Chapter 20: Phenomena

Phenomena: Below is a list of stable isotopes of different elements. Examine the data and see what patterns you can identify. The mass of a electron is 0.00055 u, the mass of a proton is 1.00728 u, and the mass of a neutron is 1.00867 u.

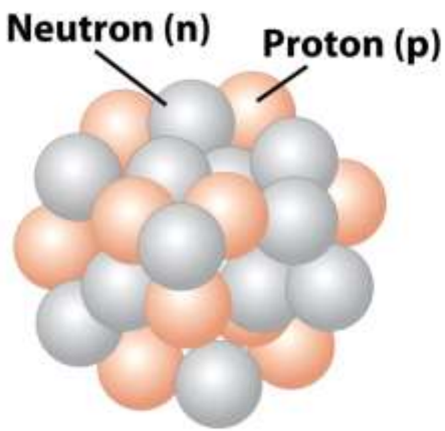
Element	Number of e^-	Number of p^+	Number of n	Mass
H	1	1	0	1.00794 u
H	1	1	1	2.01355 u
Si	14	14	14	27.97693 u
Si	14	14	15	28.97649 u
Fe	26	26	30	55.93539 u
Fe	26	26	32	57.93328 u
Ag	47	47	60	106.90510 u
Ag	47	47	62	108.90475 u
Pt	78	78	116	193.96268 u
Pt	78	78	118	195.96495 u

Chapter 20: The Nucleus: A Chemist's View

- Nuclear Decay
- Nuclear Radiation
- Kinetics of Nuclear Decay
- Nucleosynthesis
- Nuclear Energy

Big Idea: Changes in the nucleus of an atom can result in the ejection of particles, the transformation of the atom into another element, and the release of energy.

Nuclear Decay



- **Nucleus (plural nuclei):** Mass at the center of an atom where protons and neutrons are located.
- **Nucleon:** A particle in an atomic nucleus, either a proton or a neutron.

Note: If a problem asks for energy per nucleon, divide the energy by the mass number (A).

- **Nuclear Decay:** The process by which a nucleus of an unstable atom loses energy by emitting particles and/or energy.

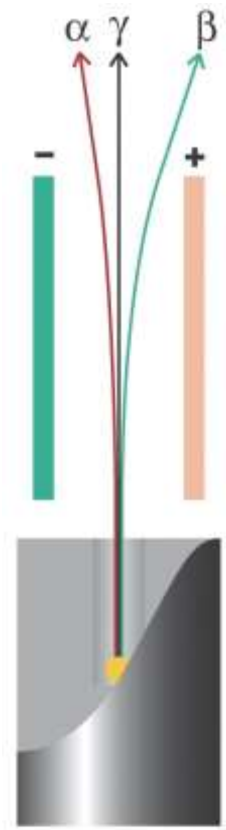
- **Kinetic Stability:** The probability that a nucleus will undergo decomposition to form a different nucleus.

Nuclear Decay

- Henri Becquerel stored uranium oxide in a drawer with photographic plates. The uranium oxide darkened the plates therefore the uranium oxide must have given off some type of radiation.

Nuclear Decay

- Ernest Rutherford passed the radiation through two electrically charged plates and found that the radiation was made up of three primary particles (α, β, and γ) each having a different charge.



Nuclear Decay

Name of Radiation	What is Emitted	How it Appears in Equation
Alpha (α)	Helium nucleus (2 protons and 2 neutrons)	${}^{4}_{2}He$
Beta (β)	electron	${}^{0}_{-1}e$ or β^{-}
Gamma (γ)	Electromagnetic radiation	Does not appear in equation

Note: Shorthand notation ${}^{A}_{Z}element\ symbol$ where A is the mass number (A=n+p) and Z is the atomic number (Z=p).

Nuclear Decay

TABLE 20.2

Various Types of Radioactive Processes Showing the Changes That Take Place in the Nuclides

Process	Change in A	Change in Z	Change in Neutron/Proton Ratio	Example
β-Particle (electron) production	0	+1	Decrease	$^{227}_{89}\mathrm{Ac} \longrightarrow {}^{227}_{90}\mathrm{Th} + {}^{0}_{-1}\mathrm{e}$
Positron production	0	−1	Increase	$^{13}_{7}\mathrm{N} \longrightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{1}\mathrm{e}$
Electron capture	0	−1	Increase	$^{73}_{33}\mathrm{As} + {}^{0}_{-1}\mathrm{e} \longrightarrow {}^{73}_{32}\mathrm{Ge}$
α-Particle production	−4	−2	Increase	$^{210}_{84}\mathrm{Po} \longrightarrow {}^{206}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$
γ-Ray production	0	0	—	Excited nucleus $\longrightarrow$ ground-state nucleus + ${}^{0}_{0}\gamma$
Spontaneous fission	—	—	—	$^{254}_{98}\mathrm{Cf} \longrightarrow$ lighter nuclides + neutrons

- Scientists have discovered other types of particles but these types of radiation are far less common than α, β, and γ radiation.
- **Positron Production:** A mode of nuclear decay in which a particle is formed having the same mass as an electron but opposite in charge. (positron= ${}^{0}_{1}e$)
- **Electron Capture:** A process in which one of the inner-orbital electrons in an atom is captured by the nucleus.

Nuclear Decay

Student Question

Identify the nucleus produced by electron capture of beryllium-7 (Z = 4)

