NE585
NUCLEAR FUEL CYCLES
Nuclear engineering basics
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R. A. Borrelli

University of Idaho

Idaho Falls Center for Higher Education

University of Idaho
Department of Nuclear Engineering
and Industrial Management

Learning objectives

Demonstrating fundamental concepts in nuclear physics

Analyzing decay data to identify radionuclides

Summarizing different decay mechanisms

Book – Chapter 2

Learning nodes

Relativity

Atomic structure

Binding energy

Q-value

Radioactivity

Chart of the nuclides

Decay chains

Half life

Relativity

We apply energy from nuclear reactions and radiation interactions with matter

$$E_{REST} = m_0 c^2 \tag{1}$$

$$E = mc^2 \tag{2}$$

Rest mass energy for an electron – 0.511 MeV

Save that for later

Energy released or energy injected

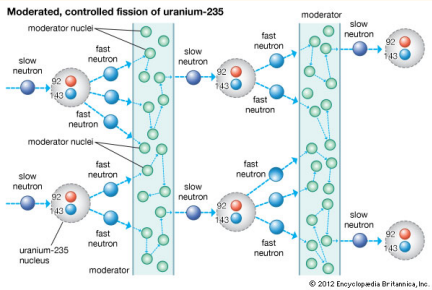

Figure 1. Fission

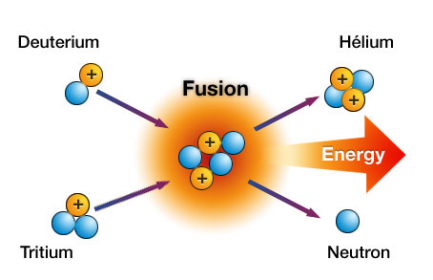

Figure 2. Fusion

Determine the energy of a fusion neutron that is not at rest

$$m = \frac{m_0}{\sqrt{1 - (\frac{v^2}{c})^2}} \rightarrow E = mc^2 \tag{3}$$

With $v = 5.2 \times 10^7\ m/s$, that is about $0.17c$; not negligible

So we have to compute the not rest mass

$m_0(n) = 1.674927211 \times 10^{-27}\ kg$

Fusion neutron at that speed has $E = 14.5\ MeV$

For relativistic calculations use MeV

Atomic structure

The shell model describes how subatomic particles are arranged

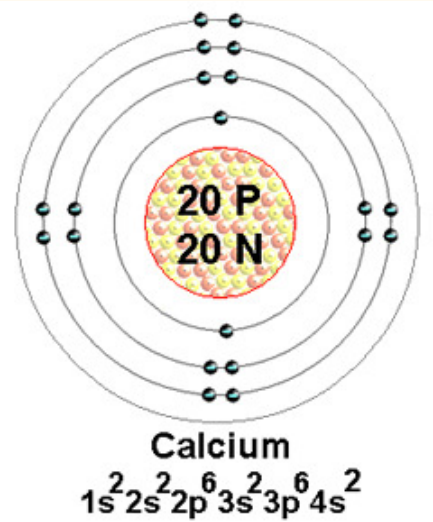

Figure 3. Calcuim shell model

15: Phosphorus 2,8,5

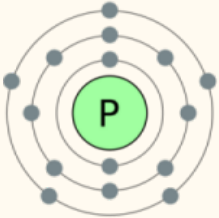

Figure 4. Phosphorus shell model

Notation

$$ {}^{A}_{Z}Q_{A-Z} = {}^{235}_{92}\ U_{143} \tag{4} $$

