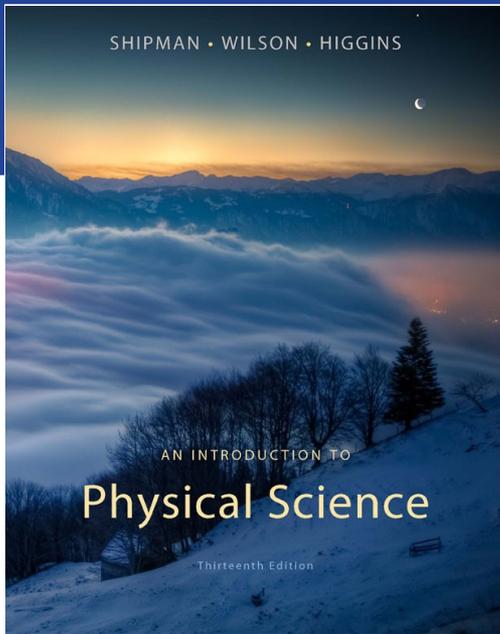


SHIPMAN • WILSON • HIGGINS



AN INTRODUCTION TO
Physical Science

Thirteenth Edition

 **BROOKS/COLE**
CENGAGE Learning™

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Chapter 10

Nuclear Physics

Nuclear Physics



- The characteristics of the atomic nucleus are important to our modern society.
- Diagnosis and treatment of cancer and other diseases
- Geological and archeological dating
- Chemical analysis
- Nuclear energy and nuclear disposal
- Formation of new elements
- Radiation of solar energy
- Generation of electricity

[Audio Link](#)

Early Thoughts about Elements



- The Greek philosophers (600 – 200 B.C.) were the first people to speculate about the basic substances of matter.
- Aristotle speculated that all matter on earth is composed of only four elements: earth, air, fire, and water.
- He was wrong on all counts!

Names and Symbols of Common Elements



Table 10.2 Names and Symbols of Some Common Elements

Name	Symbol	Name	Symbol	Name	Symbol
Aluminum	Al	Gold	Au	Phosphorus	P
Argon	Ar	Helium	He	Platinum	Pt
Barium	Ba	Hydrogen	H	Potassium	K
Boron	B	Iodine	I	Radium	Ra
Bromine	Br	Iron	Fe	Silicon	Si
Calcium	Ca	Lead	Pb	Silver	Ag
Carbon	C	Magnesium	Mg	Sodium	Na
Chlorine	Cl	Mercury	Hg	Sulfur	S
Chromium	Cr	Neon	Ne	Tin	Sn
Cobalt	Co	Nickel	Ni	Uranium	U
Copper	Cu	Nitrogen	N	Zinc	Zn
Fluorine	F	Oxygen	O		

The Atom



- All matter is composed of atoms.
- An atom is composed of three subatomic particles: electrons (-), protons (+), and neutrons (0)
- The nucleus of the atom contains the protons and the neutrons (also called nucleons.)
- The electrons surround (orbit) the nucleus.
- Electrons and protons have equal but opposite charges.

Major Constituents of an Atom



Table 10.3 Major Constituents of an Atom

Particle (symbol)	Charge (C)	Electronic Charge	Mass (kg)	Location
Electron (e)	-1.60×10^{-19}	-1	9.109×10^{-31}	Outside nucleus
Proton (p)	$+1.60 \times 10^{-19}$	+1	1.673×10^{-27}	Nucleus
Neutron (n)	0	0	1.675×10^{-27}	Nucleus

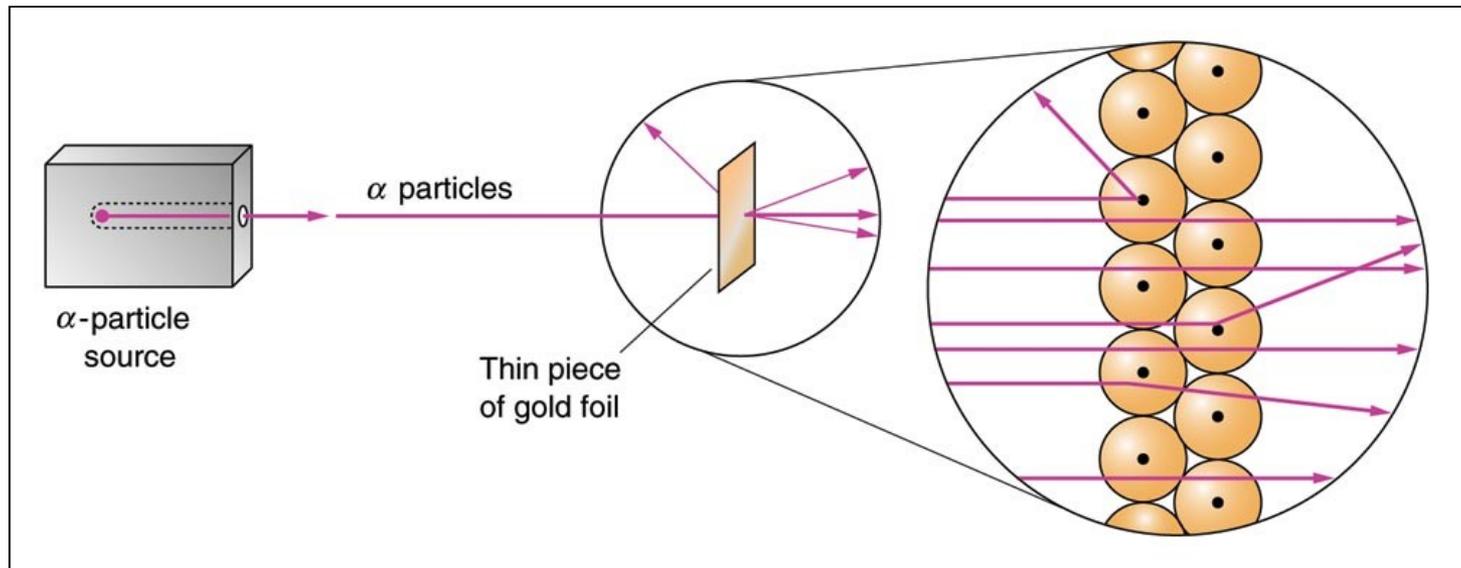
The Atomic Nucleus



- Protons and neutrons have nearly the same mass and are 2000 times more massive than an electron.
- Discovery – Electron (J.J. Thomson in 1897), Proton (Ernest Rutherford in 1918), and Neutron (James Chadwick in 1932)

Rutherford's Alpha-Scattering Experiment

- J.J. Thomson's "plum pudding" model predicted the alpha particles would pass through the evenly distributed positive charges in the gold atoms.



