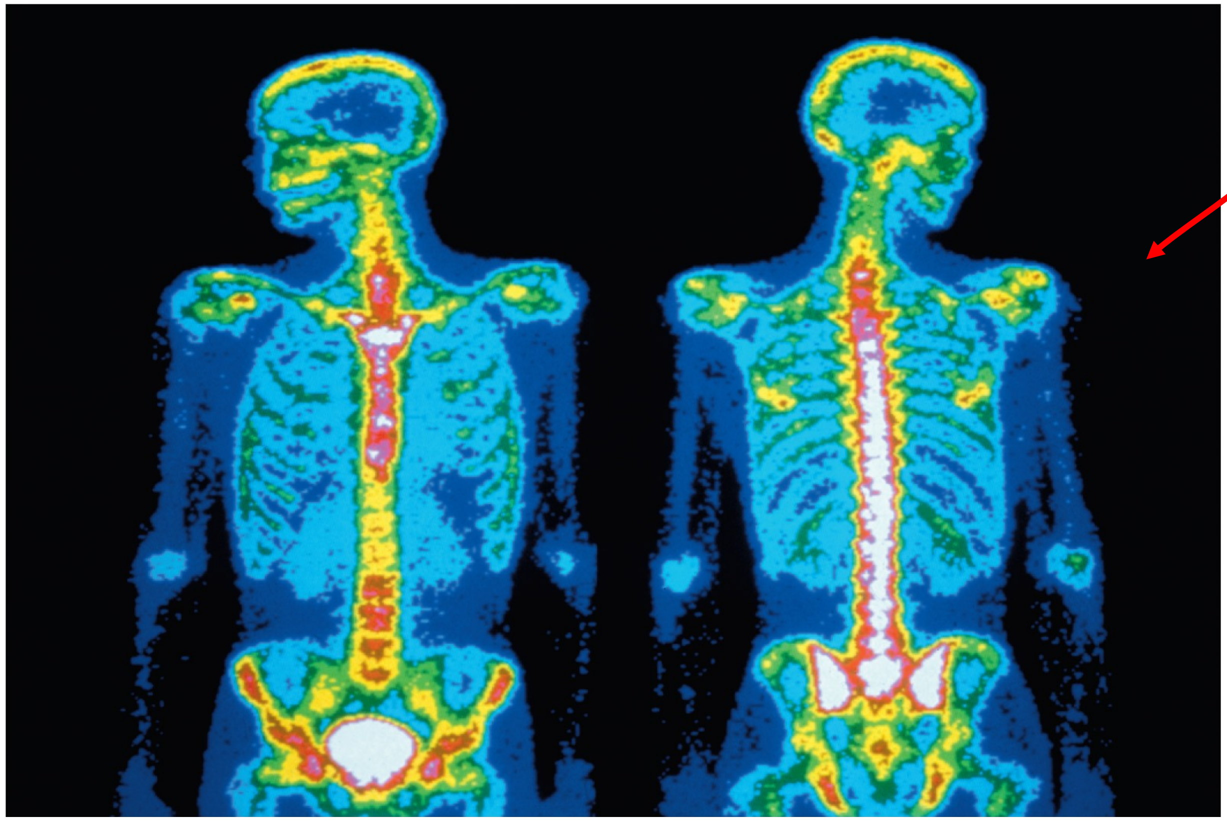
Professions with particularly high radiation risks are health workers, flight crew, underground miners.

Radiation in medicine

- Diagnosis in medicine is improved by using **radiotracers**, radioactive nuclides of elements commonly found in the body:
  - Radiotracers are easily detected
  - Radiotracers have identical chemistry to their non-radioactive counterparts
- Radioactive iodine-131 is taken into the thyroid gland with regular iodine but can be detected so the uptake rate of iodine can be quantified
- In a similar way elements are concentrated in different parts of the body and can be used for monitoring

TABLE 19.6 Common Radiotracers

Nuclide	Type of Emission	Half-Life	Part of Body Studied
Technetium-99m	Gamma (primarily)	6.01 hours	Various organs, bones
Iodine-131	Beta	8.0 days	Thyroid
Iron-59	Beta	44.5 days	Blood, spleen
Thallium-201	Electron capture	3.05 days	Heart
Fluorine-18	Positron emission	1.83 hours	PET studies of heart, brain
Phosphorus-32	Beta	14.3 days	Tumors in various organs

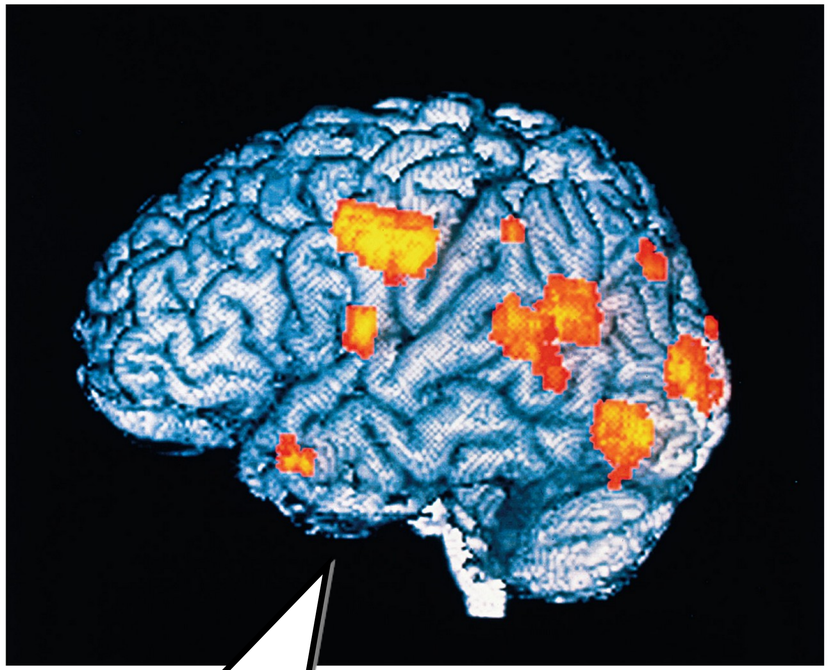


Tc-99 is concentrated in bone during a ‘bone scan’

Radiation in medicine

Positron Emission Tomography (PET)

- F-18 labeled glucose is injected into the bloodstream
- The F-18 decays by positron emission
- The emitted positron and nearby electrons collide, annihilate each other and produce 2 γ rays in opposite directions
- Detectors pinpoint when the γ rays originated



A PET scan shows area where brain activity (glucose metabolism) is highest

Radiation in medicine: Radiotherapy

- Radiation is particularly effective at killing dividing cells and is used in cancer treatment
- Focused γ rays are moved in a circle around the patient to maximize tumor and minimizes body exposure
- Patients often develop radiation sickness symptoms

Each dose ~100 rem or 1% increase in cancer risk

Radiation in medicine: Radiotherapy

- How can radiation both cause and cure cancer?
- Answer lies in risk management:

If a person has a 95% chance of dying of cancer versus a 1% increased risk of cancer for each treatment, the risk is acceptable.

Other uses of radiation

- Radiation kills bacteria and viruses:

  Sterilize surgical instruments

  Sterilize food (this does not make the food radioactive)
- Control insect populations by sterilizing males and releasing them

'Radura' logo identifies food treated with radiation

Main ideas for this section

- Be able to write nuclear reactions:
  e.g., write the products of ^{234}U alpha decay
- Kinetics of radioactive decay; half-life
- Radiometric dating (using rate or number ratio)
- Mass defect and energy release

End of the course!!!