a) ${}^{7}_{3}Li$ b) ${}^{7}_{5}B$

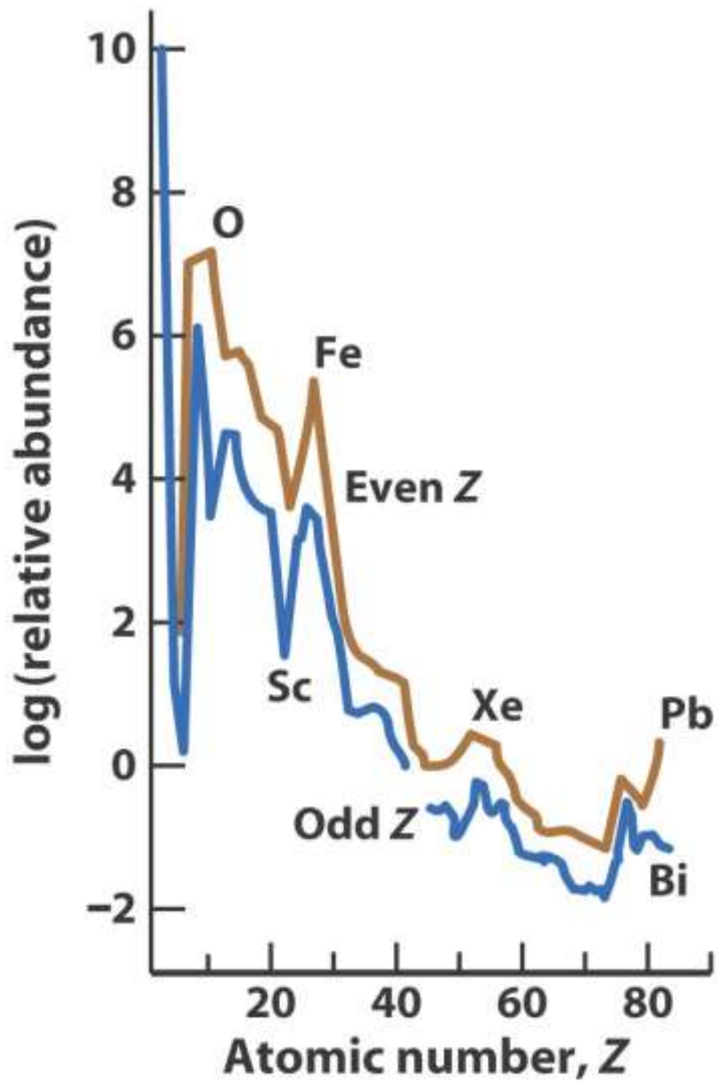
c) ${}^{3}_{2}He$ d) None of the Above

Identify the nucleus produced by positron emission of sodium-22 (Z = 11)

a) ${}^{22}_{10}Ne$ b) ${}^{22}_{12}Mg$

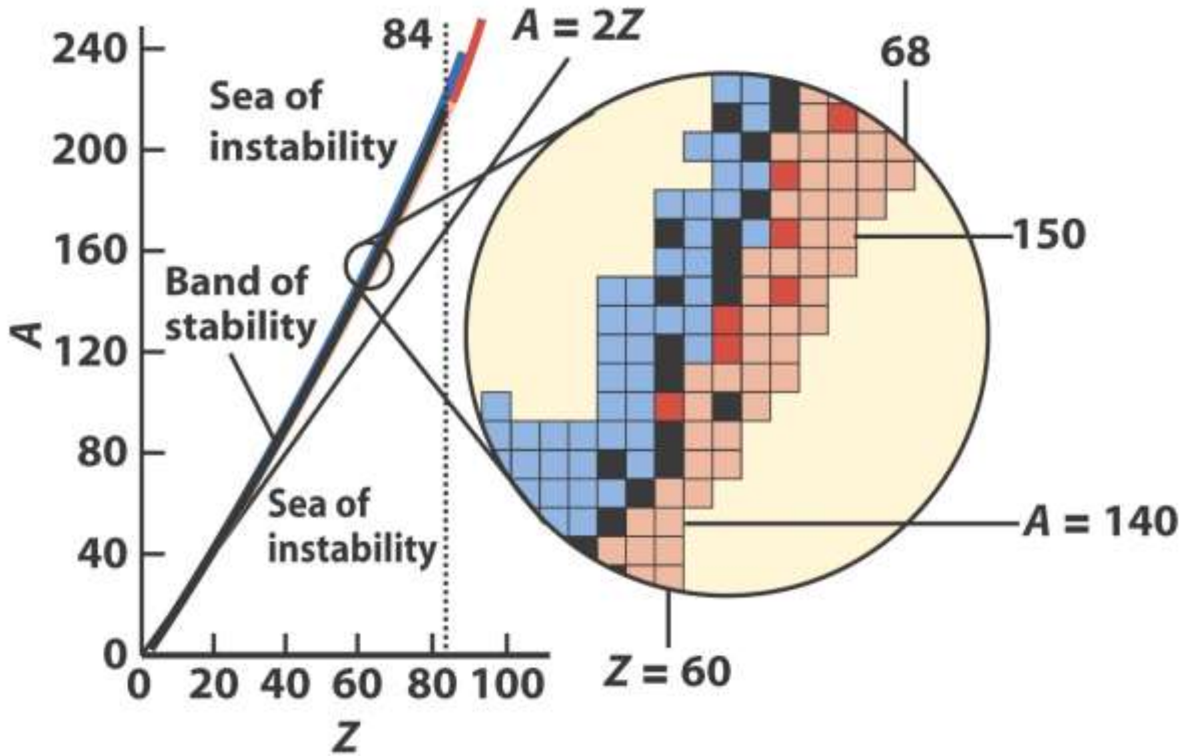
c) ${}^{18}_{9}F$ d) None of the Above

Nuclear Decay



- The number of elements with even atomic numbers are more abundant than the elements with odd atomic numbers.
- Nuclei are more likely to be stable if they are built from certain numbers of either kind of nucleons. These numbers "magic numbers" include 2, 4, 8, 20, 50, 82, 114, 126, and 184.

Nuclear Decay



- A band of stability is found with a sea of instability at either side. For low atomic numbers, the band of stability lies on the A = 2Z line. As the atomic number increases the protons repel each other more, making it necessary for more neutrons to be present in the nucleus.

