MPM: 203 NUCLEAR AND PARTICLE PHYSICS

UNIT –I: Nuclear Stability

Lecture-11

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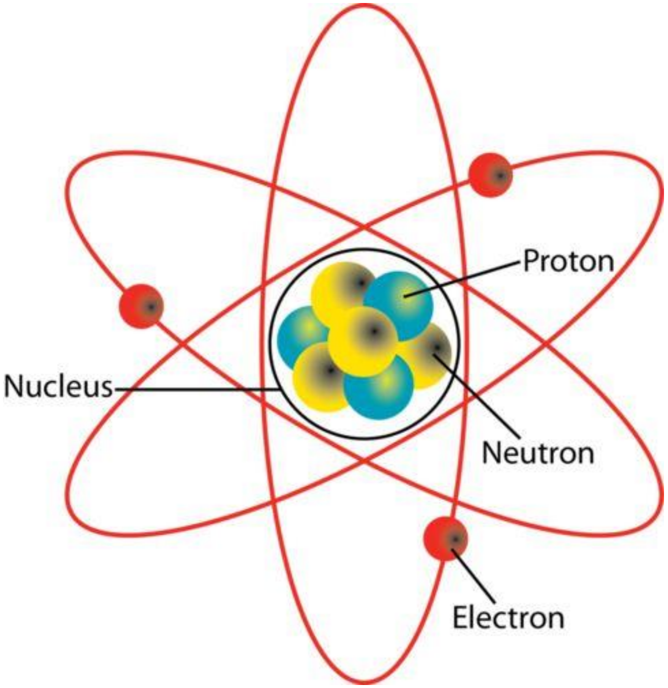
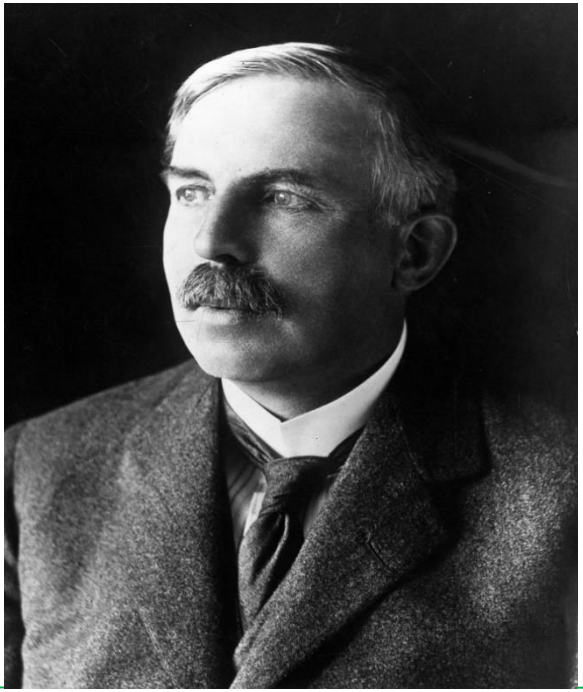




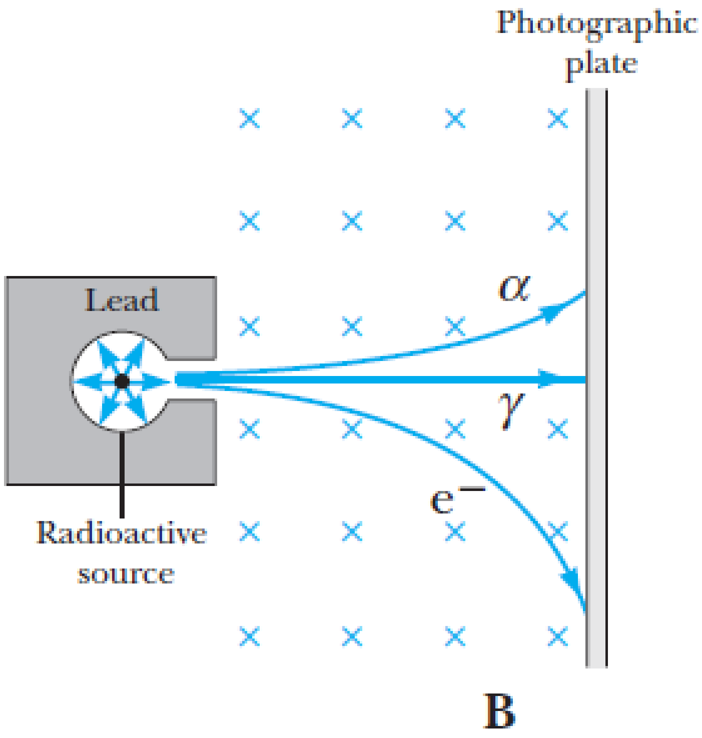


Figure 13.14 The radiation from a radioactive source can be separated into three components through the use of a magnetic field to deflect the charged particles. The photographic plate at the right records the events. The gamma ray is not deflected by the magnetic field.

Positrons have same mass and spin as electron but positive charge

e^- and e^+ are also called beta radiation

Alpha, Beta, and Gamma Decay

When a nucleus decays, all the conservation laws must be observed:

- Mass-energy
- Linear momentum
- Angular momentum
- Electric charge
- **Conservation of nucleons**
  - The total number of nucleons (*A*, the mass number) must be conserved in a typical (relatively low energy) nuclear reaction or decay.

Alpha, Beta, and Gamma Decay

- Let the radioactive nucleus ${}^{A}_{Z}X$ be called the parent and have the mass $M\left({}^{A}_{Z}X\right)$
- Two or more products can be produced in the decay.
- Let the original one be M_y (mother) and the mass of the subsequent one (*daughter*) be M_D.
- The conversation of energy is $M\left({}^{A}_{Z}X\right) = M_D + M_y + Q/c^2$

  where Q is the energy released (**disintegration energy**) and equal to the total kinetic energy of the reaction products.

$$Q = \left[M\left({}^{A}_{Z}X\right) - M_D - M_y\right]c^2$$

- If $Q > 0$, a nuclide is unstable and may decay.
- If $Q < 0$, decays emitting nucleons do not occur.