Periodic table of the elements

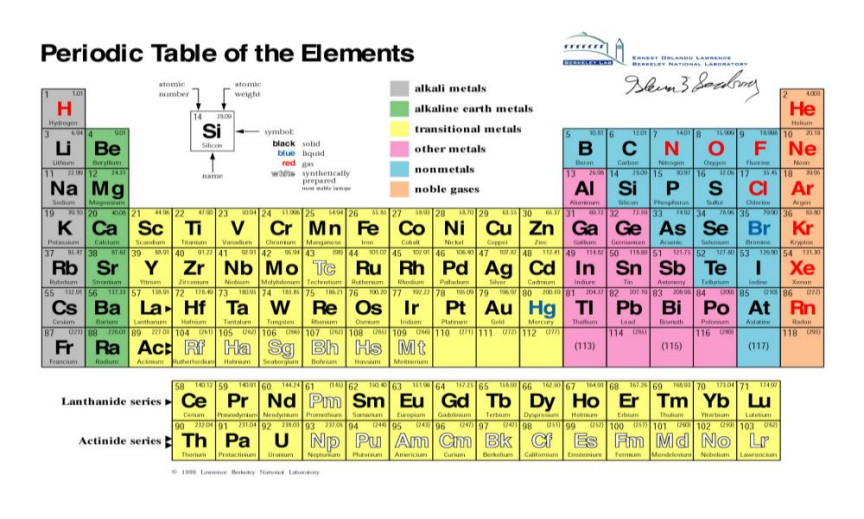

Figure 5. Periodic table of the elements

Binding energy

There are four fundamental forces of interaction

Gravity – Obvious

Strong nuclear – Holds the nucleus together

Electromagnetic – Basically electrons & magnetism

Weak nuclear – Changes the flavor of quarks

To blow out a nucleus, a lot of energy is needed

Would it be constant or variable per nucleus?

Why would you want to blow out the nucleus?

$$\Delta m = (A - Z)m_n - Zm_p - M \tag{5}$$

$$\Delta m({}^{239}_{94}Pu) = 1759\ MeV = 7.40\ \frac{MeV}{nucleon} \tag{6}$$

This energy corresponds to a velocity of 0.88c

$931.5\ \frac{MeV}{amu}$

Binding energy is used to compare atomic stability, reaction energy, probability of fission/fusion

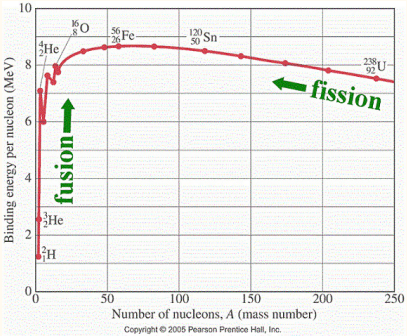

Figure 6. Binding energy curve

Light nuclei get more stable by fusion; heavy nuclei get more stable by fission

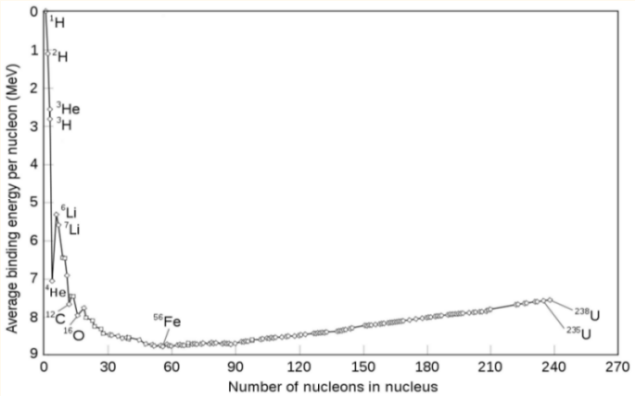

Figure 7. Inverted binding energy curve

Q-value

The Q-value for a reaction indicates energy requirements

$$ {}^{6}_{3}Li\ (n, \alpha)\ {}^{3}_{1}H \tag{7} $$

$$ {}^{6}_{3}Li + {}^{1}_{0}\ n \rightarrow {}^{4}_{2}\ \alpha + {}^{3}_{1}\ H \tag{8} $$

(1) Conservation of nucleons

(2) Conservation of charge

(3) Conservation of momentum

(4) Conservation of energy

Compute the Q value for this reaction

$$ {}^{6}_{3}Li +^{1}_{0} n \rightarrow^{4}_{2} \alpha +^{3}_{1} H \tag{9} $$

$$ Q = [(M_{Li} + M_n) - (M_\alpha + M_H)]c^2 \tag{10} $$

$$ Q = 4.78\ MeV \tag{11} $$

$Q > 0 \rightarrow ?$

$Q < 0 \rightarrow ?$

What is the energy of fission from thorium and uranium fuel cycles?

