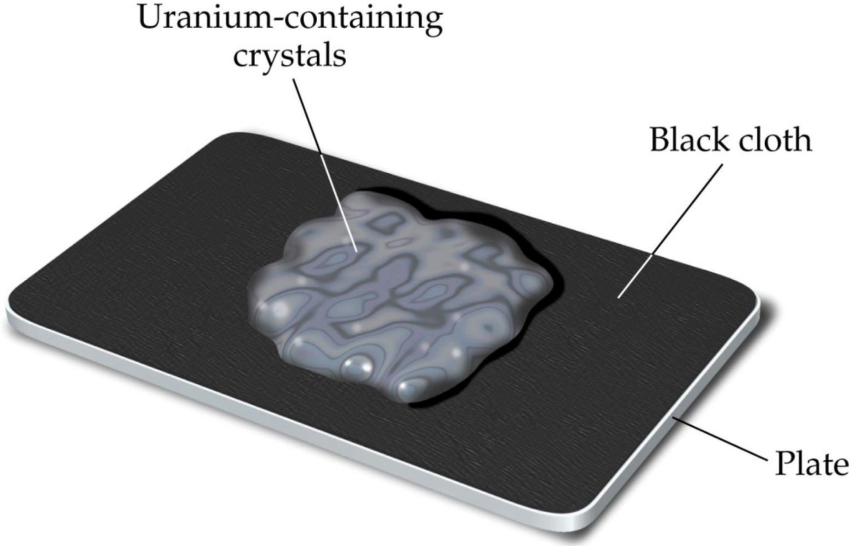
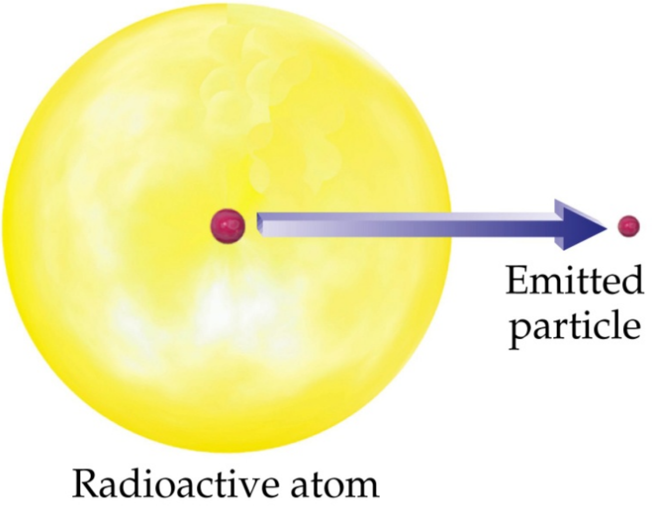
Nuclear Chemistry

Chapter 18

Radioactive Decay

- Discovered by Antoine Henri Becquerel in 1896
  - He saw that photographic plates developed bright spots when exposed to uranium metals





Types of nuclear reactions

- Radioactive Decay – nucleus decays spontaneously giving off an energetic particle

- Nuclear Bombardment – shoot a high energy particle at the nucleus of another atom and watch what happens mass number (p^+ and n^0)

$$^{A}_{Z}\mathrm{Sy}$$ — symbol of the element

atomic number (p^+)

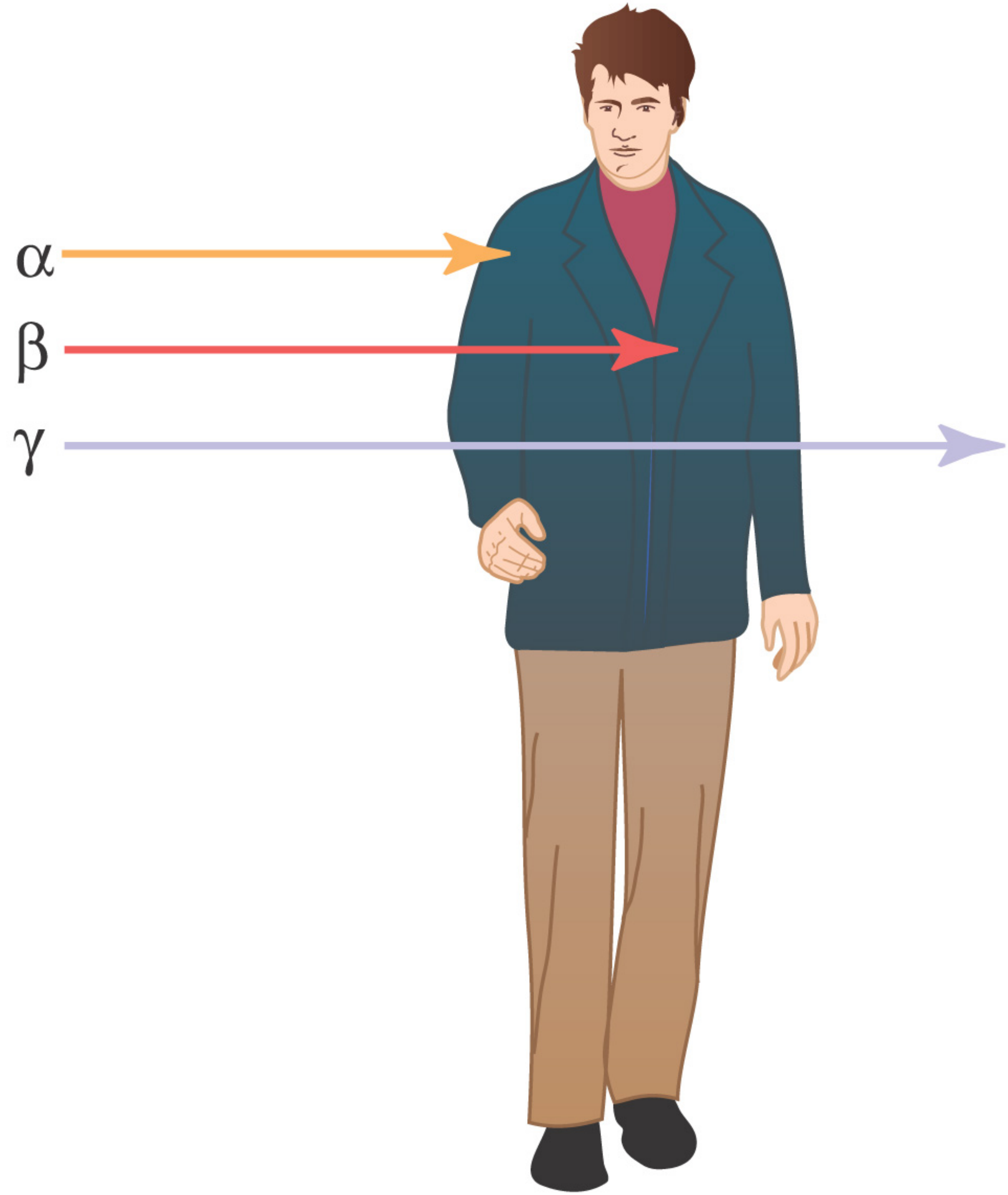
Writing Nuclear Equations

$$ {}^{232}_{90}\mathrm{Th} \longrightarrow \overbrace{\underbrace{{}^{x}_{y}? + {}^{4}_{2}\mathrm{He}}_{y + 2 = 90;\ y = 88}}^{x + 4 = 232;\ x = 228} $$

Table 18.1 Properties of Nuclear Radiation

Radiation	Identity	Approximate Velocity*	Shielding Required	Penetrating Power
alpha, α	helium nucleus	$\leq$10% c	paper, clothing	low, stopped by the skin
beta, β	electron	$\leq$90% c	30 cm wood, aluminum foil	medium, ~1 cm of flesh
gamma, γ	high-energy radiation	100% c	10 cm lead, 30 cm concrete	high, passes through body

*The letter **c** is the symbol for the velocity of light, 3×10^8 m/s.