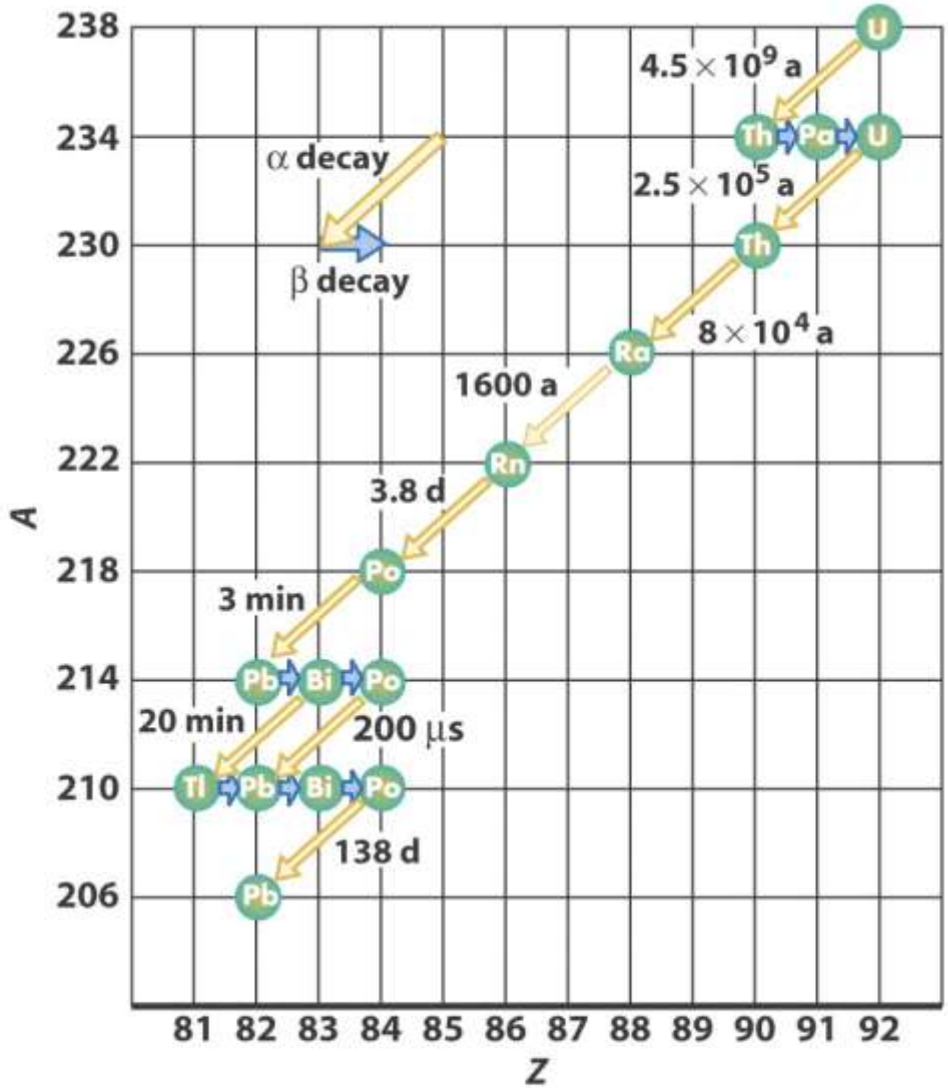
Student Question

Which of the following processes does not help $^{145}_{64}Gd$ (proton rich) become more stable?

a) Electron Capture
b) Beta Particle Emission
c) Positron Emission
d) Proton Emission

Nuclear Decay

Radioactive Series for Uranium-238



- Radioactive series is a series of radioactive decays that a nuclei undergoes until a stable nucleus is formed.

Nuclear Radiation

- *Positive Impacts of Nuclear Radiation*
  - Can be used to kill unwanted tissue (cancer)
  - Radiotracers
  - Isotropic and carbon dating
  - Energy source
  - Preserving foods
  - Identification of reaction mechanisms
  - Powering spacecraft's
- **Radiotracers:** A radioactive nuclide introduced into an organism for diagnostic purposes
- *Negative Impacts of Nuclear Radiation*
  - Radiation sickness
  - Nuclear bombs
  - Nuclear accidents

Nuclear Radiation

TABLE 17.3 Shielding Requirements of α, β, and γ Radiation

Radiation	Relative penetrating power	Shielding required
α	1	paper, skin
β	100	3-mm aluminum
γ	10 000	concrete, lead

- **Absorption Dose:** Is the energy deposited in a sample when it is exposed to radiation.

Name	Symbol	Definition
Radiation Absorbed Dose	rad	$10^{-2}\frac{J}{kg}$
Gray*	gy	$1\frac{J}{kg}$
* SI unit		

Note: 1 rad = 10^{-2} gy.

Nuclear Radiation

- Radiation damage depends on type of radiation and the type of tissues.
- **Relative biological effectiveness (Q):** A factor used when assessing the damage caused by a given dose of radiation.

Note: Q for β and γ radiation is arbitrarily set to about 1 which makes Q for α radiation about 20.

- **Dose Equivalent:** Actual dose modified to take into account the different destructive powers. Dose equivalent = Relative biological effectiveness (Q) × adsorbed dose.

Name	Symbol	Definition
Roentgen equivalent man	rem	$10^{-2}\frac{J}{kg}$
Sievert*	Sv	100 rem
* SI unit		

Nuclear Radiation

- Average people get ~6 mSv (600 mrem) a year of background radiation.

Percent	Source
40%	Radon seeping from the ground
30%	Cosmic rays
20%	Our own bodies
10%	Medical diagnosis Typical chest x-ray ~0.07 mSv

- You can use this website to calculate your yearly radiation dose https://www.epa.gov/radiation/calculate-your-radiation-dose

Nuclear Radiation

- **Activity:** The number of nuclear disintegrations per time.

Name	Symbol	Definition
Curie	Ci	$3.7\times10^{10}\ \frac{disintigrations}{s}$
Becquerel*	Bq	$1\ \frac{disintigrations}{s}$
* SI unit		

Kinetics of Nuclear Decay

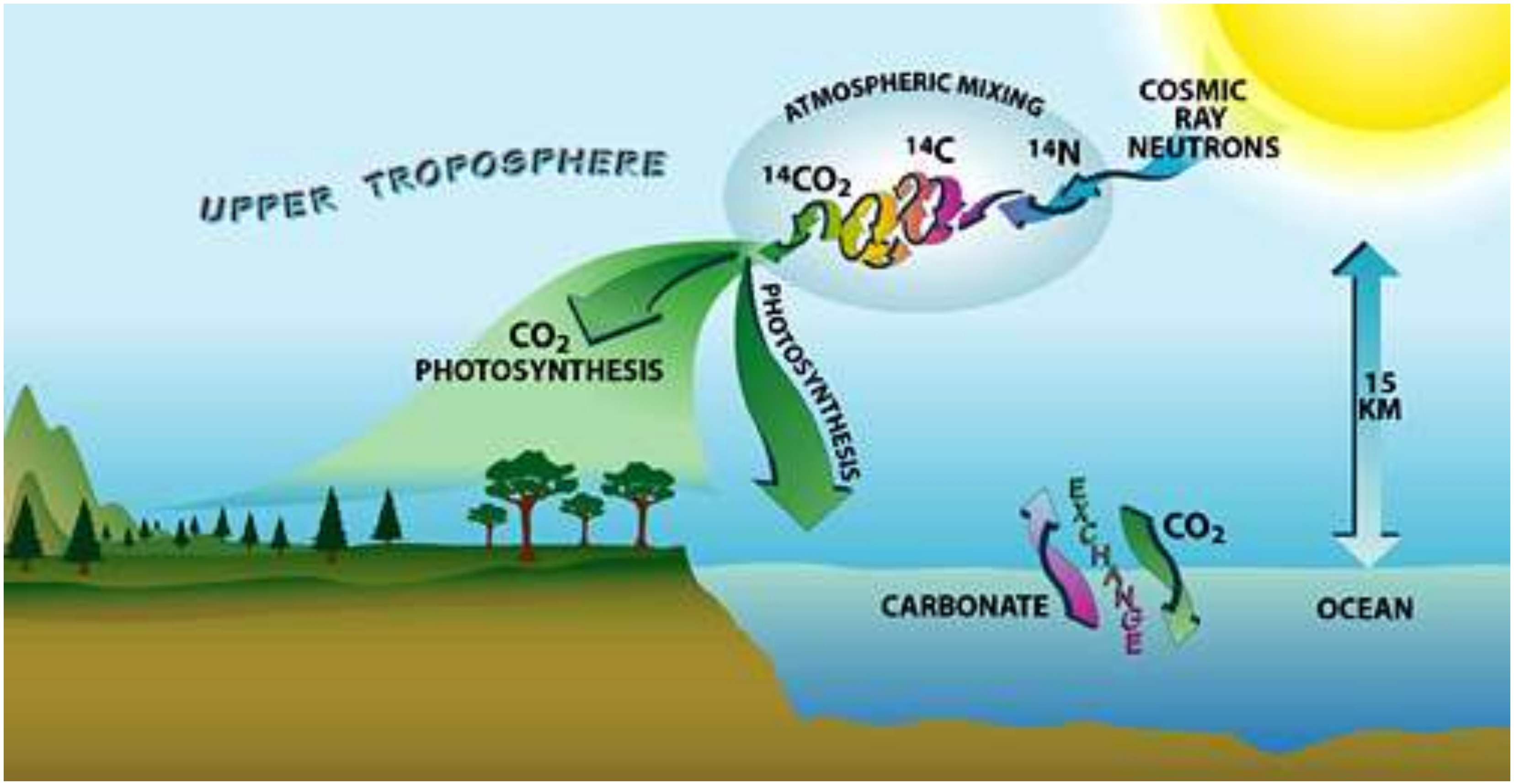
Student Question

The decay constant for fermium-254 is 210 $\frac{1}{s}$. What mass of the isotope will be present if a sample of mass 1.00 μg is kept for 10 ms?