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{92}_{36}Kr + {}^{141}_{56}Ba + {}^{1}_{0}n + {}^{1}_{0}n + {}^{1}_{0}n \tag{12} $$

$$ {}^{1}_{0}n + {}^{233}_{92}U \rightarrow {}^{92}_{36}Kr + {}^{141}_{56}Ba + {}^{1}_{0}n \tag{13} $$

For comparison, burning a carbon atom releases 4 eV

Radioactivity

Scientists in late 1800s made discoveries which would change the course of science, medicine, and history in the 20th Century

The Nobel Prize in Physics 1903 was divided, one half awarded to Antoine Henri Becquerel "*in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity*", the other half jointly to Pierre Curie and Marie Curie, née Sklodowska "*in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel*".

Figure 8. 1903 Nobel Prize in physics winners

Radiation is energy as particles or electromagnetic waves, like sunshine

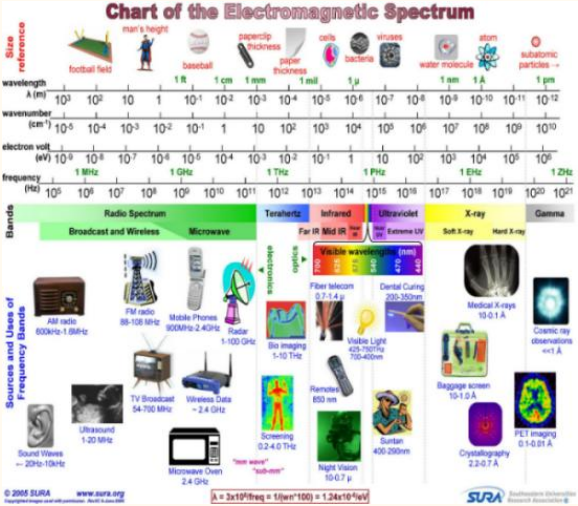

Figure 9. Chart of the electromagnetic spectrum

Radiation is energy as particles or electromagnetic waves

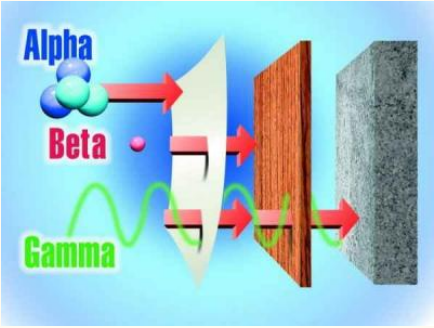

Figure 10. Radiation shielding materials

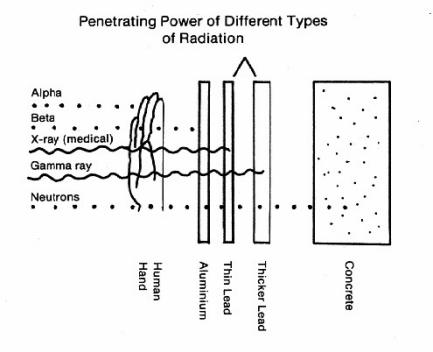

Figure 11. Radiation shielding materials

Radiation is energy as particles or electromagnetic waves

Charged particles are –

(1) protons (+)

(2) alpha (++)

(3) beta (+/-)

(4) heavy ions (varying)

(5) U,Pu (3+,4+,5+,6+)

Neutrons have no charge, but are also ionizing

Ionizing rays are x-rays, g-rays, cosmic rays

Ernest Rutherford discovered the three main kinds of radioactive decay (Chemistry Nobel 08)