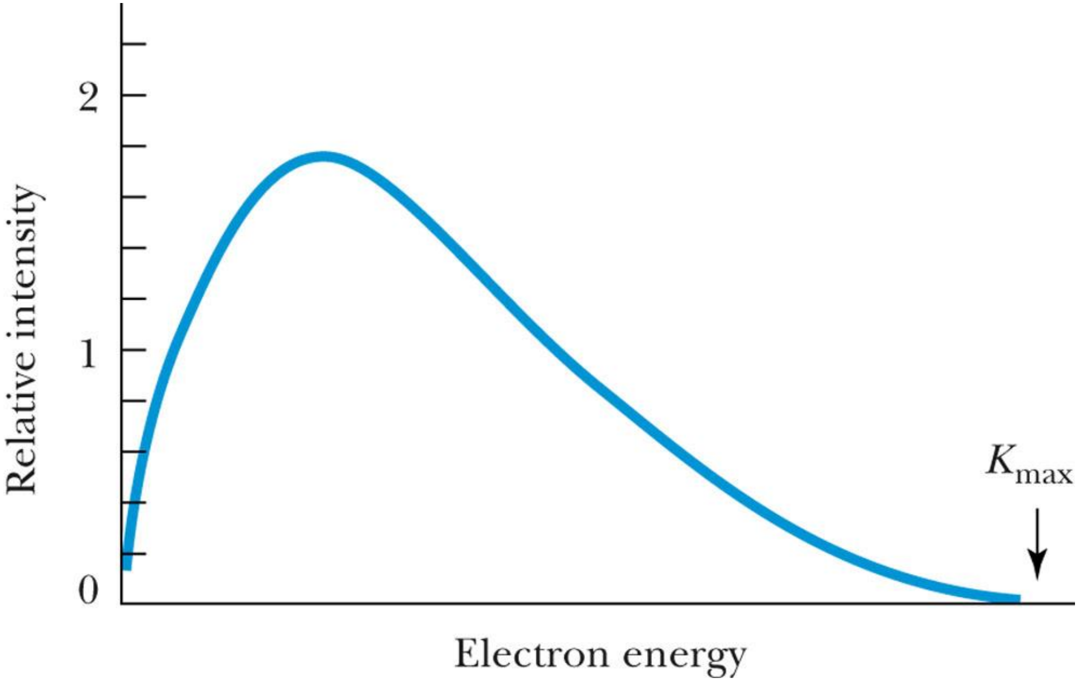
Beta Decay

- Unstable nuclei may move closer to the line of stability by undergoing beta decay.
- The decay of a free neutron is

$$n \rightarrow p + \beta^-$$

- The beta decay of ^{14}C (unstable) to form ^{14}N, a stable nucleus, can be written as

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



The electron energy spectrum from the beta decay

The electron does not exist in the nucleus, it is created from the energy that results from the decay (which is due to the weak force)

Observed experimentally, but should be impossible according to the prevailing understanding of physics before Pauli's neutrino

Beta Decay

- There was a problem in neutron decay, the spin ½ neutron cannot decay to two spin ½ particles, a proton and an electron. ^{14}C has spin 0, ^{14}N has spin 1, and the electron has spin ½.

→ we cannot combine spin ½ & 1 to obtain a spin 0.

- Wolfgang Pauli proposed a new particle, the **neutrino,** that must be produced in beta decay. It has spin quantum number ½, charge 0, and carries away the energy that is apparently missing in the fig. in the previous slide
- Momentum seems not to be conserved either, so Pauli predicts a particle that must exist and carry away just the right amount of energy so that the conservation principle of total energy is not conserved, that way, momentum will also be conserved and everything is Oki-Doki again

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That particle will actually be much later experimentally observed

Beta Decay

- An occasional electron is detected with the kinetic energy close to the required K_{max} (to conserve energy), but in most cases the electron's kinetic energy is less than K_{max}.

→ the neutrino has very very very little mass, and most of its energy is kinetic.

- Neutrinos have no charge and do not interact *electromagnetically*.
- They are not affected by the *strong* force of the nucleus.
- They are due to the *weak* interaction (result from the weak force).
- The unification of the electromagnetic and weak force is the *electroweak* force.

β^- Decay

- There are actually *anti*neutrino $\bar{\nu}$. (In beta-minus decay)
- The beta decay of both a free neutron and ^{14}C is written as

$$n \rightarrow p + \beta^- + \bar{\nu} \qquad \beta^- \text{ decay}$$

$$^{14}\mathrm{C} \rightarrow {}^{14}\mathrm{N} + \beta^- + \bar{\nu} \qquad \beta^- \text{ decay}$$

- In the general beta decay of the parent nuclide $^{A}_{Z}X$ the daughter $^{A}_{Z+1}D$ the reaction is $^{A}_{Z}X$

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}D + \beta^- + \bar{\nu} \qquad \beta^- \text{ decay}$$

- The disintegration energy Q is

Note that A is constant

$$Q = \left[M\left({}^{A}_{Z}X\right) - M\left({}^{A}_{Z+1}D\right)\right]c^2 \qquad \beta^- \text{ decay}$$

- In order for β^- to occur, we must have $Q > 0$.
- The total number of nucleons A is constant, but Z changes to $Z + 1$.

β^+ Decay

- What happens for unstable nuclides with too many protons
- Positive electron (positron) is produced.
- Positron is the antiparticle of the electron.
- A free proton *might* decay with $t_{1/2} > 10^{32}$ y, nobody knows for sure
- The nucleus ^{14}O is unstable and decays by emitting a positron and a neurino to become stable ^{14}N.

$$^{14}\mathrm{O} \rightarrow {}^{14}\mathrm{N} + \beta^+ + \nu \qquad \beta^+ \text{ decay}$$

- The general β^+ decay is

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}D + \beta^+ + \nu \qquad \beta^+ \text{ decay}$$

Electron Capture

- Classically, inner K-shell and L-shell electrons are tightly bound and L-orbits are highly elliptical, possibility of atomic electron capture.
- The reaction for a proton is $p + e^- \longrightarrow n + v$
- The general reaction is

$$ {}^{A}_{Z}X + e^- \rightarrow {}^{\;\;\,A}_{Z-1}D + v \qquad \text{Electron capture} $$