α
β
γ

Types of radioactive decay

- alpha particle emission
- beta emission
- positron emission
- electron capture
- gamma emission

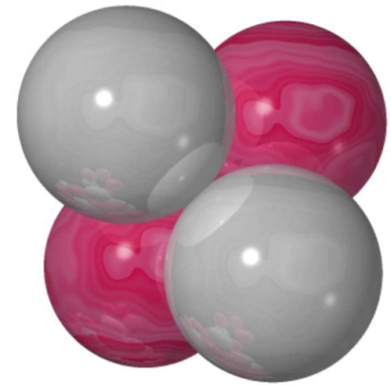
Table 18.2 Particles in Nuclear Reactions

Particle	Notation	Mass	Charge
alpha, α	${}^{4}_{2}\mathrm{He}$	~4 amu	2+
beta, β^-	${}^{0}_{-1}\mathrm{z}$	~0 amu	1−
gamma*, γ	${}^{0}_{0}\gamma$	0 amu	0
positron, β^+	${}^{0}_{+1}\mathrm{e}$	~0 amu	1+
neutron, n°	${}^{1}_{0}\mathrm{n}$	~1 amu	0
proton, p^+	${}^{1}_{1}\mathrm{H}$	~1 amu	1+

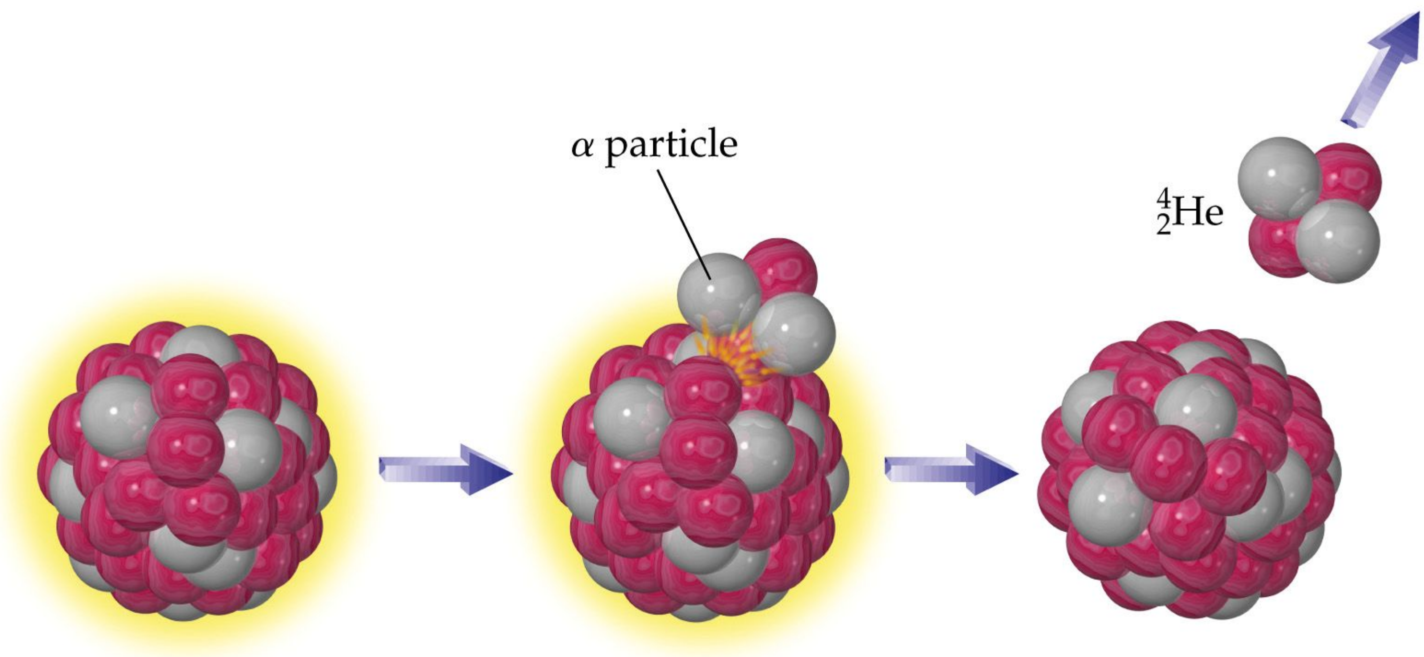
*Gamma rays are high-energy light waves, not particles, which have no mass.

Types of radioactive decay

- alpha particle emission
  - loss of a helium nucleus.