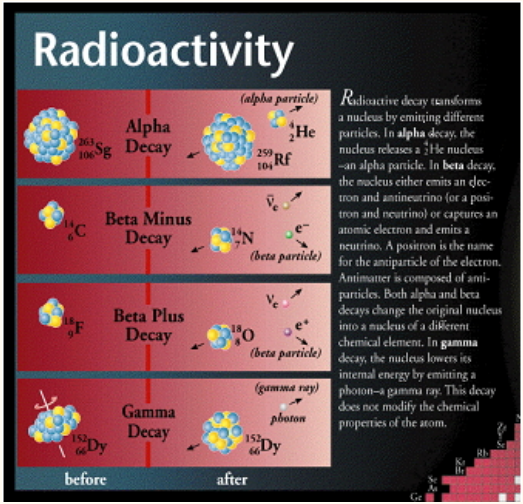

Figure 12. Types of radioactive decay

Alpha particle decay is the ejection of a helium atom from a heavy nucleus

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}\alpha \tag{14}$$

$$Q = 4.268\ MeV \tag{15}$$

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)

Discrete energy spectrum

Some % decay at certain energy

Radium-226 decays to radon-222

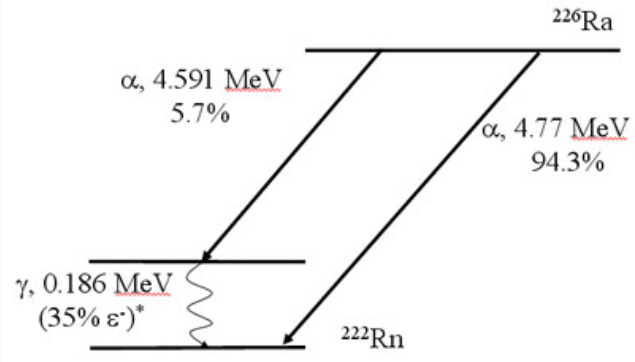

Figure 13. Radium-226 decay

β^- particle decay occurs for unstable nuclei with excessive neutrons

$$ {}^{19}_{8}O \rightarrow {}^{19}_{9}F + \beta^- + \overline{\nu} \tag{16} $$

The neutron is converted to a proton and a beta negative (electron) and anti-neutrino (momentum) are ejected

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)

Gold-198 decays to mercury-198

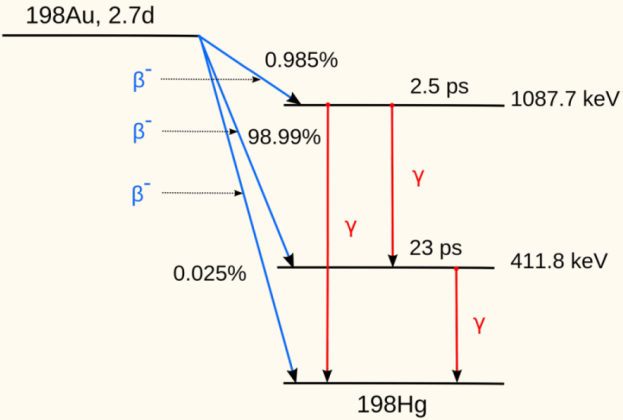

Figure 14. Gold-198 decay

β^+ particle decay occurs for unstable nuclei with deficient neutrons

$$ {}^{11}_{6}C \rightarrow {}^{11}_{5}B + \beta^+ + \nu \tag{17} $$

The proton is converted to a neutron and a beta positive (positron) and neutrino (momentum) are ejected

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)