- The disintegration energy Q is

$$ Q = \left[M\left({}^{A}_{Z}X\right) - M\left({}^{\;\;\,A}_{Z-1}D\right) \right] c^2 \qquad \text{Electron capture} $$

Gamma Decay $^{A}_{Z}X^{*} \longrightarrow {}^{A}_{Z}X + \gamma$

- If the decay proceeds to an excited state of energy *E_x* rather than to the ground state, then *Q* for the transition to the excited state can be determined with respect to the transition to the ground state. The disintegration energy *Q* to the ground state *Q_0*.

$$^{12}_{5}B \longrightarrow {}^{12}_{6}C^{*} + e^{-} + \overline{\nu}$$

$$^{12}_{6}C^{*} \longrightarrow {}^{12}_{6}C + \gamma$$

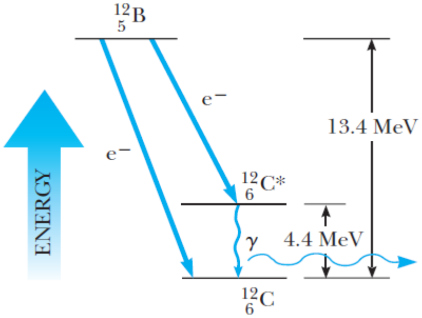
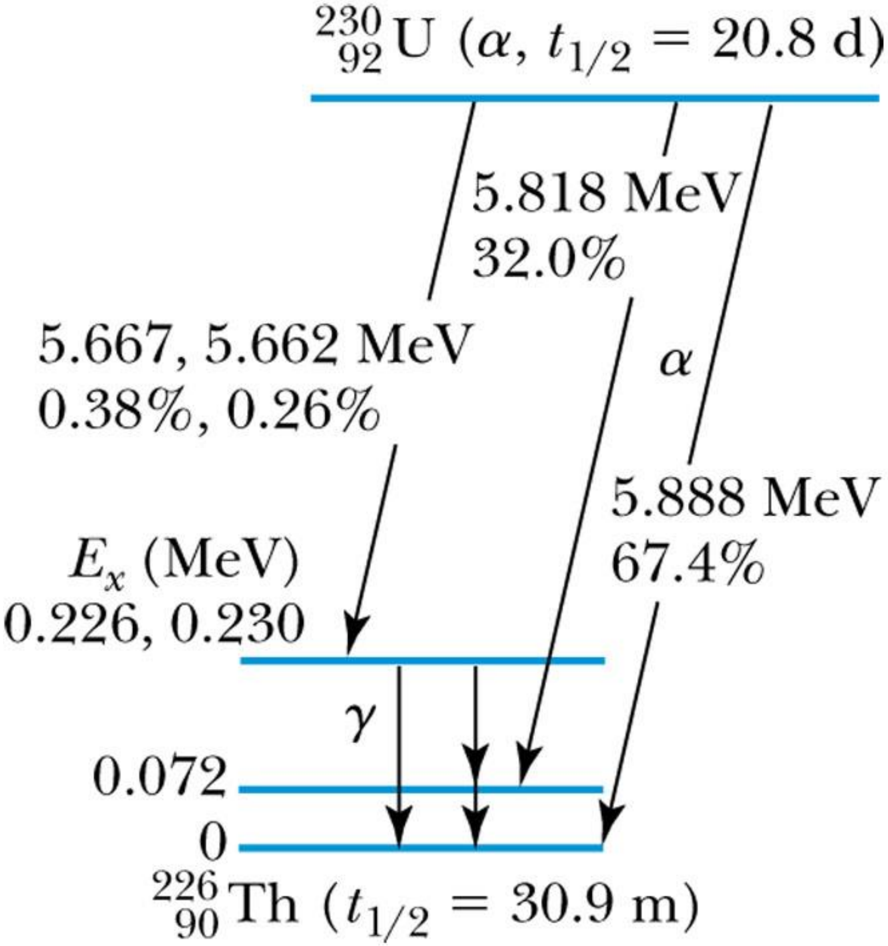


Figure 13.20 An energy-level diagram showing the initial nuclear state of a ^{12}B nucleus and two possible lower-energy states of the ^{12}C nucleus. The beta decay of the ^{12}B nucleus can result in either of two situations: The ^{12}C nucleus is in the ground state or in the excited state, in which case the nucleus is denoted as $^{12}C^{*}$. In the latter case, the beta decay to $^{12}C^{*}$ is followed by a gamma decay to ^{12}C as the excited nucleus makes a transition to the ground state.

- *Q* for a transition to the excited state *E_x* is

$$Q = Q_0 - E_x$$


$^{230}_{92}$U (α, $t_{1/2}$ = 20.8 d)
5.818 MeV
32.0%
5.667, 5.662 MeV
0.38%, 0.26%
α
5.888 MeV
67.4%
E_x (MeV)
0.226, 0.230
γ
0.072
0
$^{226}_{90}$Th ($t_{1/2}$ = 30.9 m)

Gamma Decay

- The excitation energies tend to be much larger, many keV or even MeV.
- The possibilities for the nucleus to rid itself of this extra energy is to emit a very high energy photon (gamma ray).
- The gamma-ray energy *hf* is given by the difference of the higher energy state $E_>$ and lower one $E_<$.

$$hf = E_> - E_<$$

- The decay of an excited state of $^{A}X^{*}$ (where * is an excited state) to its ground state is

$$^{A}X^{*} \rightarrow {}^{A}X + \gamma$$

- A transition between two nuclear excited states $E_>$ and $E_<$ is

$$^{A}X^{*}(E_>) \rightarrow {}^{A}X^{*}(E_<) + \gamma$$

Gamma Decay

- The gamma rays are normally emitted soon after a nucleus is put into an excited state.

- Sometimes selection rules prohibit a certain transition, and the excited state may live for a long time.
- These states are called **isomers** or **isomeric states** and are denoted by a small *m* for *metastable*.

- Example: one state of ${}^{210\mathrm{m}}_{83}\mathrm{Bi}$ at 0.271 MeV excitation energy does not gamma decay because of a large spin difference transition.