α particle = helium nucleus

Rutherford's Alpha-Scattering Experiment



- Only 1 out of 20,000 alpha particles bounced back.
- Rutherford could only explain this by assuming that each gold atom had its positive charge concentrated in a very small “nucleus.”
- Diameter of nucleus = about 10^{-14} m
- Electron orbit diameter = about 10^{-10} m
- Atomic Mass is concentrated in the nucleus (>99.97%)

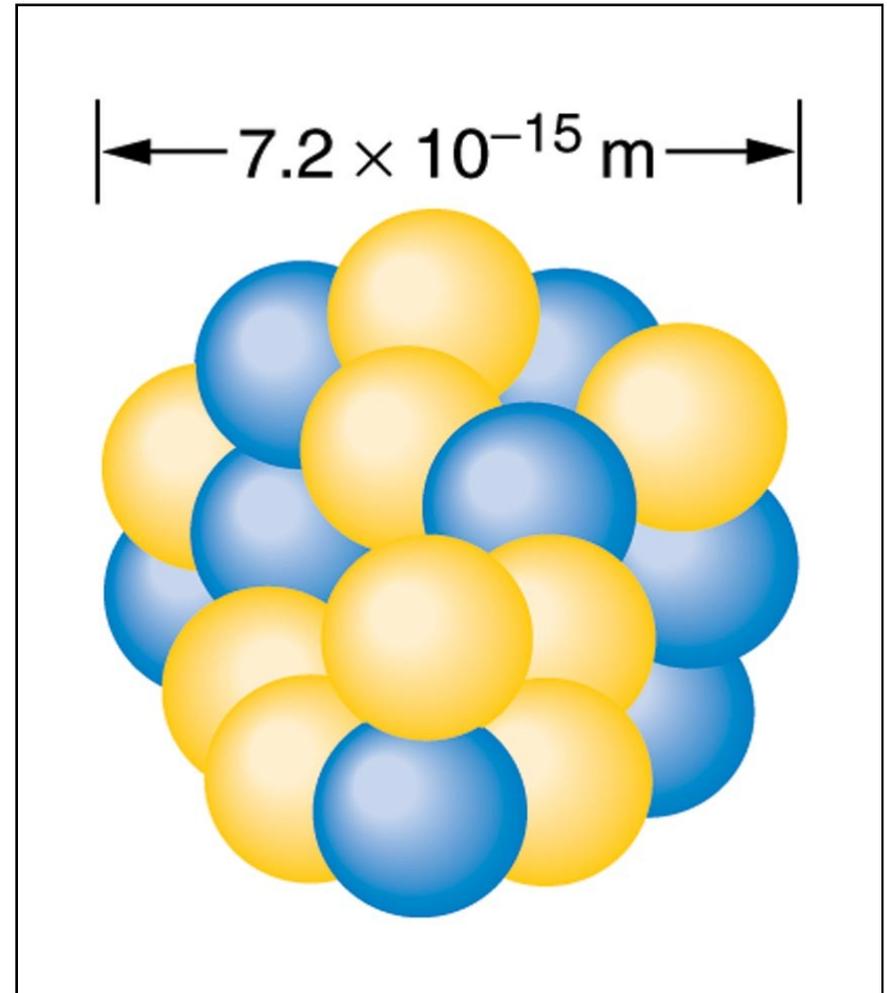
Atomic Mass is Concentrated in the Nucleus!



- Therefore the volume (or size) of an atom is determined by the orbiting electrons.
 - The diameter of an atom is approximately 10,000 times the diameter of the nucleus.
- If only nuclear material (protons and neutrons) could be closely packed into a sphere the size of a ping-pong ball it would have the incredible mass of 2.5 billion metric tons!

Visual Representation of a Nucleus

- Tightly Packed Protons and Neutrons



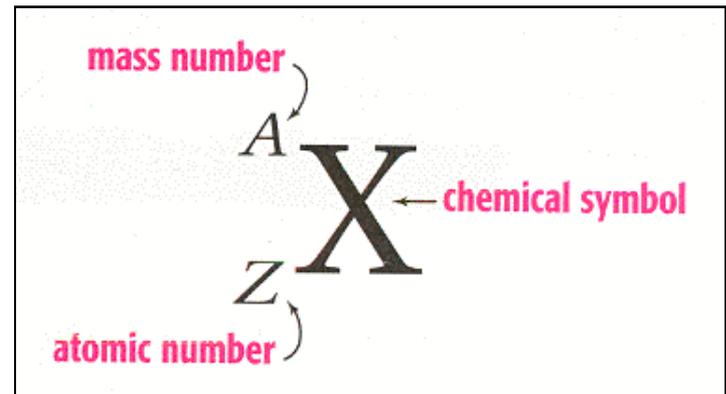
Atomic Designations



- Atomic Number (Z) – the # of protons in the nucleus (“defines” the element – the # of protons is always the same for a given element)
- Atomic Number also designates the number of electrons in an element.
- If an element either gains or loses electrons, the resulting particle is called an ion.
- For example, if a sodium atom (Na) loses an electron it becomes a sodium ion (Na⁺.)

More Atomic Designations

- Mass Number (A) – protons + neutrons, or the total number of nucleons
- Isotope – when the number of neutrons vary in the nucleus of a given element (always same number of protons)
- Only 118 chemical elements are known, but the total number of isotopes is about 3000.