a) 9.58×10^{-913} μg
b) 0.37 μg
c) 0.75 μg
d) None of the Above

Kinetics of Nuclear Decay

- Carbon Dating Reaction: ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e$ $t_{½}$=5730 y



- Reaction the turns N into C: ${}^{14}_{7}N + {}^{1}_{0}n \rightarrow {}^{14}_{6}C + {}^{1}_{1}p$

Kinetics of Nuclear Decay

Student Question

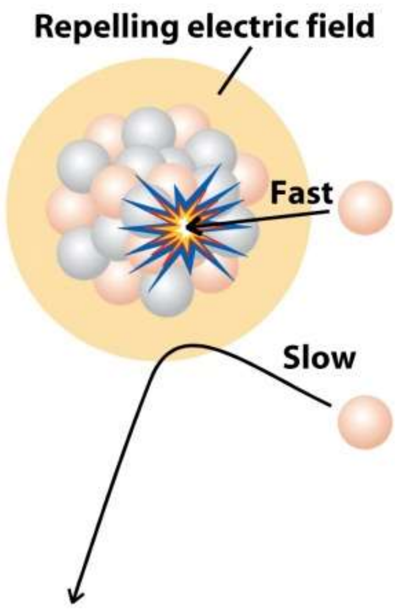
A sample of carbon (250 mg) from wood found in a tomb in Israel underwent 2480 carbon-14 disintegration in 20. h. Estimate the time since death. A modern 1.0 g sample undergoes 1.84×10^4 disintegrations in the same time period. The half life of carbon-14 is 5730 years.

a) 357 years
b) 5,105 years
c) 16,563 years
d) None of the Above

Nucleosynthesis

- **Nucleosynthesis:** The formation of elements through nuclear processes.

Note: All elements that are beyond plutonium (94) are synthetic and produced by the bombardment of target nuclei.



Nuclear Energy

- **Nuclear Binding Energy (E_{bind}):** The energy released when protons and neutrons come together to form a nucleus.

- **Thermodynamic Stability:** The potential energy of a particular nucleus compared to the sum of the potential energies of its component protons and neutrons.

Ideal Calculation of Nuclear Binding Energy

- **Step 1:** Write the nuclear equation
  - x·p+ y·n → nucleus
- **Step 2:** Calculate the change in mass
  - $\Delta m = \Sigma m(\text{prod}) - \Sigma m(\text{react}) = m_{nucleus} - (x \cdot m_p + y \cdot m_n)$
- **Step 3:** Plug into $E_{bind} = \Delta mc^2$

Note: It is hard to measure the mass of the nucleus without the mass of the electrons. It is much easier to use the molar mass which includes the mass of the electrons. *Solution:* Use the mass of $^{1}_{1}H$ (1e$^-$ and 1p) instead of the m_p this allows the mass of the e$^-$ to cancel out.

Nuclear Energy

How to Calculate the Nuclear Binding Energy

- **Step 1:** Write the nuclear equation
  - x.$^{1}_{1}H$ + y.n→ atom (x= # of p = # of e^- and y = # of n)

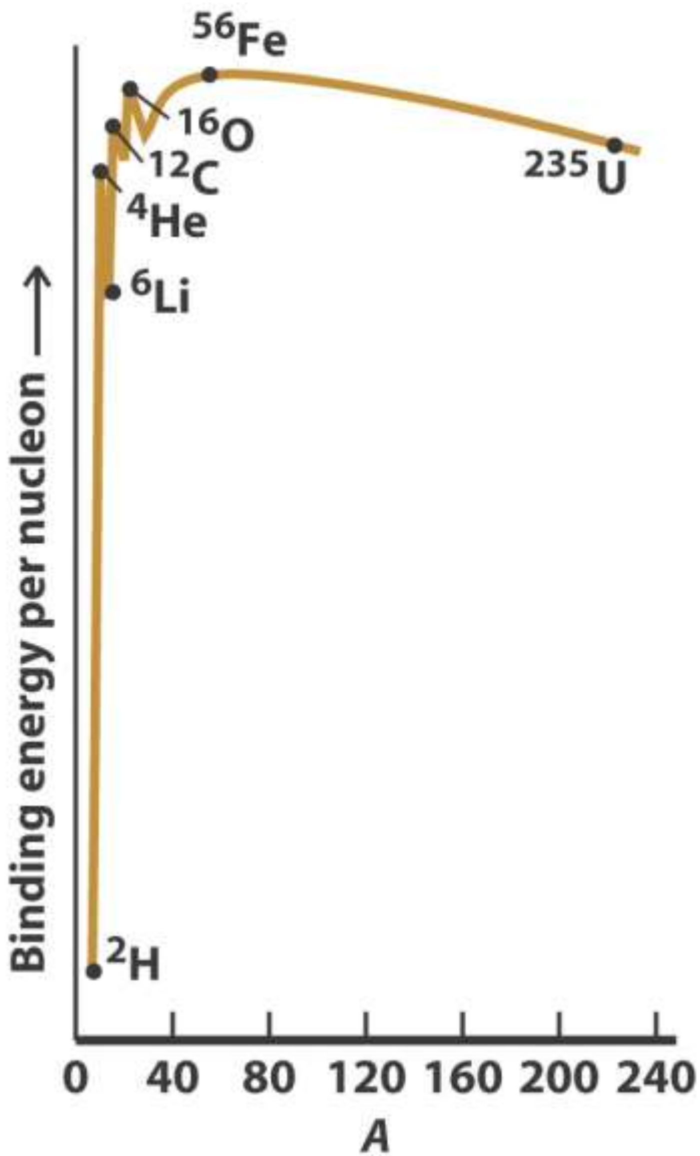
Particle	Mass
neutron	1.0087 u
$^{1}_{1}H$	1.0078 u

Note: 1 u (atomic mass unit) = 1.6605×10^{-27} kg

- **Step 2:** Calculate the change in mass
  - $\Delta m=\Sigma m(prod)-\Sigma m(react)=m_{atom}-(x.m_{^{1}_{1}H}+y.m_n)$
- **Step 3:** Plug into $E_{bind}=\Delta mc^2$
  - $-E_{bind}$ means that energy was released or the nucleus is more stable than individual protons and neutrons.