Radioactive Nuclides

- The unstable nuclei found in nature exhibit natural radioactivity.

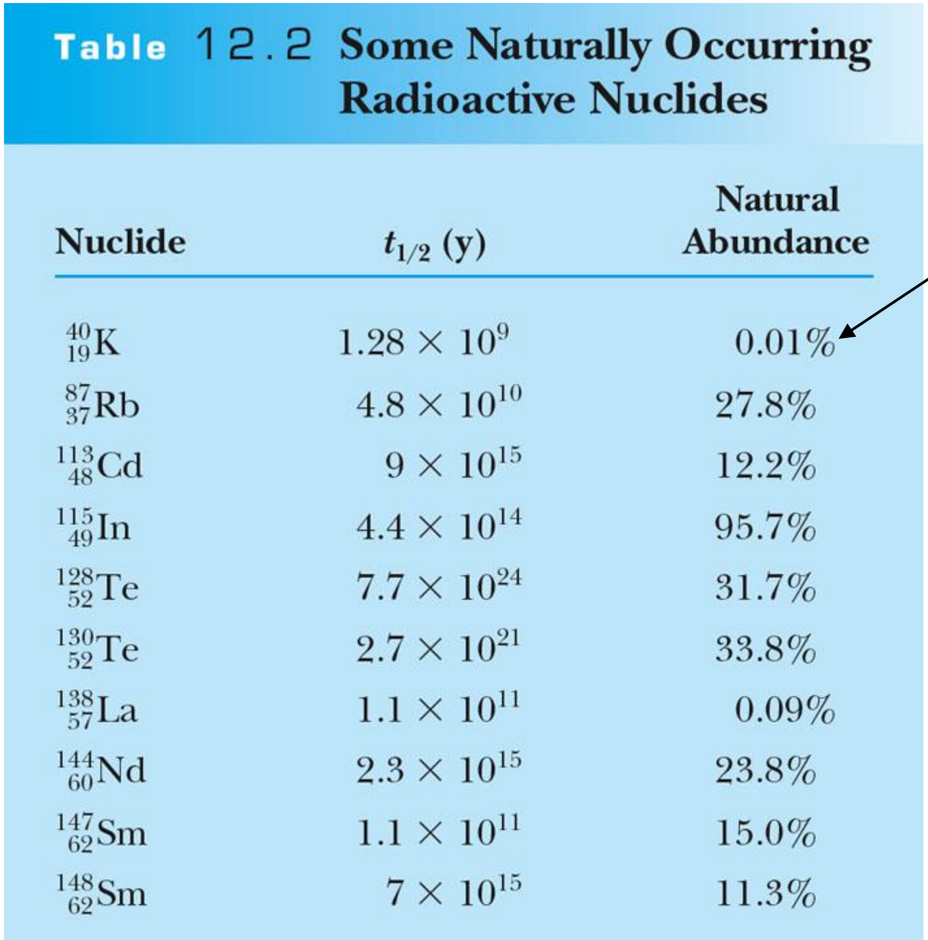


Table 12.2 Some Naturally Occurring Radioactive Nuclides

Nuclide	$t_{1/2}$ (y)	Natural Abundance
$^{40}_{19}\mathrm{K}$	1.28×10^{9}	0.01%
$^{87}_{37}\mathrm{Rb}$	4.8×10^{10}	27.8%
$^{113}_{48}\mathrm{Cd}$	9×10^{15}	12.2%
$^{115}_{49}\mathrm{In}$	4.4×10^{14}	95.7%
$^{128}_{52}\mathrm{Te}$	7.7×10^{24}	31.7%
$^{130}_{52}\mathrm{Te}$	2.7×10^{21}	33.8%
$^{138}_{57}\mathrm{La}$	1.1×10^{11}	0.09%
$^{144}_{60}\mathrm{Nd}$	2.3×10^{15}	23.8%
$^{147}_{62}\mathrm{Sm}$	1.1×10^{11}	15.0%
$^{148}_{62}\mathrm{Sm}$	7×10^{15}	11.3%

All living people are somewhat radioactive, e.g. depending on how much NaCl they eat (it is obtained from mines, where there is some KCl present as well

Radioactive Nuclides

- There are **only four paths** that the heavy naturally occurring radioactive nuclides may take as they decay.
- Mass numbers expressed by either:
    - 4*n*
    - 4*n* + 1
    - 4*n* + 2
    - 4*n* + 3