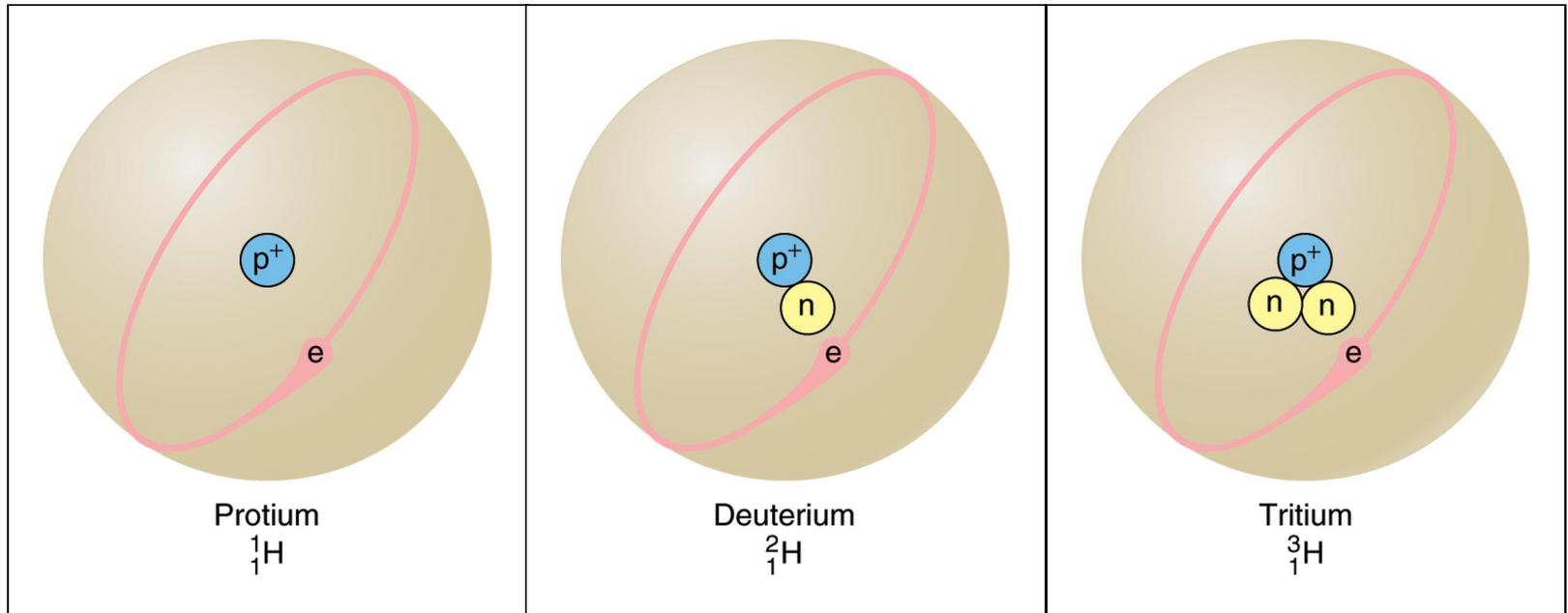


Isotopes



- Some elements have several isotopes (like carbon – ^{12}C , ^{13}C , ^{14}C)
- Isotopes of a single element have the 'same' chemical properties (due to same number of electrons), but they have different masses (due to varying number of neutrons.)
- Due to their various masses isotopes behave slightly different during reactions.

Three Isotopes of Hydrogen

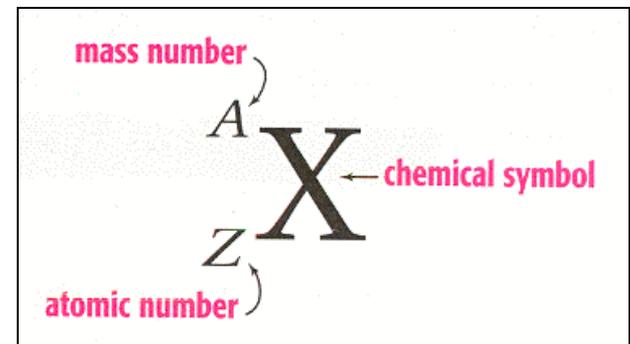


In naturally occurring Hydrogen - 1 atom in 6000 is deuterium and 1 in 10,000,000 is tritium. *Heavy water* = D_2O

Determining the Composition of an Atom



- *Determine the number of protons, electrons, and neutrons in the fluorine atom ${}^{19}_9\text{F}$*
- Atomic Number (Z) = 9
- \therefore protons = 9 & electrons = 9
- Mass Number (A) = 19
- $A = N + Z$ {N = Neutron Number}
- $\therefore N = A - Z = 19 - 9 = 10$
- neutrons = 10



Atomic Review



- Protons & Neutrons – in nucleus
- Electrons – orbit around nucleus
- Mass Number (A) = protons + neutrons
- Atomic Number (Z) = # of protons
- Neutron Number (N) = # of neutrons
- Isotope – an element with different # of neutrons (same # of protons)

Atomic Mass



- The weighted average mass of an atom of the element in a naturally occurring sample
- The Atomic Mass is measured in unified atomic mass units (u) – basically the weight of a proton or neutron.
- The ^{12}C atom is used as the standard, and is assigned the Atomic Mass of exactly 12 u.
- The weighted average mass of all carbon is slightly higher than 12 (12.011) because some is ^{13}C and ^{14}C .

Fundamental Forces of Nature - *Review*



- We have previously discussed two fundamental forces of nature – gravitational and electromagnetic.
- The electromagnetic force between a proton (+) and an electron (-) is 10^{39} greater than the gravitational forces between the two particles.
- Therefore the electromagnetic forces are the only important forces on electrons and are responsible for the structure of atoms, molecules and all matter in general.