An α particle



Parent nuclide

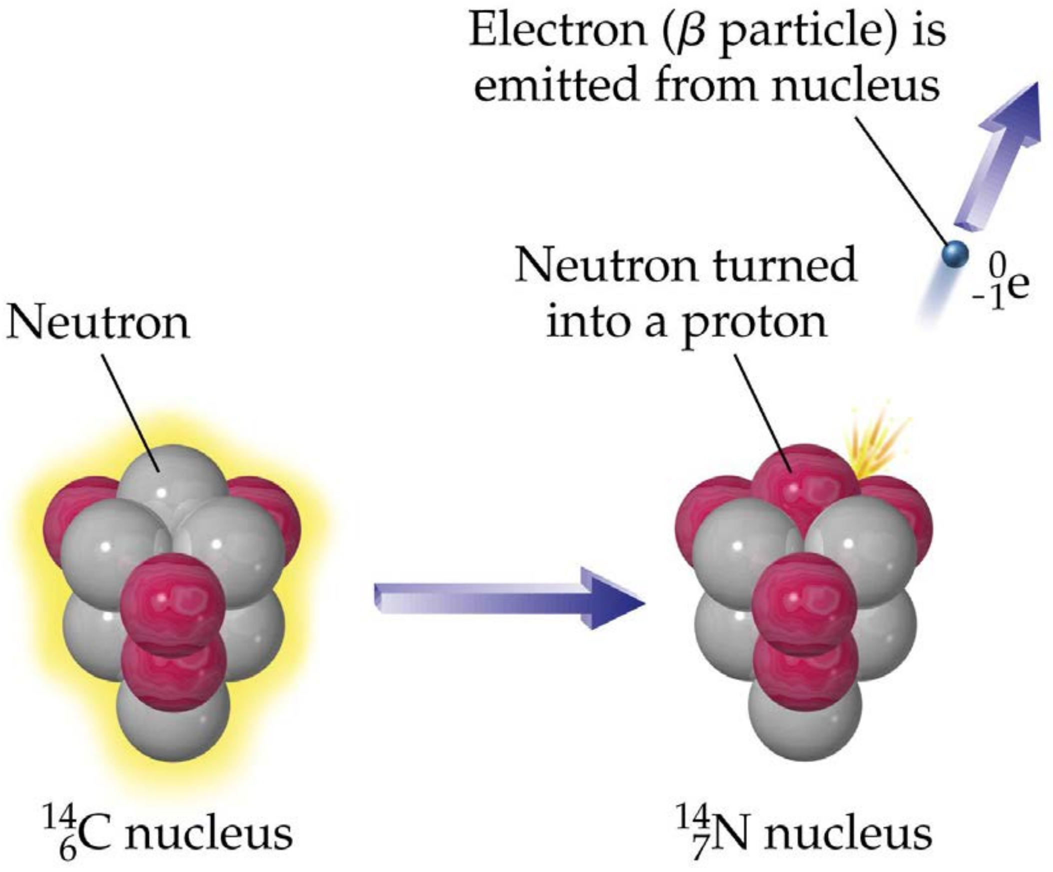
Daughter nuclides

$$^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$

- Problem Pu-239 (plutonium 239) loses an alpha particle (He nucleus). Write the nuclear reaction

Types of radioactive decay

- beta emission
  - A neutron splits into a proton and electron which is spit out as a b particle.



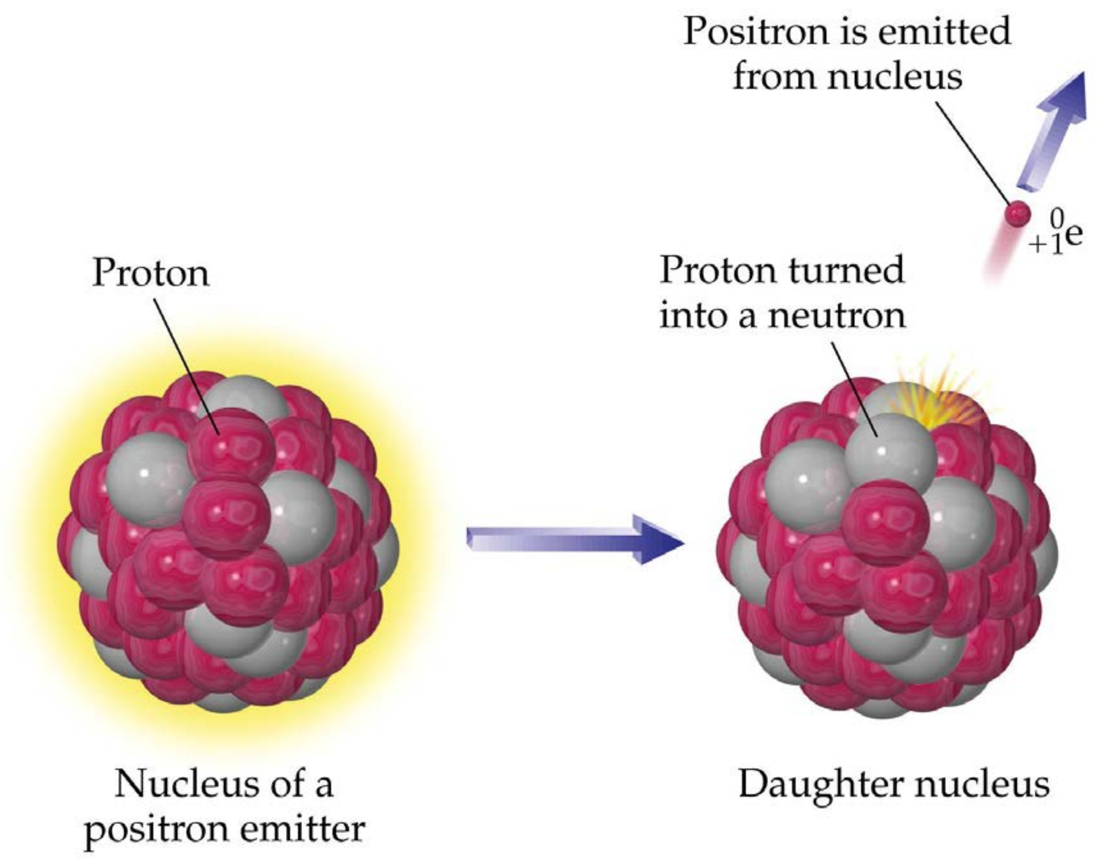
β particle emission

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

$${}^{210}_{82}Pb \rightarrow {}^{210}_{83}Bi + {}^{0}_{-1}e$$

Types of radioactive decay

- positron emission
  - A proton kicks out positive charge (a positron, β+) to become a neutron.



Types of radioactive decay

- electron capture (EC)
  - an electron (from inner shell) is sucked into the nucleus to combine with a proton – produces a neutron.

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

- gamma emission
  - emission of energy (photon) from an unstable nucleus.

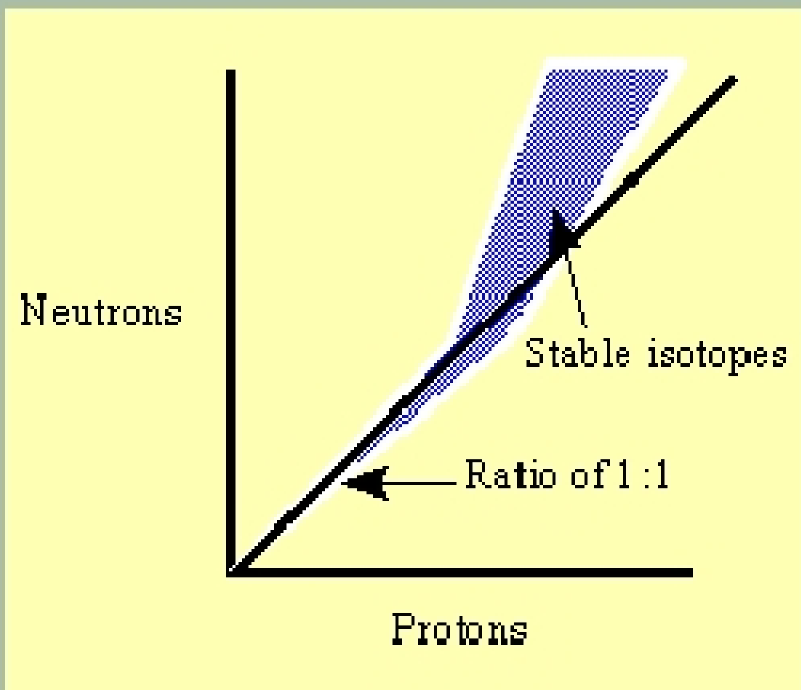
$$^{\overbrace{99m}^{metastable}}_{43}Tc \rightarrow ^{99}_{43}Tc + ^{0}_{0}\gamma$$

Can we predict types of radioactive decay that will occur?