Sodium-22 decays to neon-22

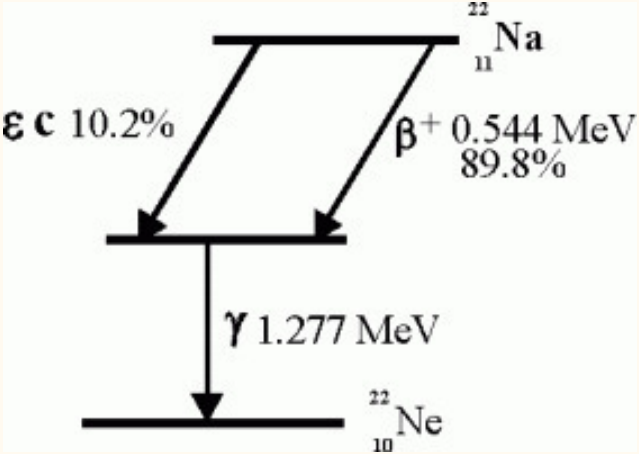

Figure 15. Sodium-22 decay

In both forms of beta decay, the energies are exhibited by a continuous energy spectrum

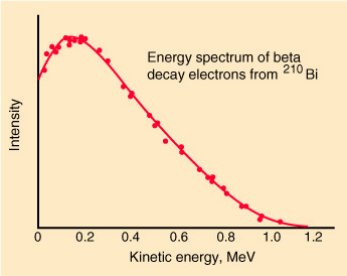

Figure 16. Beta decay energy spectrum

$$\overline{E}(\beta^-) = 0.3E_{MAX} \tag{18}$$

$$\overline{E}(\beta^+) = 0.4E_{MAX} \tag{19}$$

Electron capture also occurs for unstable nuclei with deficient neutrons

$$^{22}_{11}Na \rightarrow \epsilon^{-} + ^{22}_{10}Ne + \nu \tag{20}$$

The K shell electron (not free) is absorbed by the nucleus to convert the proton to a neutron

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)

Electron is captured by the nucleus

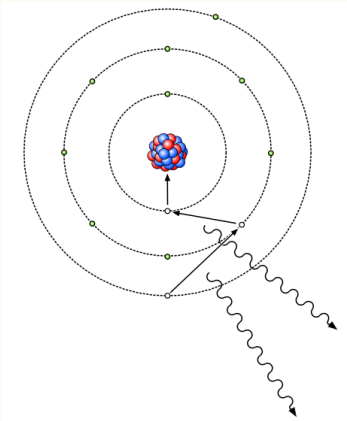

Figure 17. Notional electron capture

Electron capture and β^+ are competing processes

$$^{22}_{11}Na \rightarrow \epsilon^- + ^{22}_{10}Ne + \nu \tag{21}$$

$$^{22}_{11}Na \rightarrow ^{22}_{10}Ne + \beta^+ + \nu \tag{22}$$

$$Q = 2.842\ MeV \tag{23}$$

$Q > 1.022\ MeV$ positron favored

$Q < 1.022\ MeV$ electron capture favored

Why?

γ-ray emission is not a decay mode, but superfast de-excitation of the nucleus

Interactions of gamma rays with matter is a very important branch of nuclear physics