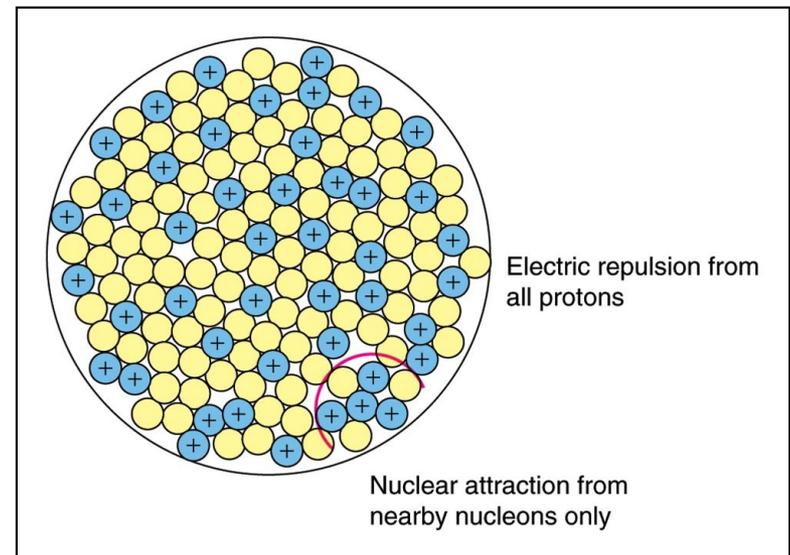
The (Strong) Nuclear Force



- Remember that the nucleus of any atom is extremely small and packed with a combination of neutrons and protons (+).
- According to Coulomb's Law like charges repel each other. Therefore the repulsive forces in a nucleus are huge and the nucleus should fly apart.
- There must exist a third fundamental force that somehow holds the nucleus together. This is the strong force which is attractive at distances less than about 10^{-14} m.

Large Nucleus & the Nuclear Force

- For a large nucleus the forces are complicated.
- An individual proton is only attracted by the 6 or 7 closest nucleons, but is repelled by all the other protons.
- When the # of protons exceeds 83, the electrical repulsion overcomes the nuclear force, and the nucleus is unstable.
- Spontaneous disintegration or decay occurs to adjust for the neutron-proton imbalance.



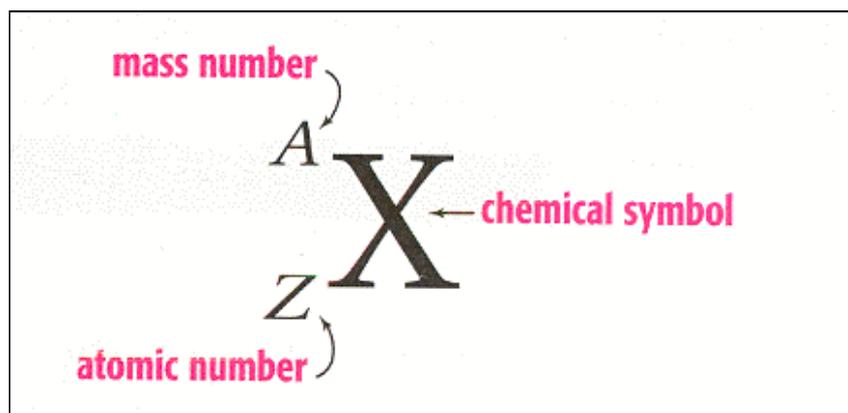
Standard Model



- Physicists have also identified a weak nuclear force within an atom.
 - This is a very short-range force that reveals itself principally in beta decay.
 - It is weaker than the strong force and the electromagnetic force
- Physicists have organized three of the known atomic forces (electromagnetic, weak nuclear, and strong nuclear) into a single unifying theory called the standard model.

Atomic Review

- Mass Number (A) – protons + neutrons, or the total number of nucleons
- Isotope – when the number of neutrons vary in the nucleus of a given element (always same number of protons)
- Atomic Number (Z) – number of protons



Radioactivity



- Radioactivity (radioactive decay) – the spontaneous process of nuclei undergoing a change by emitting particles or rays
- Nuclide – a specific type of nucleus: ^{238}U or ^{14}C
- Radionuclides (radioactive isotopes or radioisotopes) – nuclides whose nuclei undergo spontaneous decay (disintegration)
- Substances that give off such radiation are said to be radioactive

[Audio Link](#)

Radioactive Decay



- Parent nucleus – the original nucleus before decay
- Daughter nucleus (or daughter product) – the resulting nucleus after decay
- Radioactive nuclei can decay (disintegrate) in three common ways
 - Alpha decay
 - Beta decay
 - Gamma decay