- Nuclear particles are held together by a strong attractive force
- Like electrons, protons are arranged in shells
- Even numbers of protons and neutrons are most stable.
-
  An approximately 1-1 neutron to proton ration is generally most stable
- Atomic number > 83 is never stable.

# protons	# neutrons	# stable isotopes
even	even	157
even	odd	52
odd	even	50
odd	odd	5

Band of Nuclear Stability



- A plot of the known isotopes on a neutron/proton grid gives
- Stable isotopes form a band of stability from H to U
- Z:N ratios to either side of this band are too unstable & are not known

Nuclear Bombardment Reactions

- Transmutation – changing one element to another by shooting a nuclear particle at its nucleus.

- All transuranium elements (more than 92 protons) were created synthetically in particle accelerators.

Transmutation Reaction

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

or

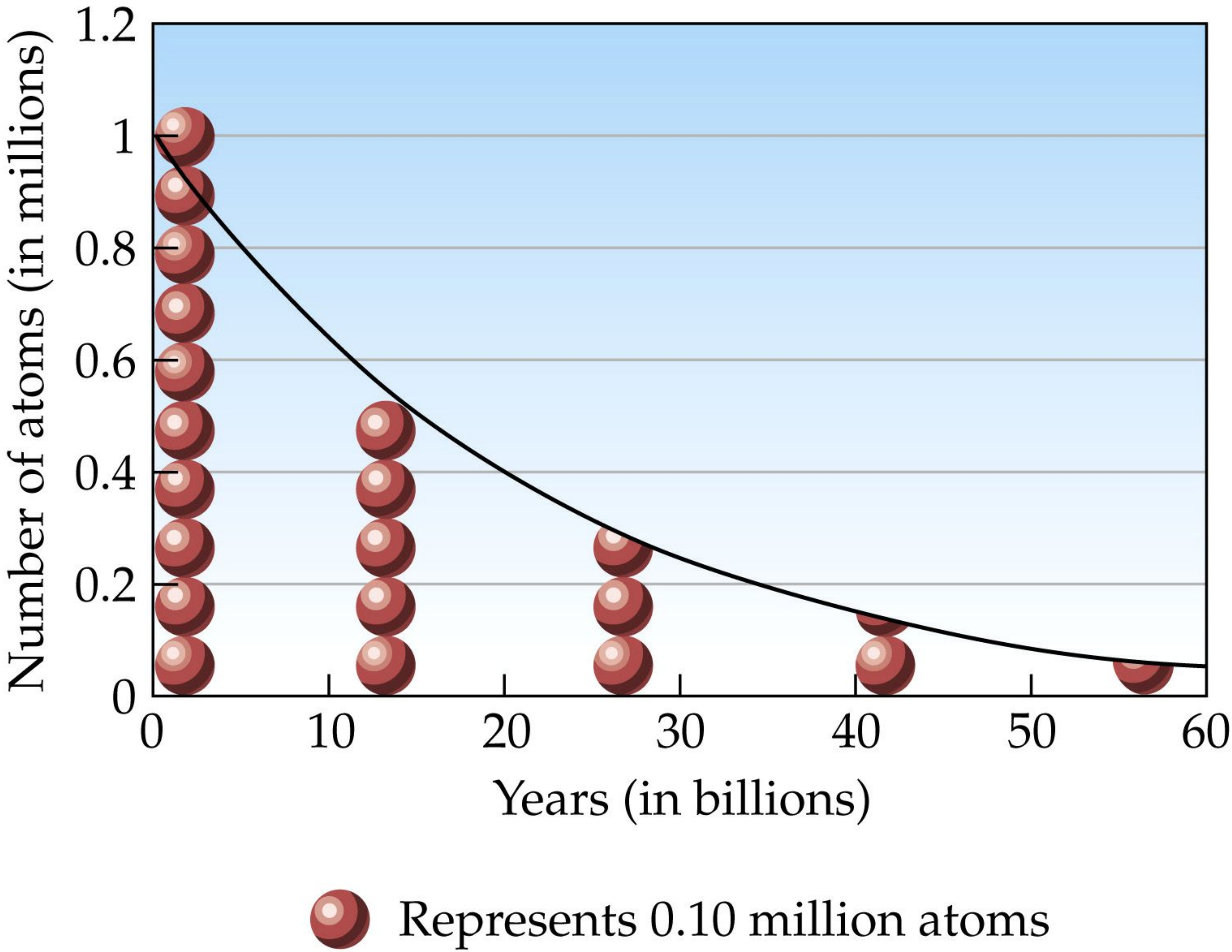
$$\underbrace{^{14}_{7}N}_{\substack{original\\particle}} \left(\underbrace{\alpha}_{\text{"bullet"}} \; , \; \underbrace{p}_{\substack{particle\\emitted}} \right) \underbrace{^{17}_{8}O}_{\substack{new\\atom}}$$

Energy of Nuclear Reactions

$$\underbrace{{}^{6}_{3}Li}_{6.01512} + \underbrace{{}^{1}_{1}H}_{1.00782} \rightarrow \underbrace{{}^{3}_{2}He}_{3.01603} + \underbrace{{}^{4}_{2}He}_{4.00260}$$

$$6.1512 + 1.00782 \neq 3.01603 + 4.00260$$

$$7.02294 \neq 7.01863 \quad .$$


Number of atoms (in millions)
1.2
1
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
Years (in billions)
Represents 0.10 million atoms

- If a radioactive isotope has a ½ life of 20 minutes, what percent of the sample will remain after 1 hour?

- If 75% of a sample decays after 6 hours, what is its half life?

- If a radioisotope has a half-life of 2 weeks, how long will it take for 99% of the sample to decay?