Note: Binding energy are reported in eV 1 eV = 1.602×10^{-19} J

Nuclear Energy



- A plot of the binding energy per nucleon vs. atomic number shows that the nucleons that are most strongly bonded together are near iron and nickel. This is one of the reasons that iron and nickel are abundant in meteorites and on rocky planets such as earth. Suggesting that nuclei of lighter atoms become more stable when they "fuse" together and that the heaver nuclei become more stable when they undergo "fission" and split into lighter nuclei.

Student Question

Uranium-235 can undergo fission in the following reaction.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{135}_{52}Te + ^{100}_{40}Zr + ^{1}_{0}n$$

Calculate the energy released when 1.0 g of uranium-235 undergoes fission in this way.

Helpful Information: $m_{^{235}_{92}U} = 235.04\,u$,

$m_{^{135}_{52}Te} = 134.92\,u$, $m_{^{100}_{40}Zr} = 99.92\,u$, and $m_n = 1.0087\,u$

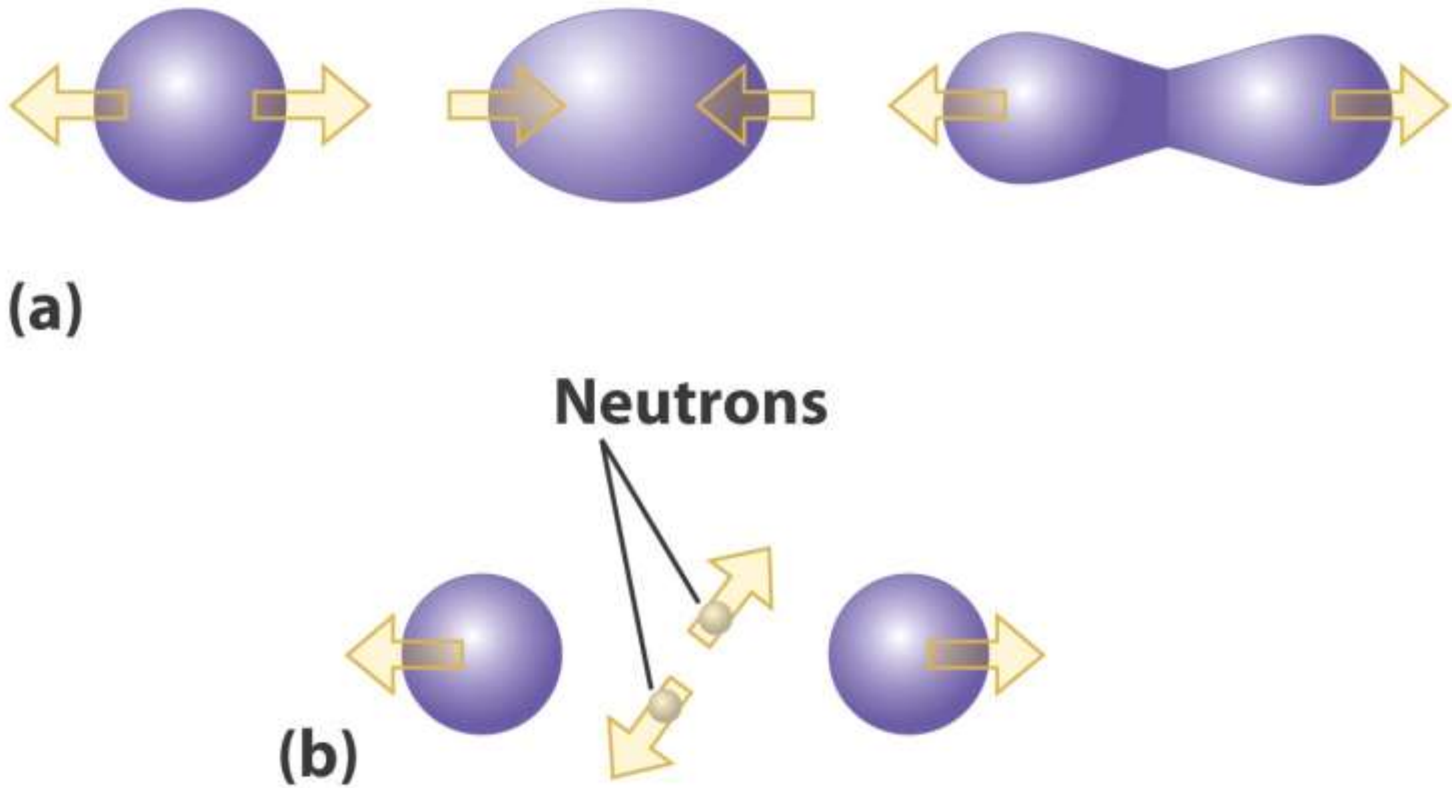
a) 1.3×10^{-13} J

b) 3.0×10^{-11} J

c) 7.7×10^{10} J

d) None of the Above

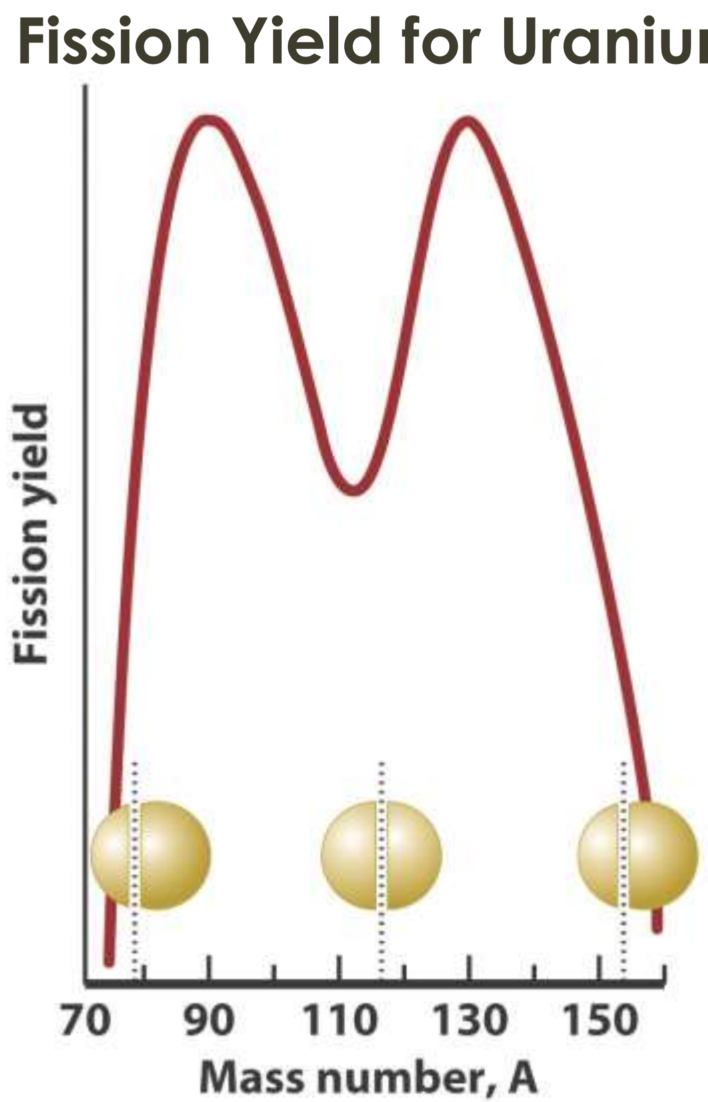
Nuclear Energy



- Spontaneous nuclear fission takes place when the natural oscillation of a heavy nucleus causes it to break into two nuclei of similar mass. An example is the disintegration of americium-244 into iodine and molybdenum.