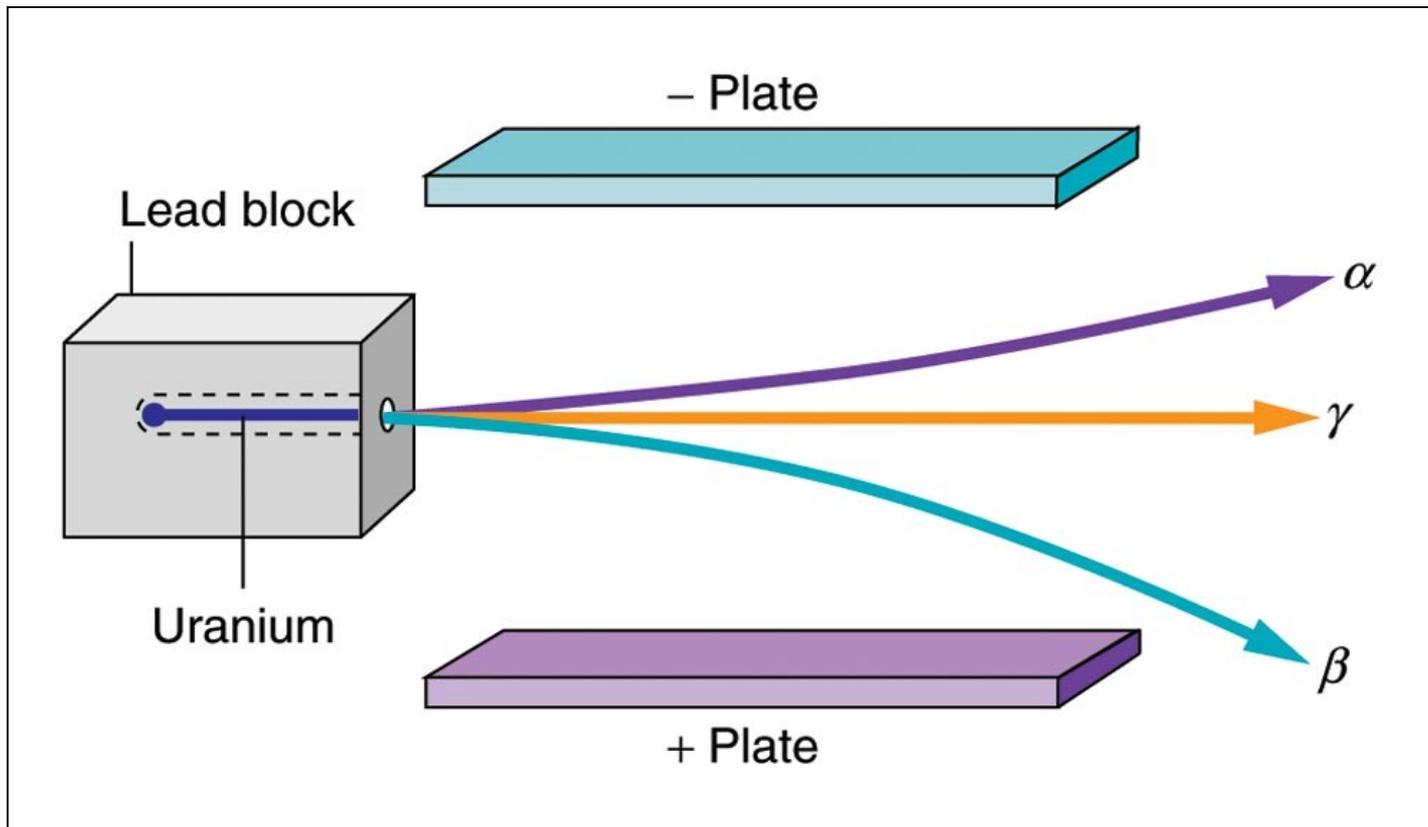
Radioactive Decay (disintegration)

- Alpha decay – disintegration of a nucleus into a nucleus of another element, w/ the emission of an alpha particle (α) - a helium nucleus (${}^4_2\text{He}$)
- Beta decay – a neutron is transformed into a proton, w/ the emission of a beta particle (β) – an electron (${}^0_{-1}\text{e}$)
- Gamma decay – occurs when a nucleus emits a gamma ray (γ) and becomes a less energetic form of the same nucleus

Three Components of Radiation from Radionuclides



Alpha(α), Beta(β), Gamma(γ)



Nuclear Decay Equations - Examples



- Alpha decay = ${}_{90}^{232}\text{Th} \rightarrow {}_{88}^{228}\text{Ra} + {}_2^4\text{He}$
- Beta decay = ${}_6^{14}\text{C} \rightarrow {}_7^{14}\text{N} + {}_{-1}^0\text{e}$
- Gamma decay = ${}_{82}^{204}\text{Pb}^* \rightarrow {}_{82}^{204}\text{Pb} + \gamma$
- In a nuclear decay equation, the sums of the mass numbers (A) and the sums of the atomic numbers (Z) will be equivalent on each side

The Products of Alpha Decay – Example



- ${}^{238}_{92}\text{U}$ undergoes alpha decay. Write the equation for the process
- ${}^{238}_{92}\text{U} \rightarrow ?$
- ${}^{238}_{92}\text{U} \rightarrow \underline{\quad ?? \quad} + {}^4_2\text{He}$
- ${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{?} + {}^4_2\text{He}$
- Must determine the mass number (A), the atomic number (Z), and the chemical symbol for the daughter product
- ${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^4_2\text{He}$