Applications – Carbon Dating

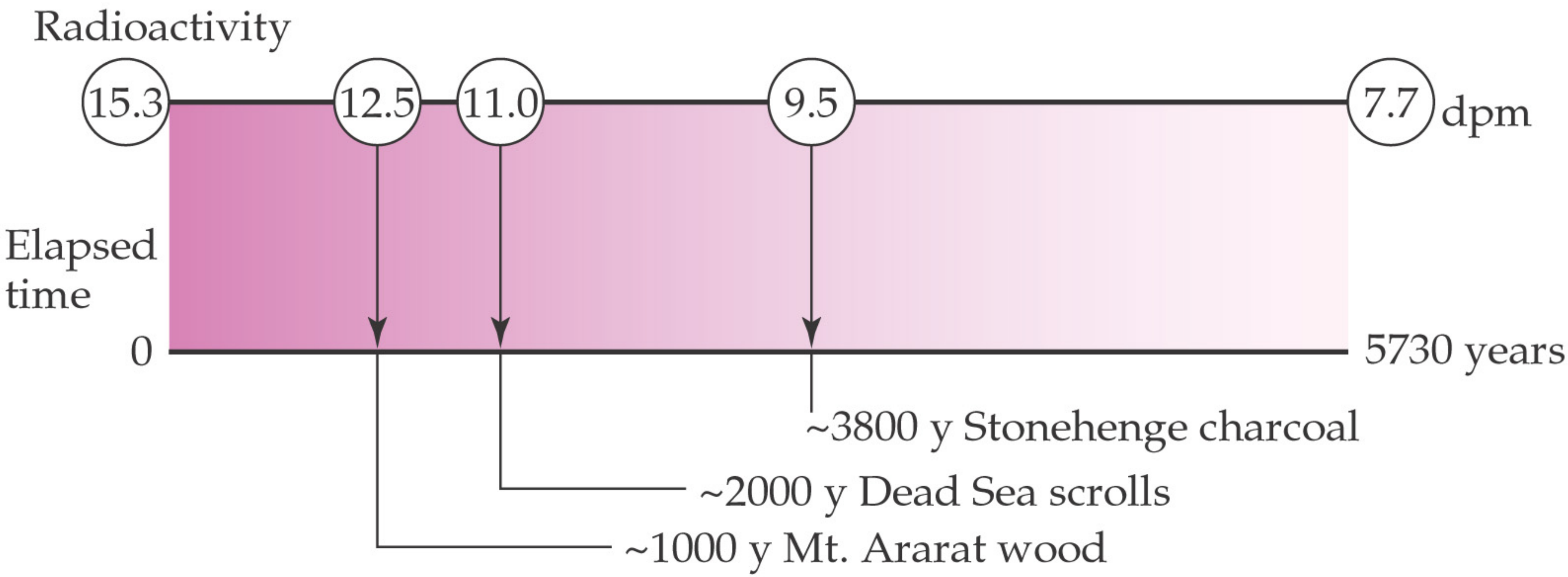
- nitrogen in the atmosphere is bombarded by neutrons to form ^{14}C

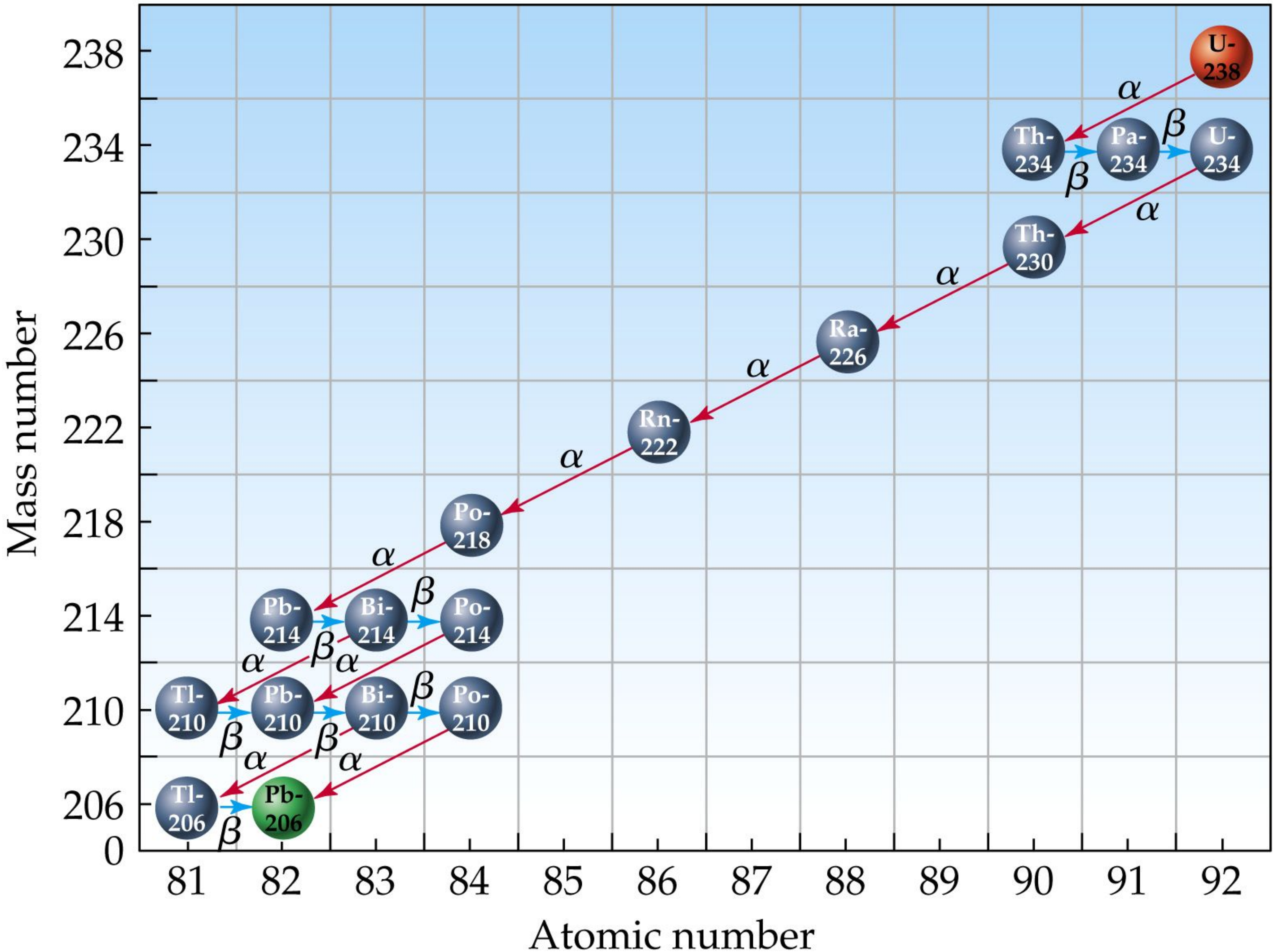
$$\boxed{{}^{14}_{7}N + {}^{1}_{0}n \rightarrow {}^{14}_{6}C + {}^{1}_{1}H}$$

- This carbon is integrated into CO_2 which then enters the food chain

$${}^{14}_{6}C \rightarrow {}^{14}_{6}CO_2 \rightarrow plants \rightarrow animals$$

Applications – Carbon Dating





Mass number
238
234
230
226
222
218
214
210
206
0
Atomic number
81
82
83
84
85
86
87
88
89
90
91
92
U-238
Th-234
Pa-234
U-234
Th-230
Ra-226
Rn-222
Po-218
Pb-214
Bi-214
Po-214
Tl-210
Pb-210
Bi-210
Po-210
Tl-206
Pb-206
α
β

Applications – Chemical Analysis

- Radioactive tracer – used to follow fate of a chemical using radio labeling

- Isotopic dilution – used to determine quantity of a substance when you can't measure it conveniently

- Neutron Activation Analysis – used to determine concentration of trace elements

Applications - Medicine

- Medicine
  - Diagnostic tracers
    - PET – Positron Emission Tomography
    - Patient fed radio-labeled glucose and it goes to where there is lots of metabolic activity. This often indicates a region of tumor activity.
  - Radiotherapy
  - Power pacemakers

- **Nuclear-Powered Cardiac Pacemakers**

- Pacemakers are used to stimulate a regular heartbeat when the body's natural electrical pacing system is irregular or not transmitting properly. Over the years, various power sources have been used for pacemakers, including thermoelectric batteries containing 2 to 4 curies of plutonium-238 (88 year half-life). As the term "thermoelectric" implies, the heat from the decaying plutonium is used to generate the electricity that stimulates the heart. At present (2003), there are between 50 and 100 people in the US who have nuclear powered pacemakers. When one of these individuals dies, the pacemaker is supposed to be removed and shipped to Los Alamos where the plutonium will be recovered.