Chart of the nuclides

Chart of the nuclides wide shot

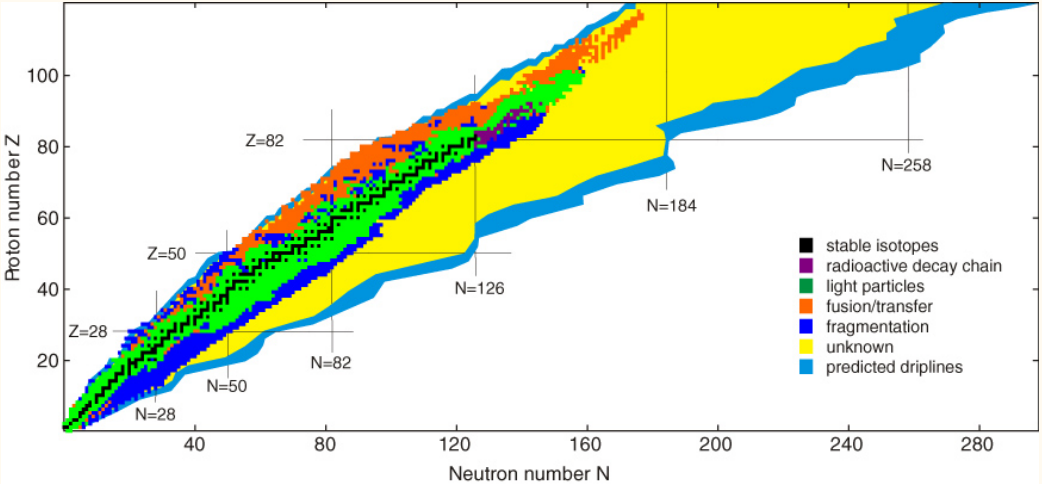

Figure 18. Chart of the nuclides

Chart of the nuclide example

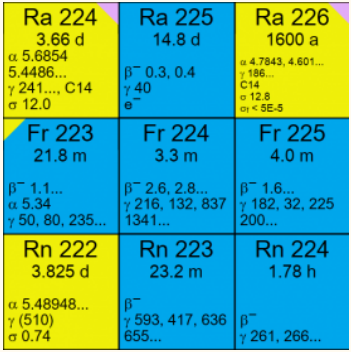

Figure 19. Chart of the nuclides example

Decay chains

Thorium decays to lead

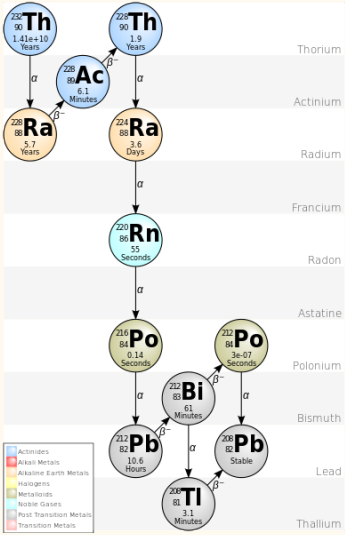

Figure 20. Thorium decay chain

Neptunium decays to thallium

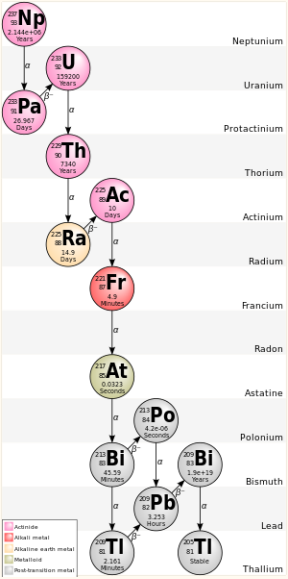

Figure 21. Neptunium decay chain

Uranium-238 decays to lead

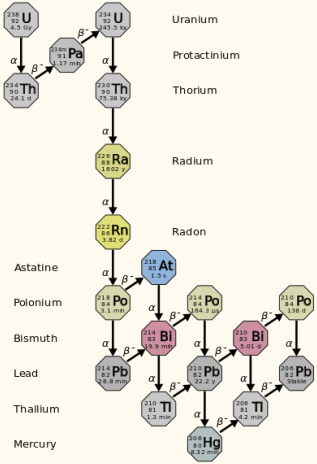

Figure 22. Uranium-238 decay chain

Uranium-235 decays to lead

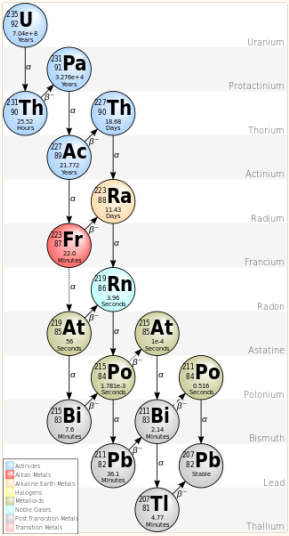

Figure 23. Uranium-235 decay chain

Half life

A radioactive isotope decays with a unique characteristic time

Decay is stochastic, characterized by Poisson distribution

So the decay of any one radionuclide cannot be predicted

The probability per time that a nucleus will decay is a constant

Decay is described by a Poisson process

Poisson process notes

Occurrences are randomly distributed in time

What is the ‘occurrence’ here?