$$^{244}_{95}Am \rightarrow \, ^{134}_{53}I + \, ^{107}_{42}Mo + 3\,^{1}_{0}n$$

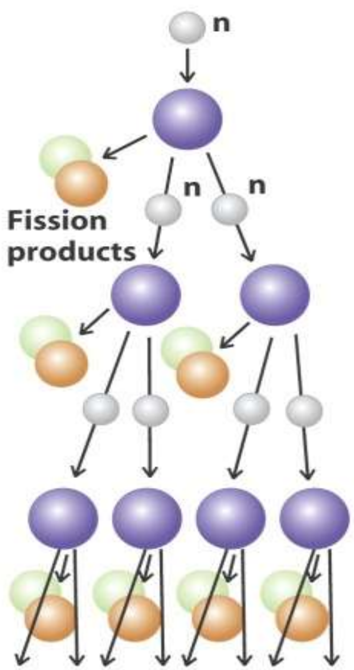
Nuclear Energy



- Fission does not happen the same way every time. The fission yield of uranium-235 mainly yields products close to A=90 and A=130 and relatively few nuclide corresponding to symmetric fission (close to 117) are formed.

Nuclear Energy

Critical Mass: The minimum mass of fissionable particles that are needed to prohibit the majority of the neutrons from escaping thus sustaining a fission chain reaction.



Example Reaction:

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

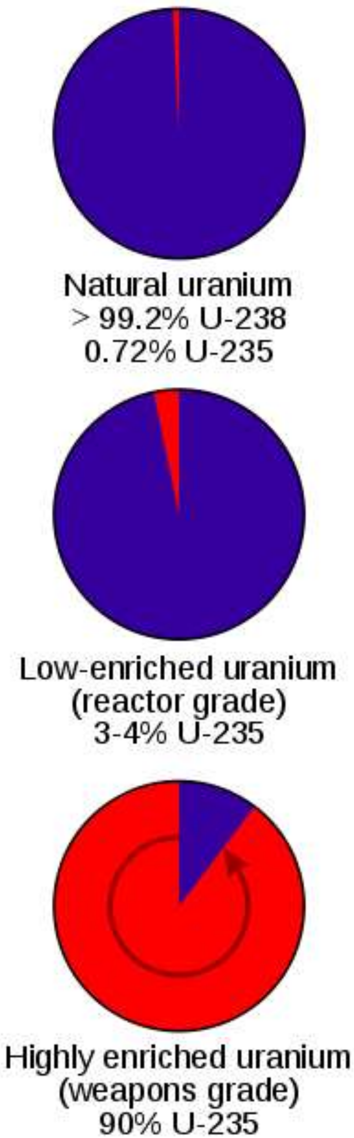
- **Subcritical:** Does not sustain chain reactions.
- **Critical:** Sustains chain reactions.
- **Supercritical:** Sustains chain reactions and is hard to control.

Nuclear Energy

- **Little Boy:** Detonated by pushing two subcritical masses together to produce a supercritical mass.

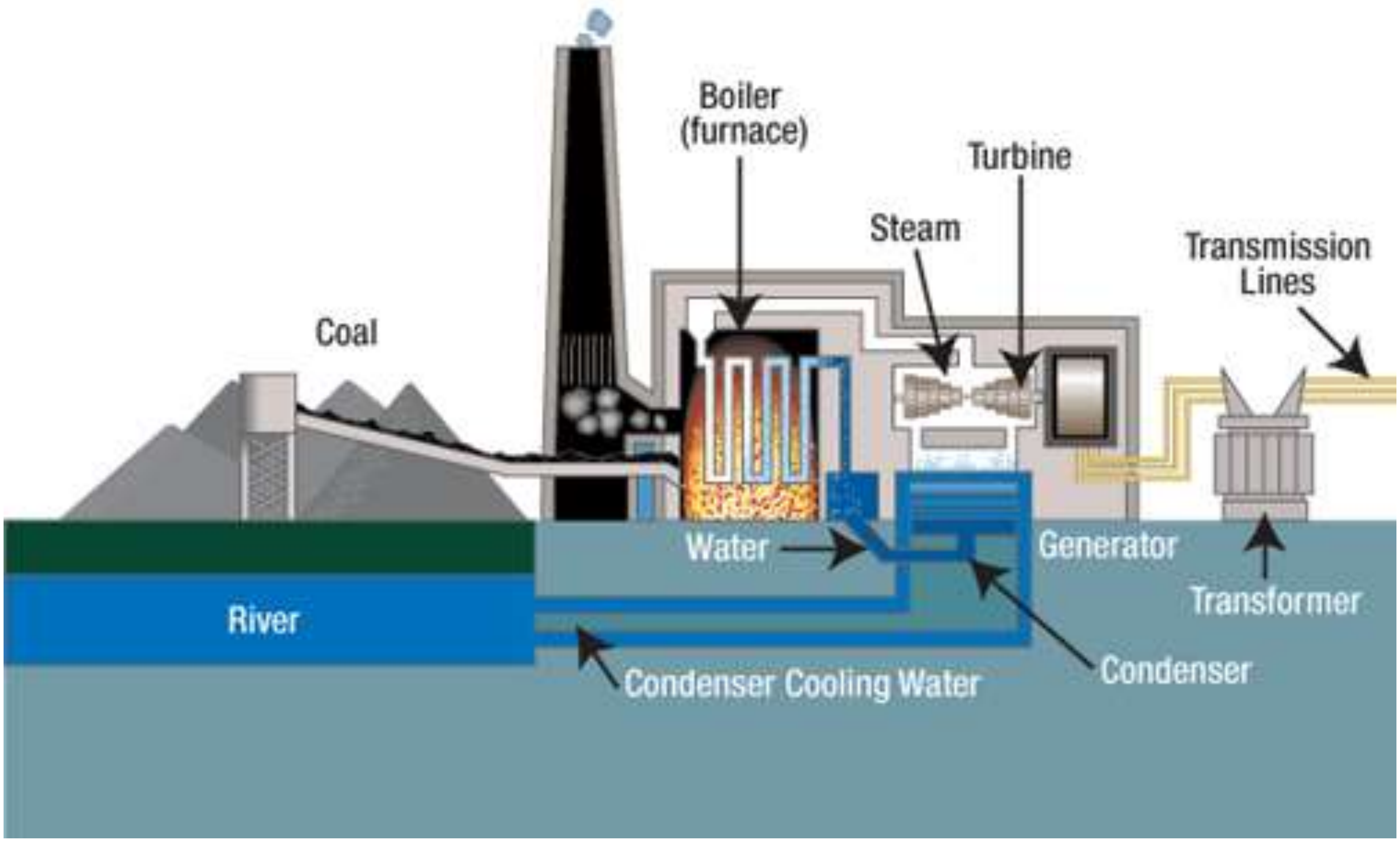
- **Fat Man:** Detonated by imploding a single subcritical mass and using a strong neutron emitter to initiate the chain reaction.