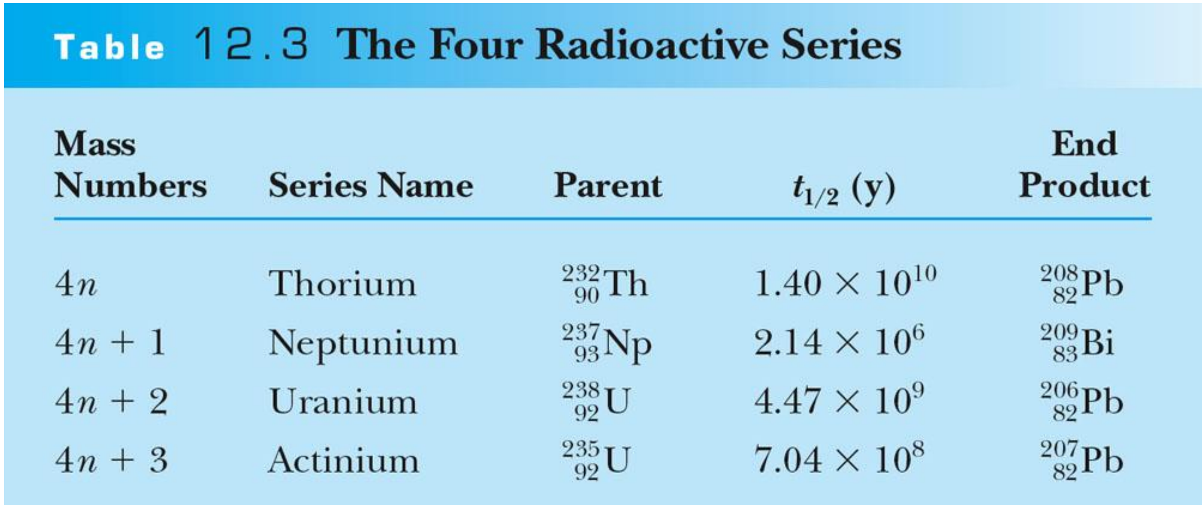


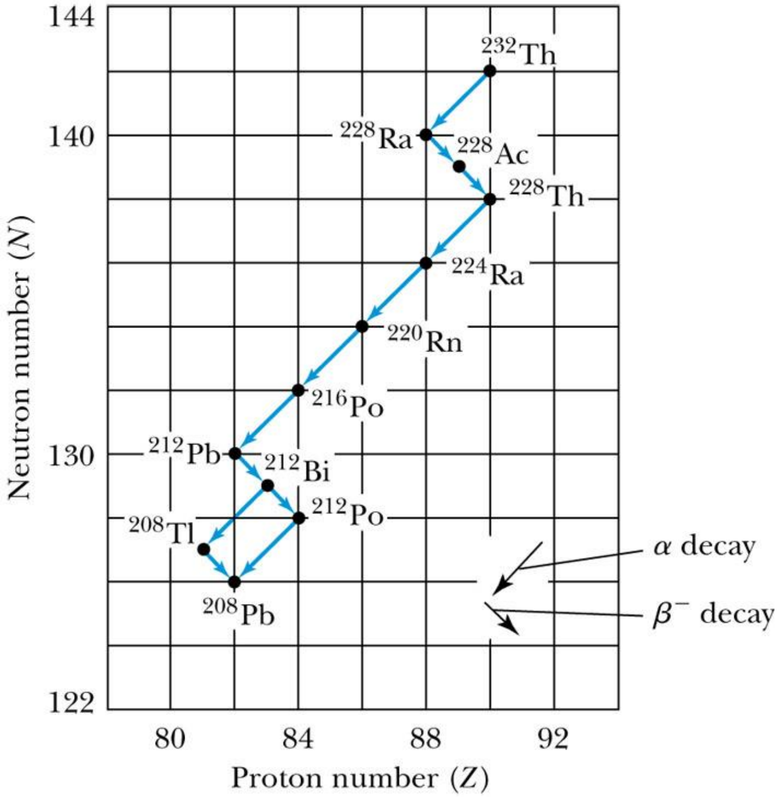
Table 12.3 The Four Radioactive Series

Mass Numbers	Series Name	Parent	$t_{1/2}$ (y)	End Product
$4n$	Thorium	$^{232}_{90}\mathrm{Th}$	1.40×10^{10}	$^{208}_{82}\mathrm{Pb}$
$4n + 1$	Neptunium	$^{237}_{93}\mathrm{Np}$	2.14×10^{6}	$^{209}_{83}\mathrm{Bi}$
$4n + 2$	Uranium	$^{238}_{92}\mathrm{U}$	4.47×10^{9}	$^{206}_{82}\mathrm{Pb}$
$4n + 3$	Actinium	$^{235}_{92}\mathrm{U}$	7.04×10^{8}	$^{207}_{82}\mathrm{Pb}$

All four paths lead to different types of isotopes of Pb

Radioactive Nuclides

- The sequence of one of the radioactive series ^{232}Th



- ^{212}Bi can decay by either alpha or beta decay (*branching*).

Applications

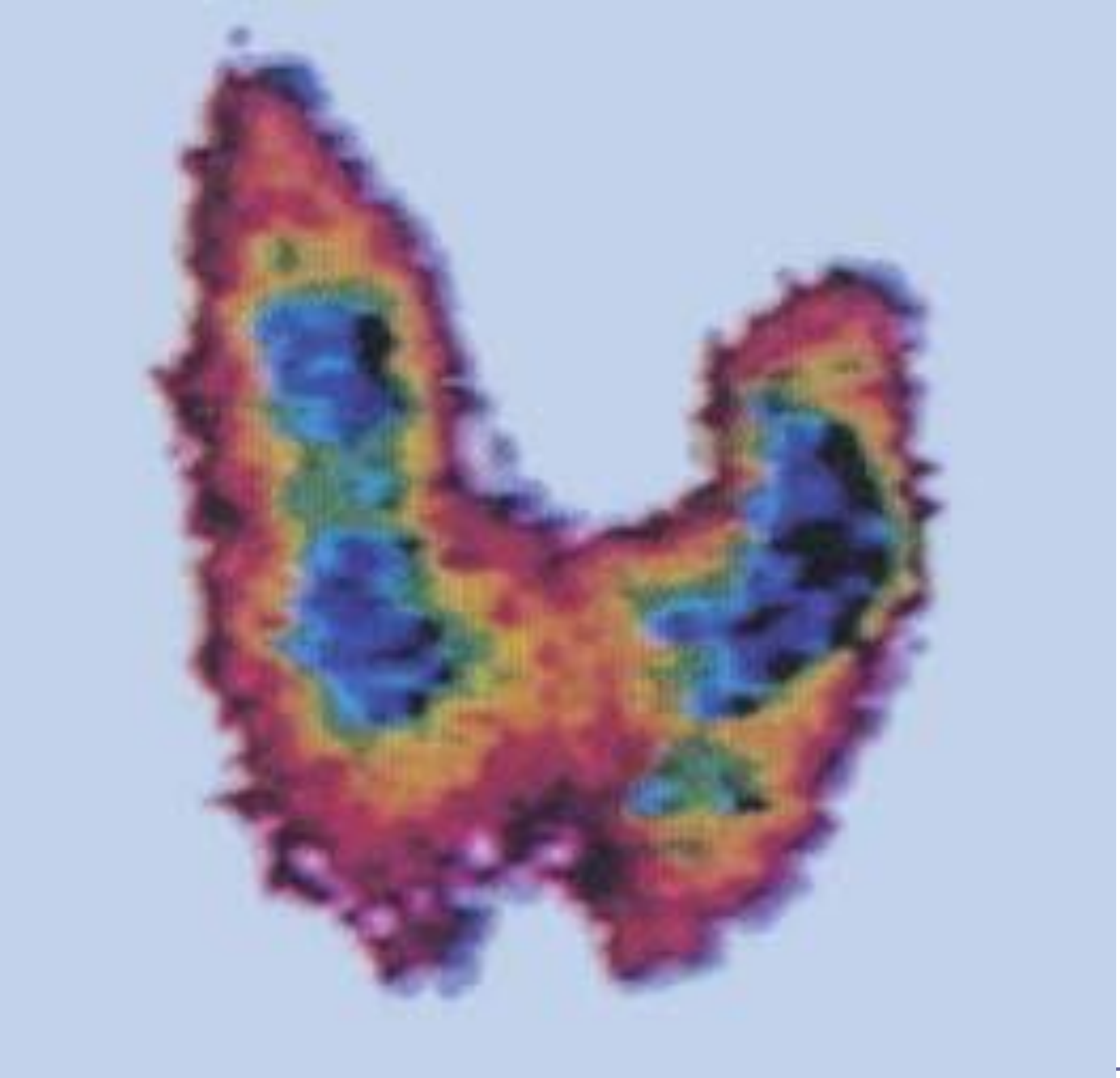
- Medicine
  - Chemotherapy
  - Power pacemakers
  - Diagnostic tracers
- Agriculture
  - Irradiate food
  - Pesticide
- Energy
  - Fission
  - Fusion