- Nuclear powered pacemakers were discontinued in the 1970s.

http://www.orau.org/PTP/collection/Miscellaneous/pacemaker.htm

- **What Is PET**
- Positron Emission Tomography (PET) is a major diagnostic imaging modality used predominantly in determining the presence and severity of cancers, neurological conditions, and cardiovascular disease. It is currently the most effective way to check for cancer recurrences, and it offers significant advantages over other forms of imaging such as CT or MRI scans in detecting disease in many patients. In 2005, an estimated 1,129,900 clinical PET patient studies were performed at 1,725 sites around the country. If you're interested in learning how a PET scan can benefit you and need additional information, talk with your local health care provider or referring physician. At the end of this page are links to other sites with PET information too.
- PET images demonstrate the chemistry of organs and other tissues such as tumors. A radiopharmaceutical, such as FDG (fluorodeoxyglucose), which includes both sugar (glucose) and a radionuclide (a radioactive element) that gives off signals, is injected into the patient, and its emissions are measured by a PET scanner.
- A PET scanner consists of an array of detectors that surround the patient. Using the gamma ray signals given off by the injected radionuclide, PET measures the amount of metabolic activity at a site in the body and a computer reassembles the signals into images. Cancer cells have higher metabolic rates than normal cells, so they show up as denser areas on a PET scan. PET is useful in diagnosing certain cardiovascular and neurological diseases because it highlights areas with increased, diminished or no metabolic activity, thereby pinpointing problems.
- **Cancer and PET**
- PET is considered particularly effective in identifying whether cancer is present or not, if it has spread, if it is responding to treatment, and if a person is cancer free after treatment. Cancers for which PET is considered particularly effective include lung, head and neck, colorectal, esophageal, lymphoma, melanoma, breast, thyroid, cervical, pancreatic, and brain as well as other less-frequently occurring cancers.
- **Early Detection:** Because PET images biochemical activity, it can accurately characterize a tumor as benign or malignant, thereby avoiding surgical biopsy when the PET scan is negative. Conversely, because a PET scan images the entire body, confirmation of distant metastasis can alter treatment plans in certain cases from surgical intervention to chemotherapy.
- **Staging of Cancer:** PET is extremely sensitive in determining the full extent of disease, especially in lymphoma, malignant melanoma, breast, lung, colon and cervical cancers. Confirmation of metastatic disease allows the physician and patient to more accurately decide how to proceed with the patient's management.
- **Checking for recurrences:** PET is currently considered to be the most accurate diagnostic procedure to differentiate tumor recurrences from radiation necrosis or post-surgical changes. Such an approach allows for the development of a more rational treatment plan for the patient.
- **Assessing the Effectiveness of Chemotherapy:** The level of tumor metabolism is compared on PET scans taken before and after a chemotherapy cycle. A successful response seen on a PET scan frequently precedes alterations in anatomy and would therefore be an earlier indicator of tumor response than that seen with other diagnostic modalities.

From http://interactive.snm.org/index.cfm?PageID=972

• What is radiation therapy?

- Radiation therapy (also called radiotherapy, x-ray therapy, or irradiation) is the use of a certain type of energy (called ionizing radiation) to kill cancer cells and shrink tumors. Radiation therapy injures or destroys cells in the area being treated (the "target tissue") by damaging their genetic material, making it impossible for these cells to continue to grow and divide. Although radiation damages both cancer cells and normal cells, most normal cells can recover from the effects of radiation and function properly. The goal of radiation therapy is to damage as many cancer cells as possible, while limiting harm to nearby healthy tissue.
- There are different types of radiation and different ways to deliver the radiation. For example, certain types of radiation can penetrate more deeply into the body than can others. In addition, some types of radiation can be very finely controlled to treat only a small area (an inch of tissue, for example) without damaging nearby tissues and organs. Other types of radiation are better for treating larger areas.

http://www.cancer.gov/cancertopics/factsheet/Therapy/radiation

Other Applications

- Agriculture
  - Irradiate food
  - Pesticide
- Energy
  - Fission
  - Fusion

Irradiation of food

How will I know if meat and poultry products are irradiated?

The international symbol for irradiation, the radura, must be on packages if the entire product was irradiated, as well as the phrase, "treated by irradiation" (or "with irradiation"). The radura, pictured here, can be any color. This required labeling gives consumers the option to choose between irradiated and non-irradiated meat and poultry.

What is food irradiation?

Food irradiation is a process in which approved foods are exposed to radiant energy, including gamma rays, electron beams, and x-rays. In 1963, the Food and Drug Administration (FDA) found the irradiation of food to be safe. Irradiation of meat and poultry is done in a government-approved irradiation facility. Irradiation is not a substitute for good sanitation and process control in meat and poultry plants. It is an added layer of safety.

What foods are irradiated?

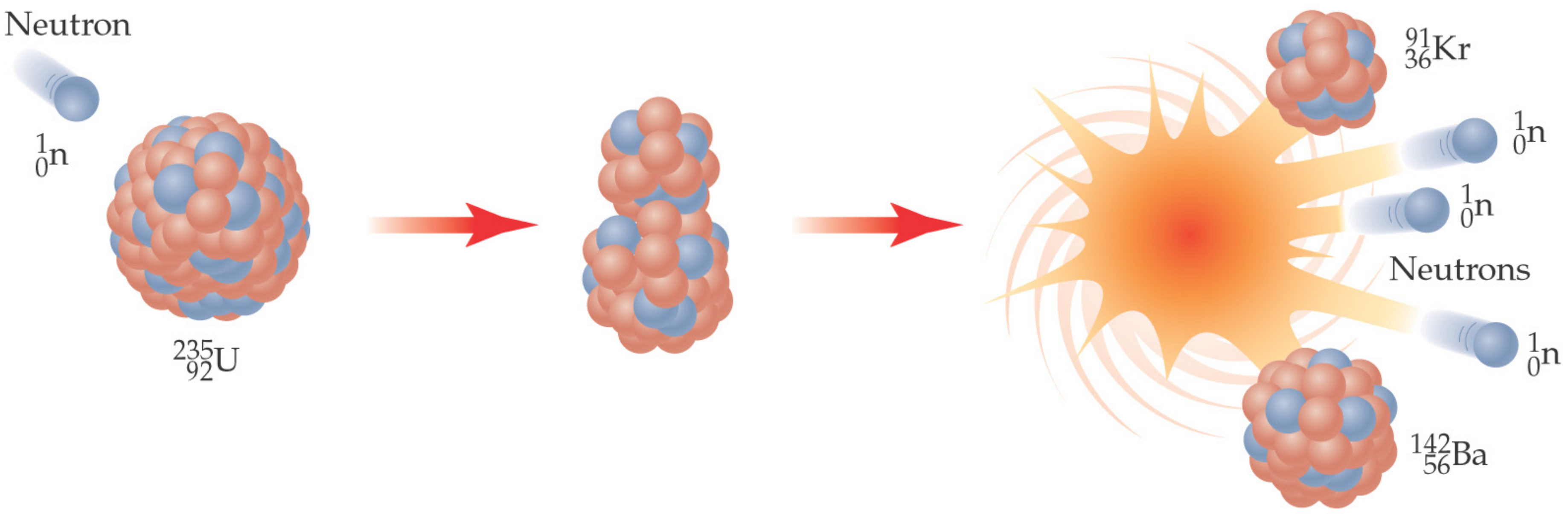
Fresh meat and poultry including whole or cut up birds, skinless poultry, pork chops, roasts, stew meat, liver, hamburgers, ground meat, and ground poultry are approved for irradiation.