Nuclear Energy

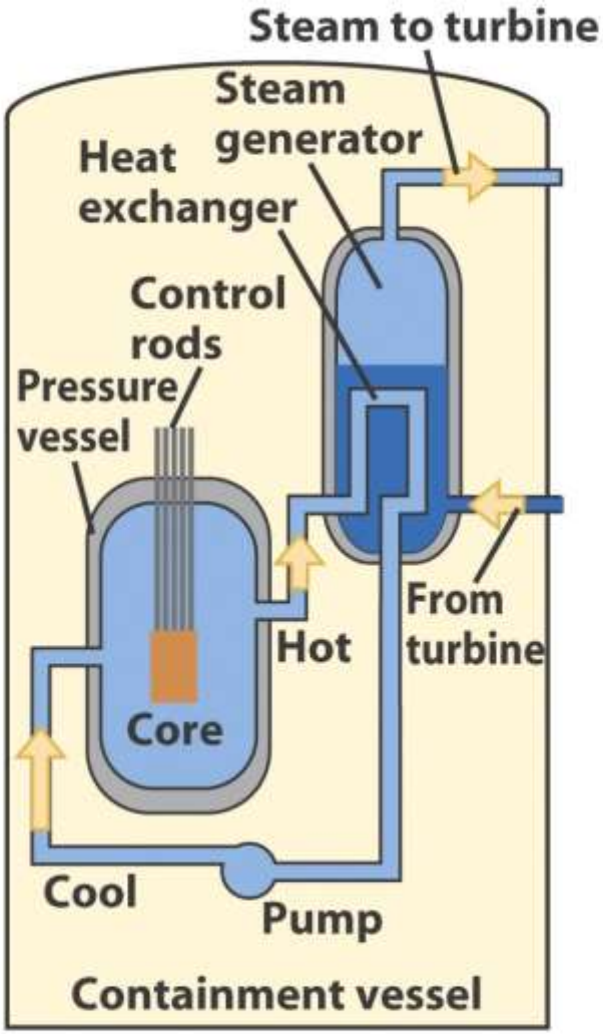


- Both nuclear weapons and nuclear power plants need uranium-235. Uranium-235 is the only isotope that is fissile with thermal neutrons.

Nuclear Energy



Nuclear Energy



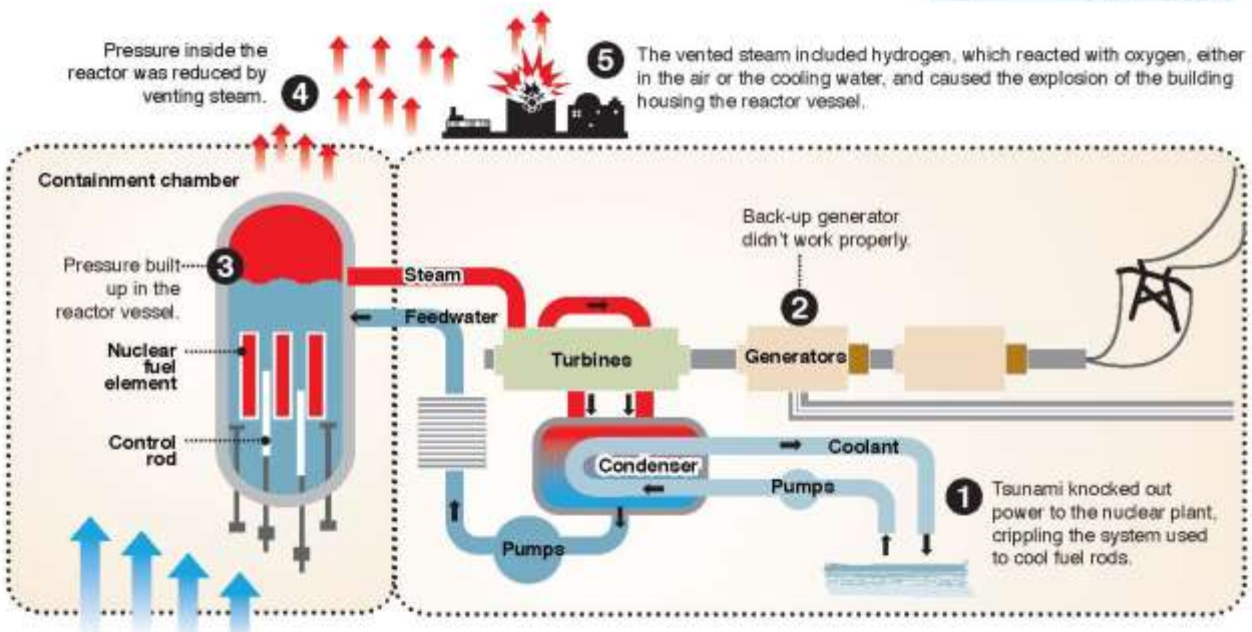
- Nuclear reactors undergo controlled chain reactions.
- Core is usually made out of ^{235}U
- Neutrons are slowed down by putting the core into a moderator.
- Control rods are made from neutron absorbing materials (usually B or Cd) that can be adjusted to control neutron numbers.

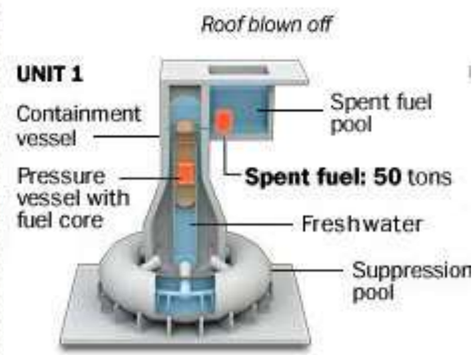
Nuclear Energy

Diagramming a disaster

The six reactors at the Fukushima Dai-ichi plant are boiling water reactors. In a typical commercial boiling water reactor, the reactor core creates heat. A steam-water mixture is produced when very pure water (reactor coolant) moves upward through the core absorbing heat. The steam-water mixture leaves the top of the core and enters the two stages of moisture separation. Water droplets are removed before the steam is allowed to enter the steam line. The steam line directs the steam to the main turbine, causing it to turn the turbine generator, which produces electricity.