Courtesy Robert Maass/Corbis Images

X-ray examination of luggage at a security station.

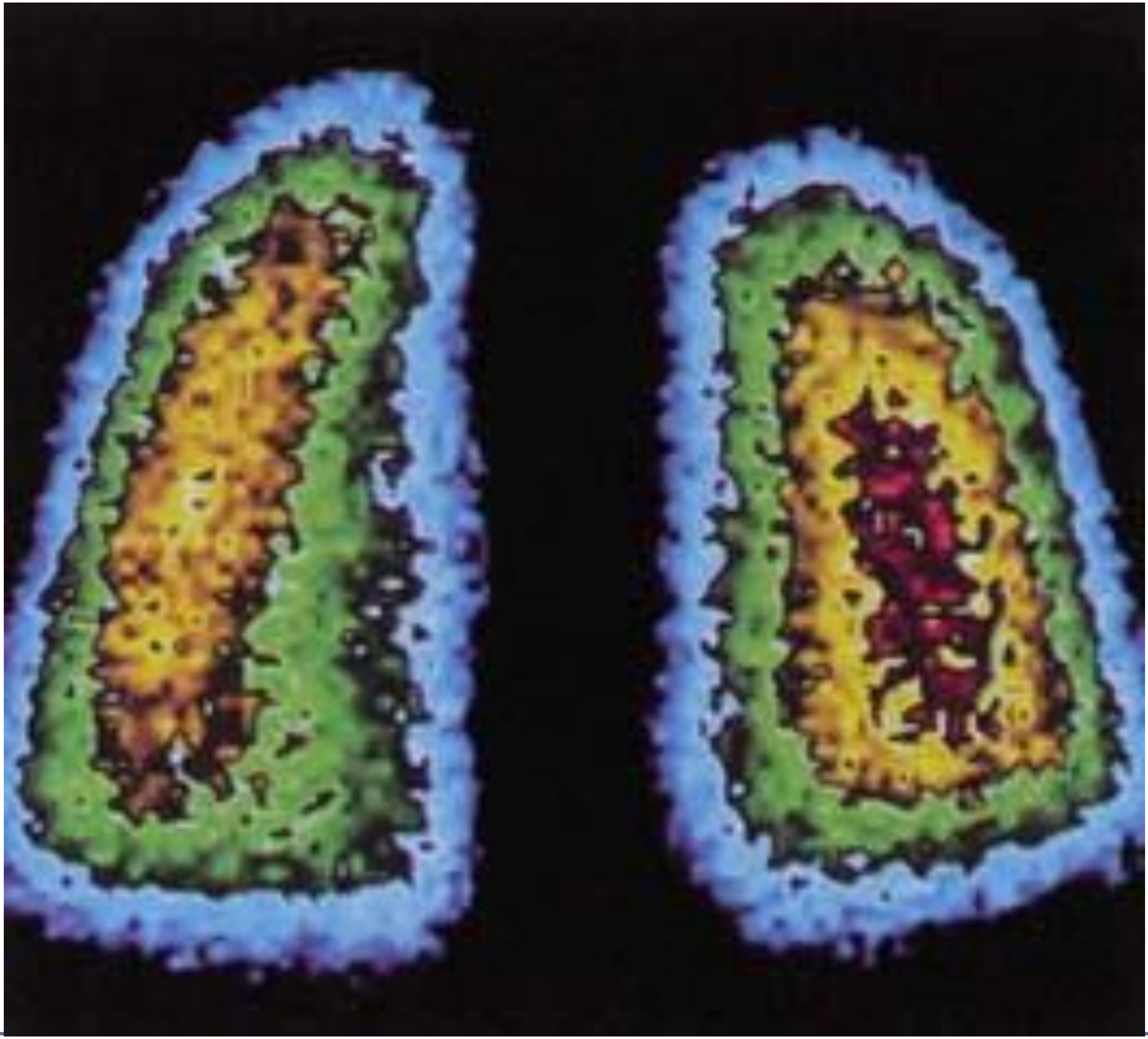
Food Irradiation

- Food can be irradiated with γ rays from ^{60}Co or ^{137}Cs.
- Irradiated milk has a shelf life of 3 mo. without refrigeration.
- USDA has approved irradiation of meats and eggs.



Courtesy Custom Medical Stock Photo

An image of a thyroid gland obtained through the use of radioactive iodine.



Courtesy CNRI/Phototake

Images of human lungs obtained from a γ-ray scan.

Courtesy Kelley Culpepper/Transparencies, Inc.