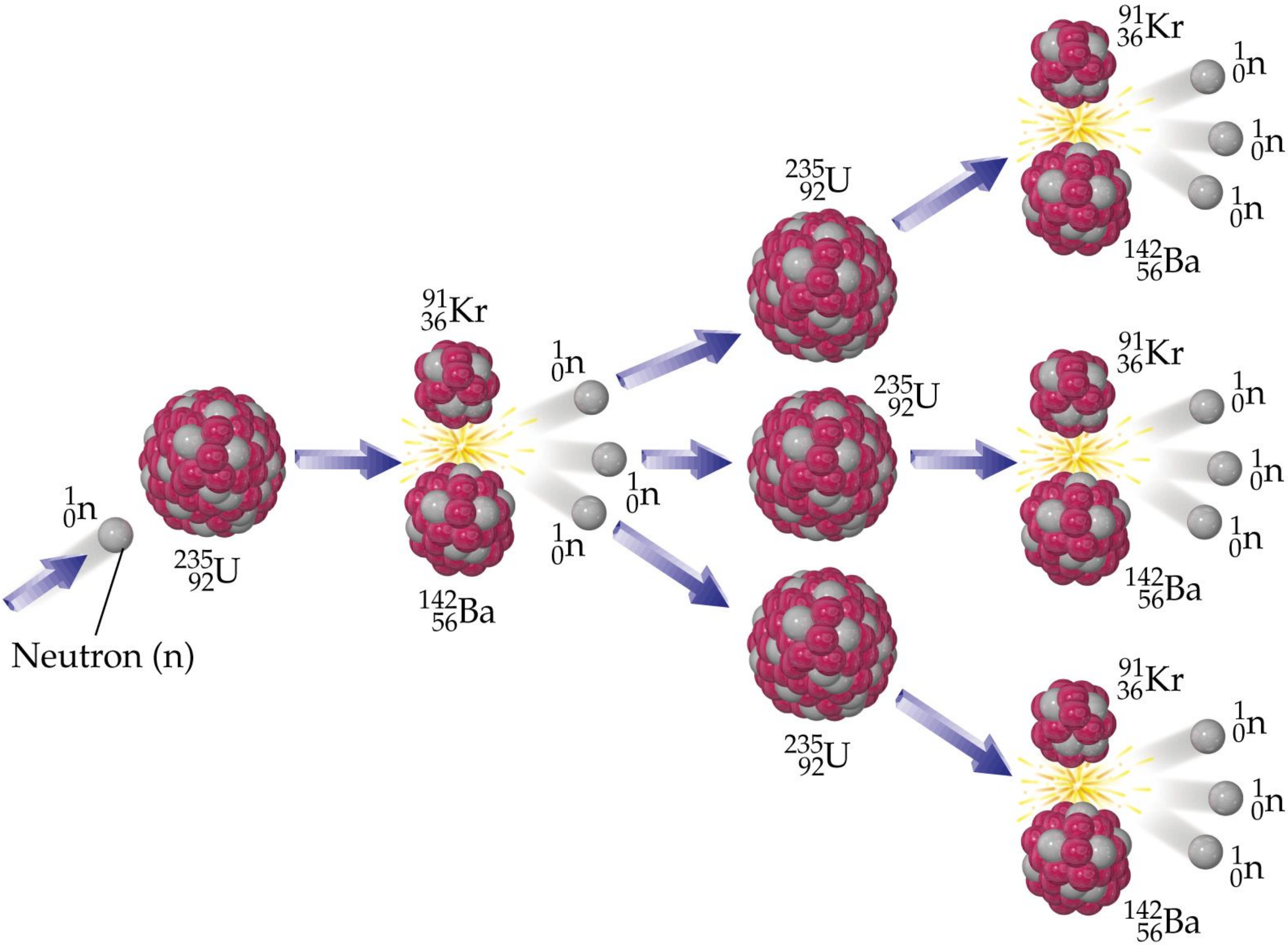
U.S. food regulations also allow the irradiation of wheat and wheat powder, white potatoes, many spices, dry vegetable seasonings, fresh shell eggs, and fresh produce.

Are irradiated foods safe to eat?

Yes. Just as pasteurization makes milk safer, irradiation makes meat and poultry safer by reducing the numbers of harmful bacteria and parasites. Irradiation is an important food safety tool in fighting foodborne illness.

http://www.fsis.usda.gov/Fact_Sheets/Irradiation_and_Food_Safety/index.asp


Neutron
$^{1}_{0}n$
$^{235}_{92}U$
$^{91}_{36}Kr$
$^{1}_{0}n$
$^{1}_{0}n$
Neutrons
$^{1}_{0}n$
$^{142}_{56}Ba$