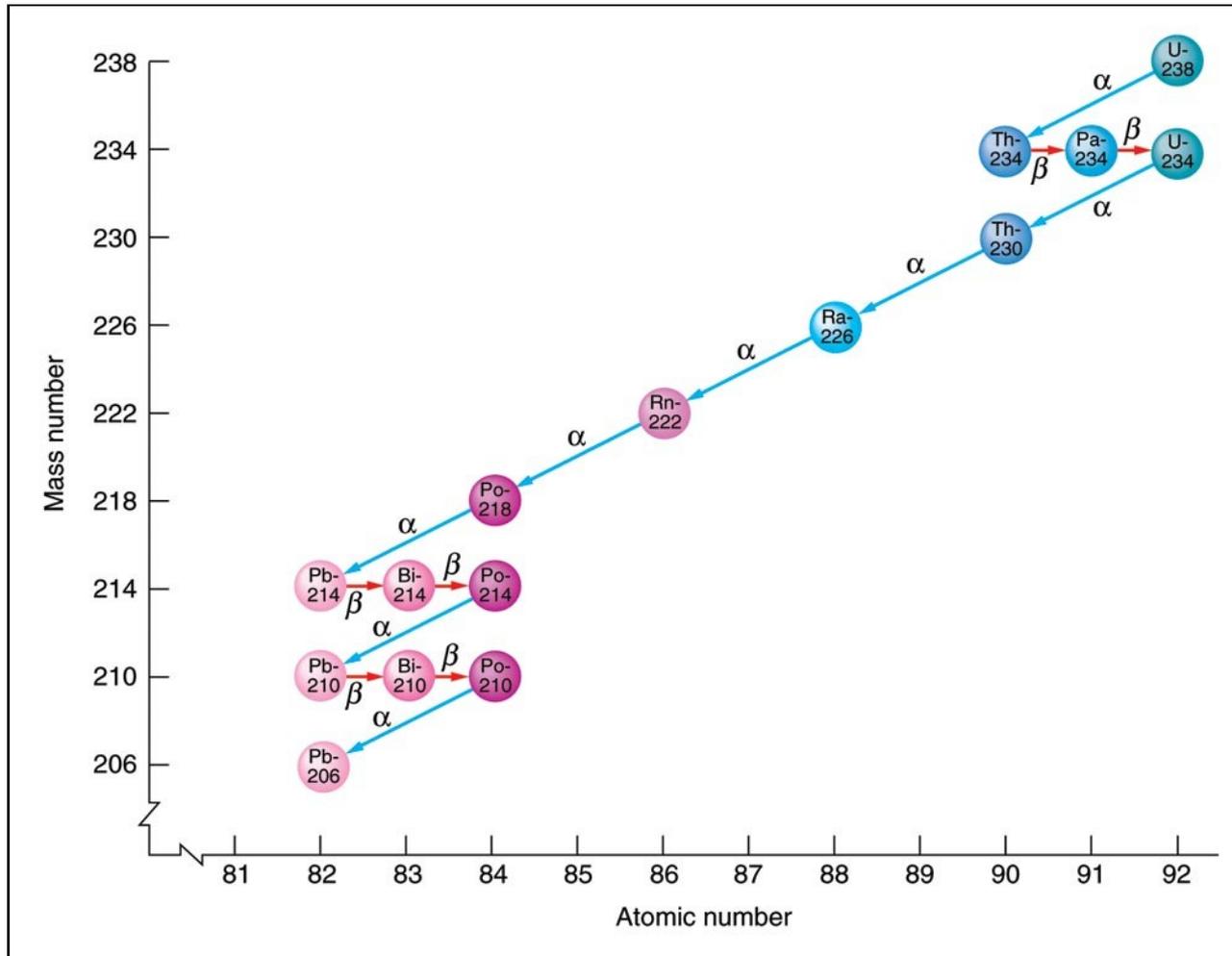
Five Common Forms of Nuclear Radiations



Table 10.4 Nuclear Radiations

Name	Symbol	Charge	Mass Number
Alpha	${}^4_2\text{He}$	2+	4
Beta	${}^0_{-1}\text{e}$	1-	0
Gamma	γ	0	0
Positron	${}^0_{+1}\text{e}$	1+	0
Neutron	${}^1_0\text{n}$	0	1

Decay Series of Uranium-238 to Lead-206



Identifying Radionuclides



- Which nuclides are unstable (radioactive) and which are stable?
- An interesting pattern emerges:
 - Most stable nuclides have an even number of both protons and neutrons (even-even nuclides)
 - Most unstable nuclides have an odd number of both protons and neutrons (odd-odd nuclides)
- A nuclide will be radioactive if:
 - Its atomic number (Z) is $>$ than 83
 - $n < p$ (except for ${}^1\text{H}$ and ${}^3\text{He}$)
 - It is an odd-odd nuclide² (except for ${}^2_1\text{H}$, ${}^6_3\text{Li}$, ${}^{10}_5\text{B}$, ${}^{14}_7\text{N}$)

Identifying Radionuclides - *Example*

- Identify the radionuclide in each pair, and state your reasoning.



- Z above 83

- fewer n than p

- odd-odd

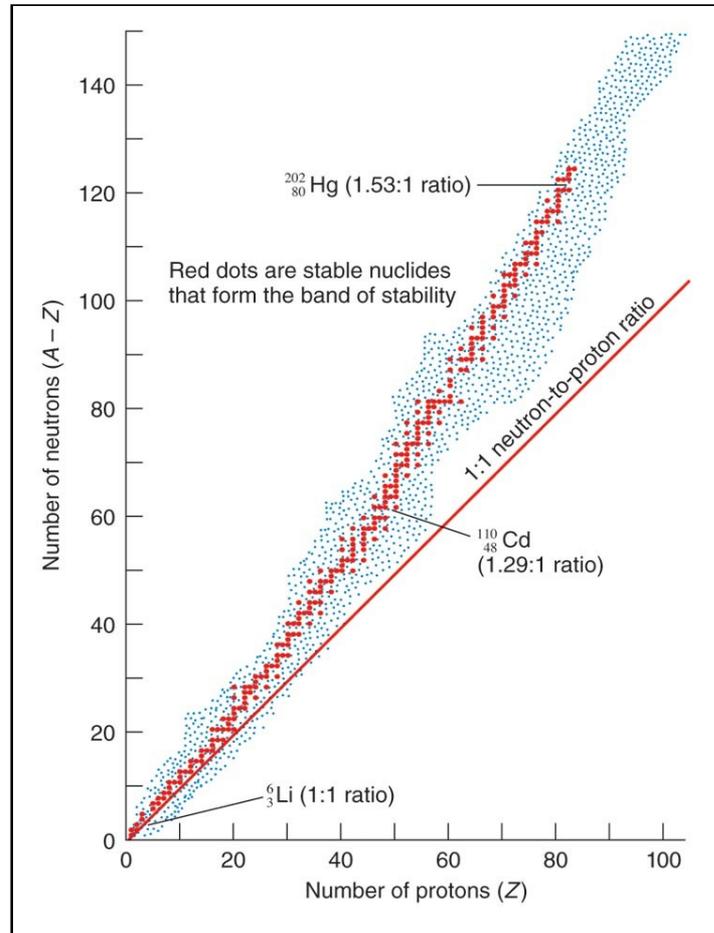
The Pairing Effect in Stabilizing Nuclei

Table 10.5 The Pairing Effect in Stabilizing Nuclei

Proton Number, Z	Neutron Number, N	Number of Stable Nuclides	Example
Even	Even	160	${}^{24}_{12}\text{Mg}$
Even	Odd	52	${}^{13}_6\text{C}$
Odd	Even	52	${}^6_5\text{Be}$
Odd	Odd	4	${}^{14}_7\text{N}$

A Plot of Number of Neutrons (N) Versus Number of Protons (Z) for the Nuclides

- Showing “band of stability” (red dots)
- Small blue dots represent known radioisotopes.