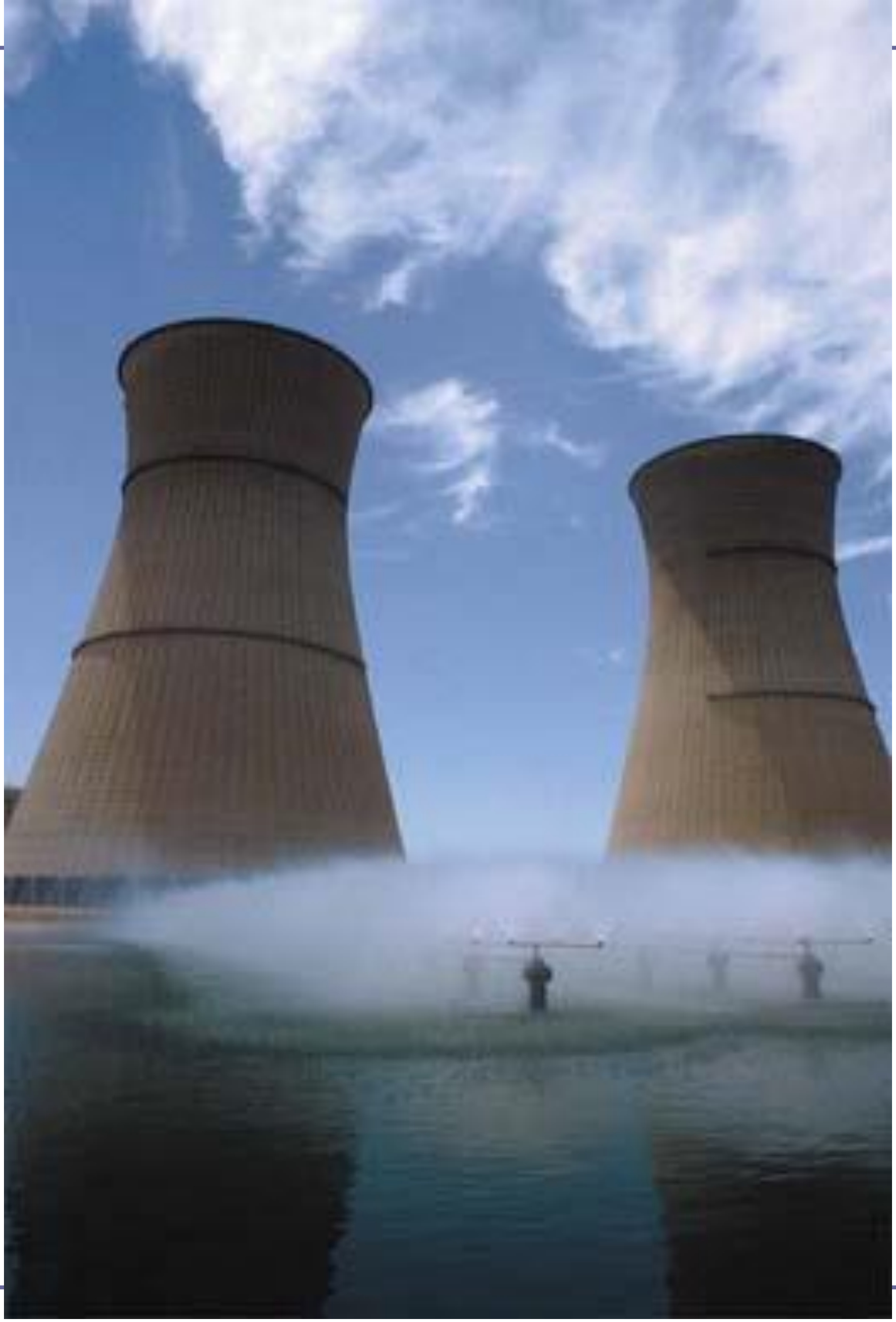
A cancer patient receiving radiation therapy.

Courtesy Scott Camazine/Photo Researchers

The world’s first atomic explosion, July 16, 1945 at Alamogordo, New Mexico.

Courtesy Shigeo Hayashi

Remains of a building after the explosion of the uranium bomb at Hiroshima, August 6, 1945.



Courtesy David Bartruff/Corbis Images

Cooling towers of a nuclear power plant.

Courtesy Sipa Press

The nuclear power plant at Chernobyl, after the accident of April 16, 1986.