$^{1}_{0}n$
Neutron (n)
$^{235}_{92}U$
$^{91}_{36}Kr$
$^{142}_{56}Ba$
$^{1}_{0}n$
$^{1}_{0}n$
$^{1}_{0}n$
$^{235}_{92}U$
$^{235}_{92}U$
$^{235}_{92}U$
$^{91}_{36}Kr$
$^{142}_{56}Ba$
$^{1}_{0}n$
$^{1}_{0}n$
$^{1}_{0}n$
$^{91}_{36}Kr$
$^{142}_{56}Ba$
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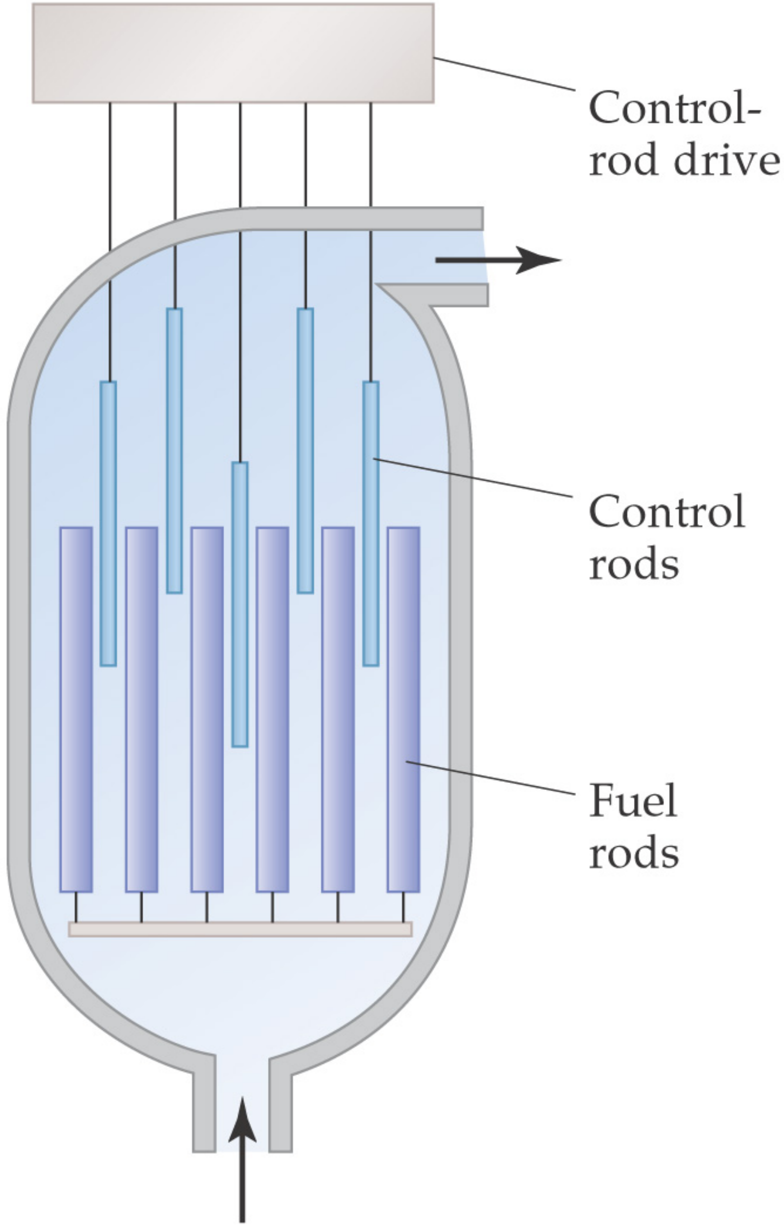
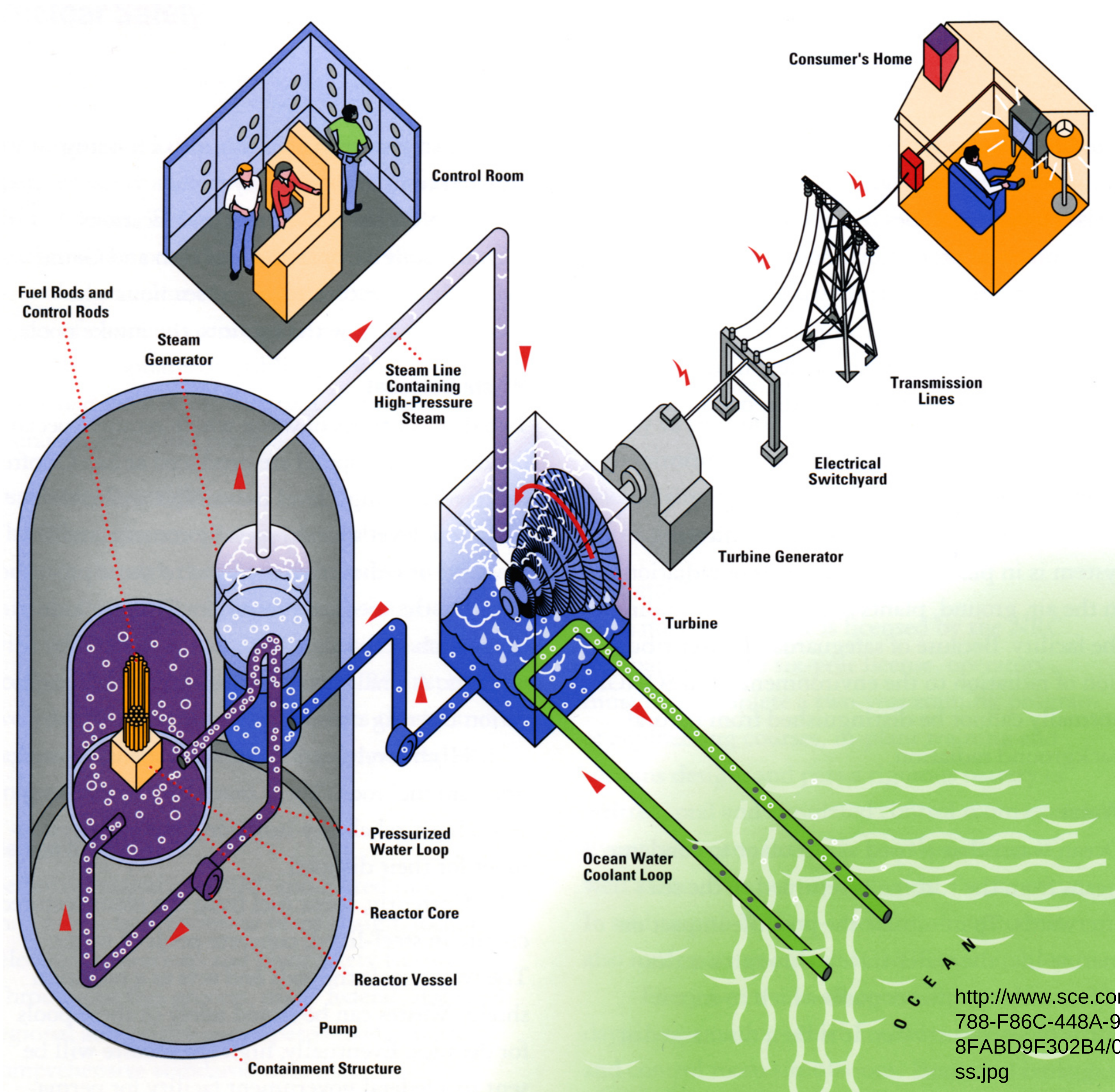
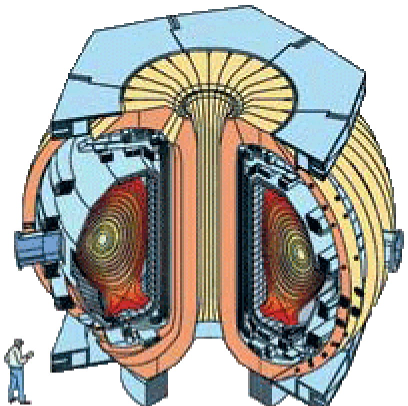

Control-
rod drive
Control
rods
Fuel
rods
Circulating
cooling fluid



http://www.sce.com/NR/rdonlyres/A050B788-F86C-448A-9A66-8FABD9F302B4/0/NuclearEnergy_process.jpg

- **What is fusion?**
- *Fusion is the process that powers the sun and the stars. It is the reaction in which two atoms of hydrogen combine together, or fuse, to form an atom of helium. In the process, some of the mass of the hydrogen is converted to energy. Fusion has the potential to be an inexhaustible source of energy.*



http://fusion.gat.com/global/Basics

EPA Map of Radon Zones