Half-Life of a Radionuclide

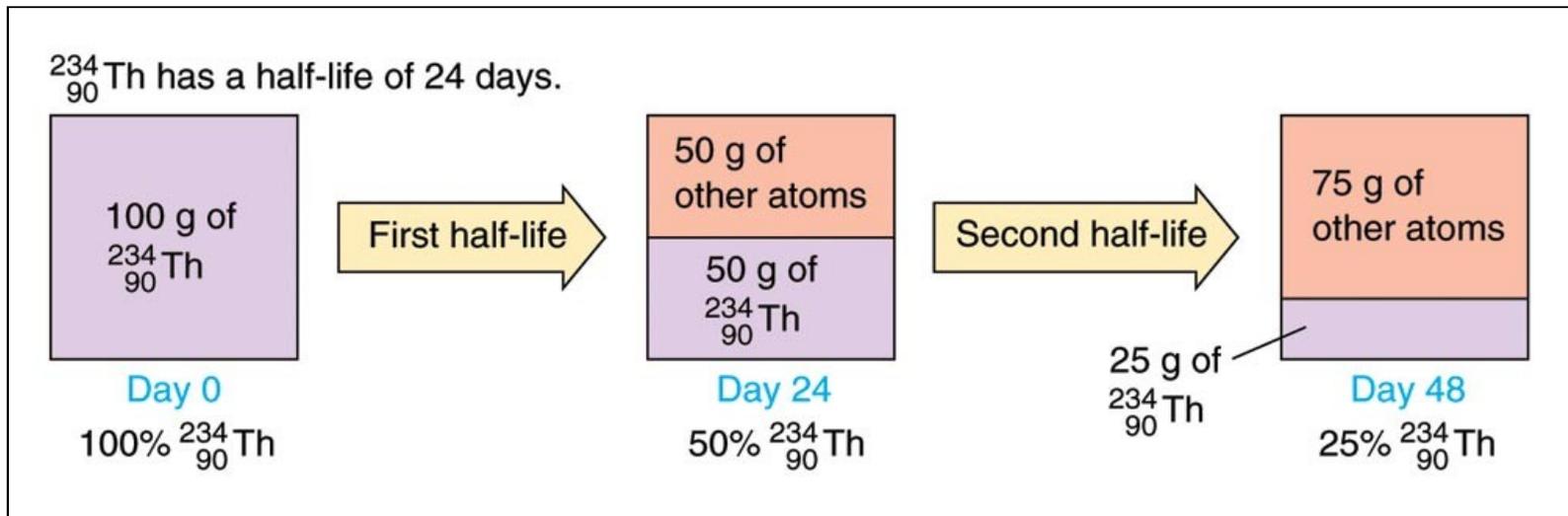


- Half-Life – the time it takes for half of the nuclei of a given sample to decay
- In other words – after one half-life has expired, only one-half of the original amount of radionuclide remains
- After 2 half-lives only one-quarter ($\frac{1}{2}$ of $\frac{1}{2}$) of the original amount of the radionuclide remains

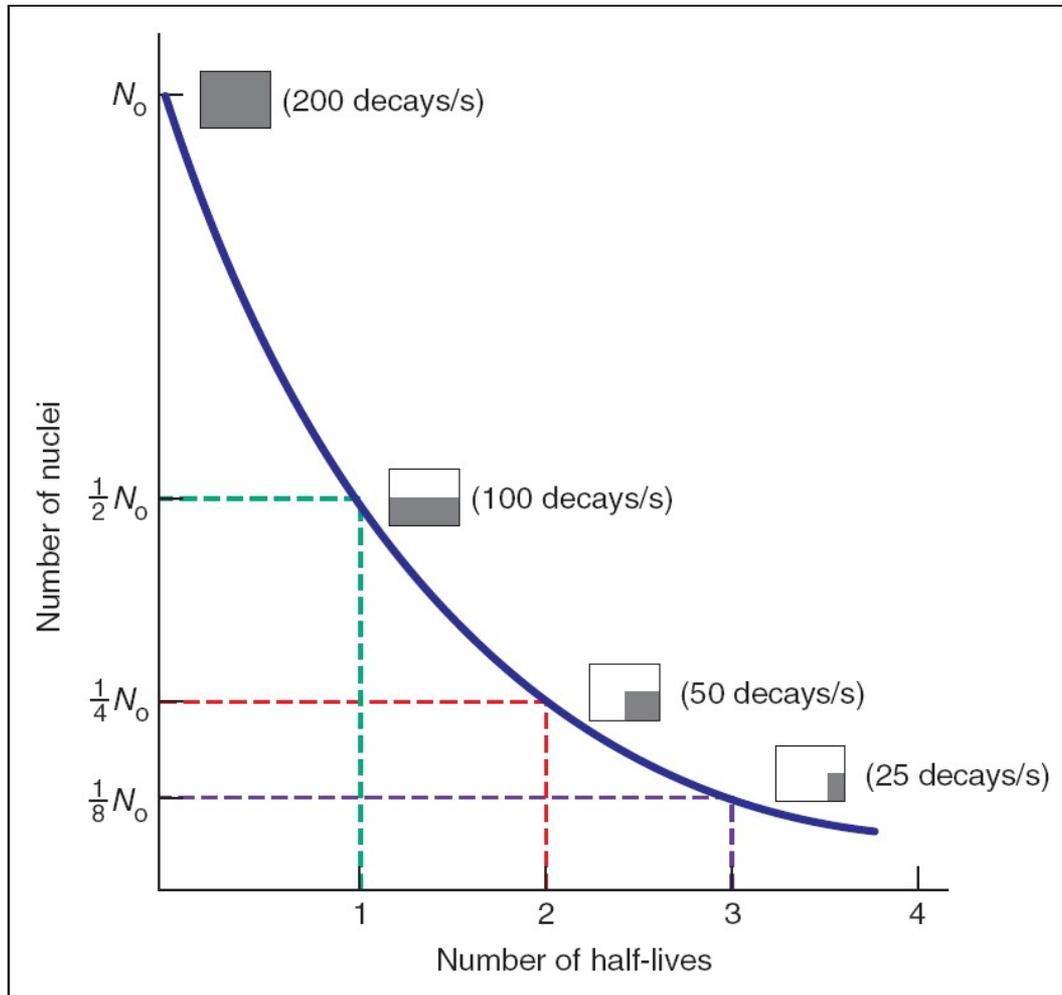
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Decay of Thorium-234 over Two Half-Lives