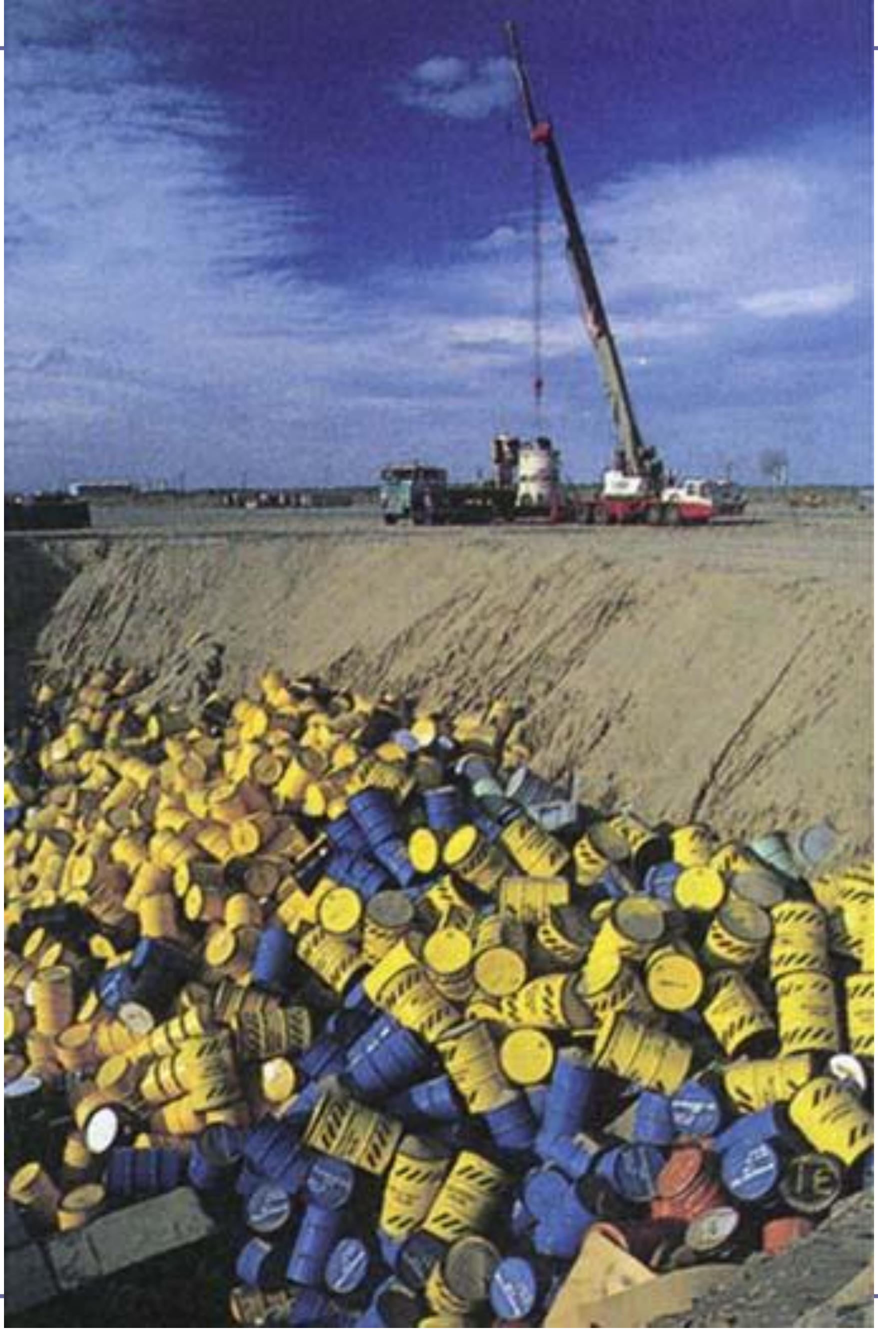
Challenges of Nuclear Power

»Disposal of waste products

- Hazardous wastes produced by nuclear reactions are problematic.
  - Some waste products, like fuel rods, can be re-used
  - Some products are very radioactive, and must be stored away from living things.
    - Most of this waste is buried underground, or stored in concrete
    - It takes 20 half-lives (thousands of years) before the material is safe.

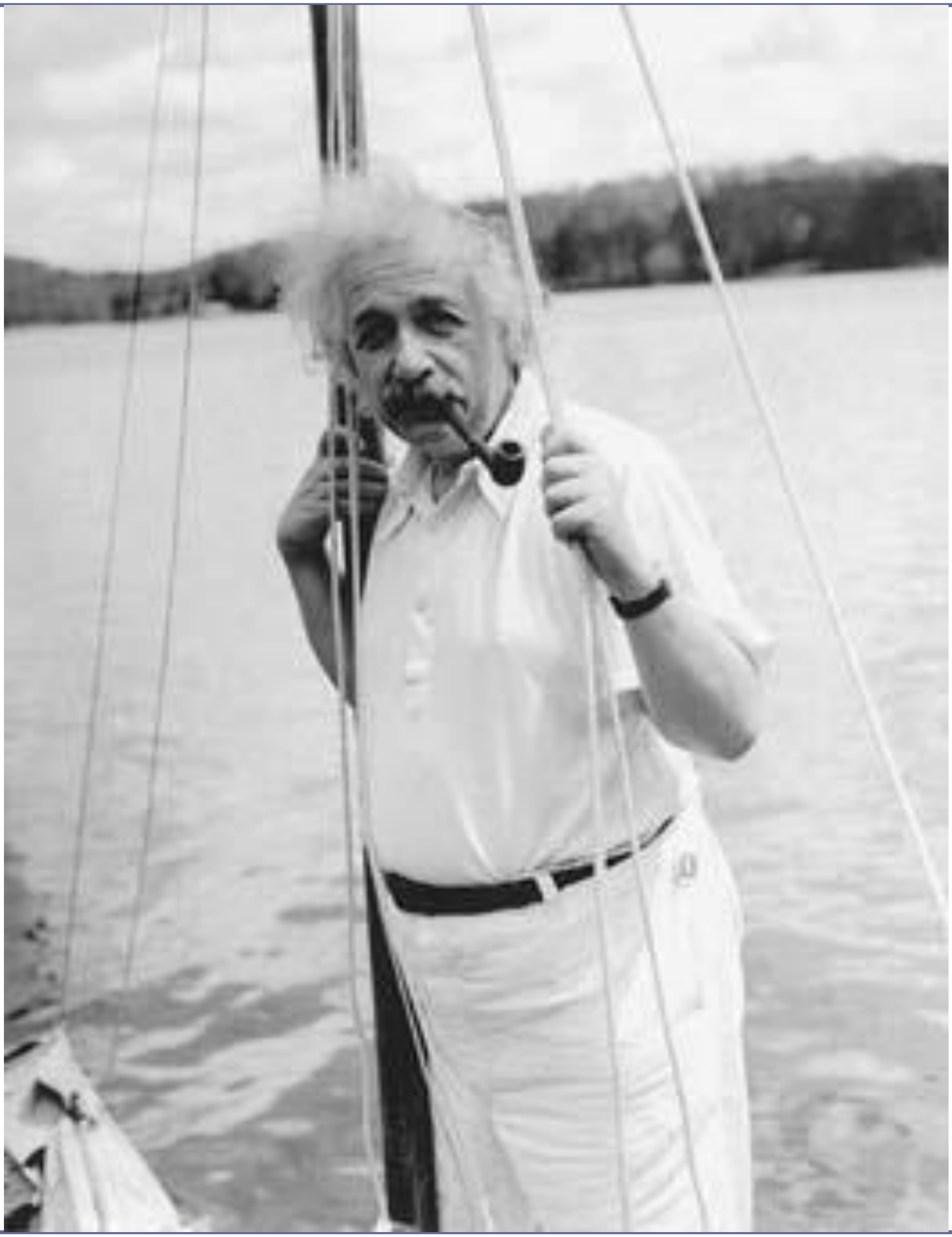
Courtesy Yucca Mountain Project

Construction of a tunnel that will be used for burial of radioactive wastes deep within Yucca Mountain, Nevada.



Courtesy Matthew Neal McVay/Stone/Getty Images

Disposal of radioactive wastes by burial in a shallow pit.



Courtesy AP/Wide World Photos

Albert Einstein, he discovered the equation that relates mass and energy.