Here is what happened at Unit 1 of the Fukushima Dai-ichi Nuclear Plant:



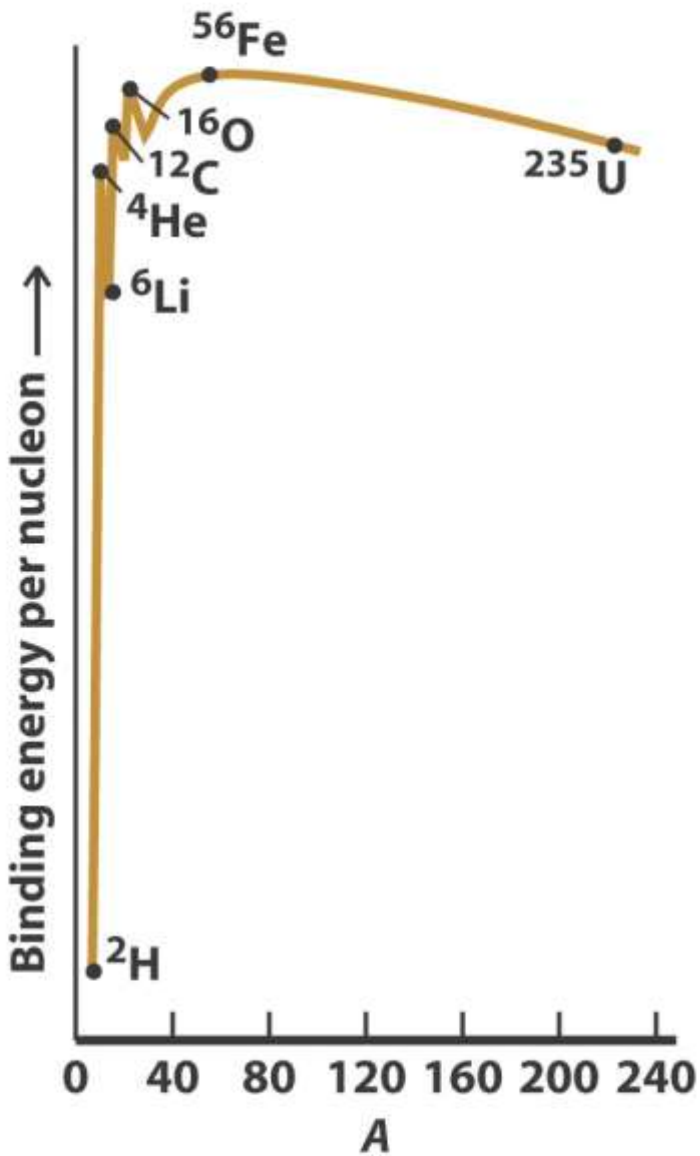


6 Nuclear agency officials say Japan is injecting seawater into the core to avoid a meltdown.

SOURCES: U.S. Energy Information Administration; AP

AP

Nuclear Energy



- It can be seen that there is a large increase in nuclear binding energy per nucleon going from one lighter element to another. Consequently a large amount of energy is released when hydrogen nuclei fuse together to form nuclei of bigger elements.

Fusion Reaction Scheme

$$4\,{}^{1}_{1}H \rightarrow 2\,{}^{2}_{1}H + 2\,{}^{0}_{1}e$$
$$2\,{}^{2}_{1}H + 2\,{}^{1}_{1}H \rightarrow 2\,{}^{3}_{2}He$$
$$2\,{}^{3}_{2}He \rightarrow 2\,{}^{1}_{1}H + {}^{4}_{2}He$$

Overall Reaction: $4\,{}^{1}_{1}H \rightarrow 2\,{}^{0}_{1}e + {}^{4}_{2}He$

How much H is needed in g to generate 3×10^{11} J?

Masses of Interest

$$m_{{}^{4}_{2}He} = 4.0026\,u$$
$$m_{{}^{0}_{1}e} = 5.586 \times 10^{-4}u$$
$$m_{{}^{1}_{1}H} = 1.0078u$$

Nuclear Energy

Student Question

How much would it cost to make 1 g of gold via the following process?

$$^{207}_{82}Pb \rightarrow \ ^{197}_{79}Au + 10\,^{1}_{1}n + 3\,^{0}_{1}e$$

Masses (u): 206.975997 196.9665687 1.008664 0.00054858

Helpful information: 1 kWhr = 3.6×10^{6} J and the cost of electricity is $0.15 per kWhr

a) $1,499
b) $\$1.713\times10^{5}$
c) $\$2.953\times10^{5}$
d) None of the above

Take Away From Chapter 20

- **Big Idea:** Changes in the nucleus of an atom can result in the ejection of particles, the transformation of the atom into another element, and the release of energy.

- **Nuclear Decay** (1)
  - Know the three major decay pathways and the particles that they emit.
    - Alpha (α): ${}_{2}^{4}He$
    - Beta (β): ${}_{-1}^{0}e$
    - Gamma(γ):electromagnetic radiation
  - Be able to predict the product of nuclear decay (write balanced equations) for alpha decay, beta decay, positron decay, gamma, and electron capture. (6,7,9)
  - Be able to determine the most likely particle to be emitted knowing weather or not the nucleus is proton or neutron rich.(13)

Numbers correspond to end of chapter questions.

Take Away From Chapter 20

- **Nuclear Radiation**
  - Know the uses of nuclear radiations (53)
- **Kinetics of Nuclear Decay**
  - Know the rate equation for nuclear processes
    - $Activity = kN$
  - Know how calculate the amount of particles after a given time. (17,18,19,29,34,77)
    - $ln(N) = -kt + ln(N_\circ)$
  - Know how to calculate the half life of a substance
    - $t_{1/2} = \frac{ln(2)}{k}$
  - Know how carbon dating works.
- **Nucleosythesis**
  - Know that nucleosythesis is the transmutation of elements into other elements

Numbers correspond to end of chapter questions.

Take Away From Chapter 20

- **Nuclear Energy**
  - Know that the energy released during a nuclear processes is dictated by Einstein's equation.(35,61)
    - $E = \Delta mc^2$
  - Be able to calculate the nuclear binding energy of a substance.(37,41,80)
    - Nuclear Binding Energy= $((m_{atom}) - (\#\text{p}\left(m_{\,^1H}\right)+\#\text{n}(m_n)))\ c^2$
      - $m_{^1_0n} = 1.0087\ u$
      - $m_{^1_1H} = 1.0078\ u$
  - Know the difference between nuclear fission and fusion.(47)
    - Fission: heavier atoms break apart
    - Fusion: small atoms combine to form larger atoms
  - Be able to calculate the energy released from fission or fusion.

Numbers correspond to end of chapter questions.