Homogeneous, long term decay rate is constant

$$\mu \equiv \lambda \Delta t \tag{24}$$

$$P(n) = e^{-\mu} \cdot \frac{\mu^n}{n!} \tag{25}$$

Defintion of expected value and variance on the OER

A radioactive isotope decays with a unique characteristic time

$n(t)$ atoms at t have decayed in dt

$$\lambda n(t)dt \tag{26}$$

The number of atoms that decay on average in the interval $t, (t + dt)$ can be expressed as –

$$-dn(t) = \lambda n(t)dt \tag{27}$$

You should be able to solve this for $n(0) = n_0$

Radionuclides are characterized by half life

$$t_{\frac{1}{2}} = \frac{ln2}{\lambda} \tag{28}$$

Half life can be derived from the decay law

A radionuclide is ‘negligible’ after 10 half-lives have elapsed

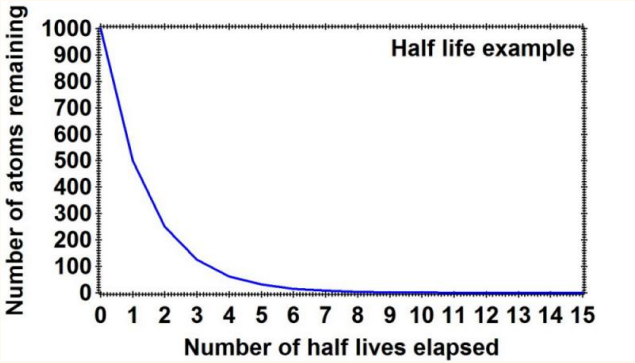

Figure 24. Notional half life

Why would this be important?

How was half-life discovered?

Rutherford discovered alpha and beta particle decay

In the course of, he noticed that there was a characteristic time

Basically observed decay time was the same for each atom

Experiments with thorium led to the discovery of radon

Then observing the radon gas led to the decay/half-life (65 s)

Gold-198 graphical half life

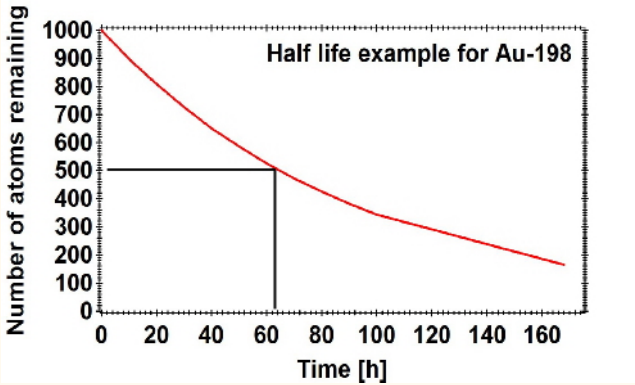

Figure 25. Gold-198 half life

Engineers like straight lines

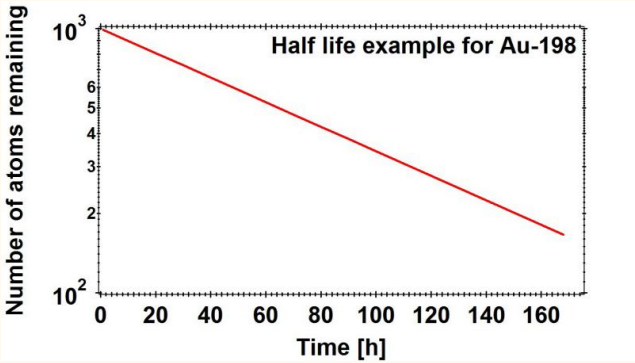

Figure 26. Gold-198 half life on a log scale

Slope of the line is the decay constant

Pets on leash
only

Acronyms I