Thorium-234 has a Half-Life of 24 days



Decay Curve for Any Radionuclide



Finding the Number of Half-Lives and the Final Amount



- *What fraction and mass of a 40 mg sample of iodine-131 (half-life = 8d) will remain in 24d?*
- Step 1 – find the number of half-lives that have passed in 24 days: $\frac{24 \text{ days}}{8\text{d/half-life}} = 3 \text{ half-lives}$
- Step 2 – Start with the given amount $N_0 = 40\text{mg}$, and half it 3 times (3 half-lives)
 - Once $\rightarrow N_0/2 = 20 \text{ mg}$ (after 8 days)
 - Twice $\rightarrow N_0/4 = 10 \text{ mg}$ (after 16 days)
 - Thrice $\rightarrow N_0/8 = 5 \text{ mg}$ (after 24 days)

Finding the Number of Half-Lives and the Final Amount – Confidence Exercise



- *What fraction of Stontium-90 produced in 1963 (half-life = 29y) will remain in 2021?*
- Step 1 – find the number of half-lives that have passed in 58 years: $\frac{58 \text{ years}}{29\text{y/half-life}} = 2$ half-lives
- Step 2 – Start with the given amount = N_0
- After 1 half-life $\rightarrow N_0/2 =$ (after 29 years)
- After 2 half-lives $\rightarrow N_0/4 =$ (after 58 years)
- \therefore One fourth of the original Strontium-90 remains

Finding the Elapsed Time



- *How long would it take a sample of ^{14}C to decay to one-fourth its original activity? (half-life of ^{14}C is 5730 years)*
- Solution: $N_0 \rightarrow N_0/2 \rightarrow N_0/4 \therefore ^{14}\text{C}$ would need to decay for *two half-lives* in order to be reduced to $1/4$ its original activity.
- $(2 \text{ half-lives})(5730 \text{ y/half-life}) = 11,460 \text{ years}$

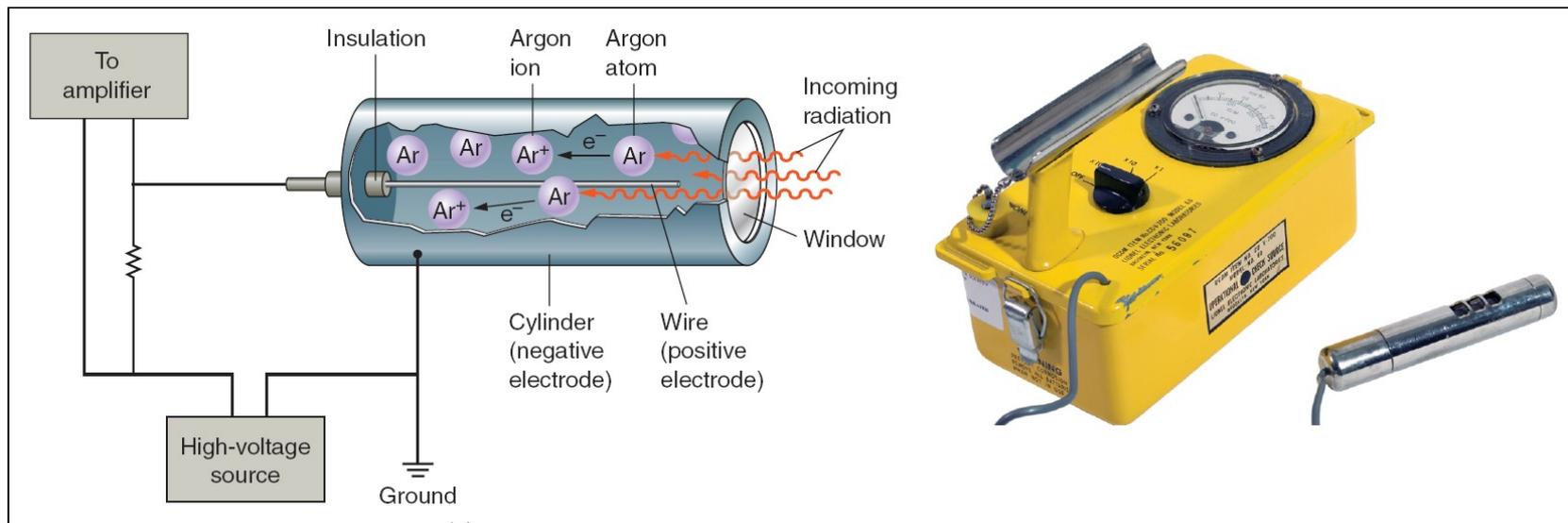
Determining the Half-Life of a Radioactive Isotope (Radionuclide)



- In order to determine the half-life of a particular radionuclide, we must monitor the activity of a known amount in the laboratory
- Activity – the rate of emission of the decay particles (usually in counts per minute, cpm)
- When (time) the initial activity rate has fallen to one-half – we have reached One Half-Life
- Measured with a Geiger Counter --

Geiger Counter

When a high-energy particle from a radioactive source enters the window it ionizes an argon atom, giving off a small pulse of current, which is counted & amplified into the familiar “clicks”



Radioactive Dating



- Because of their constant decay rates, radioisotopes can be used as nuclear “clocks.”
- Scientists can determine the age of objects that contain radioisotopes.

Carbon-14 (^{14}C) Dating



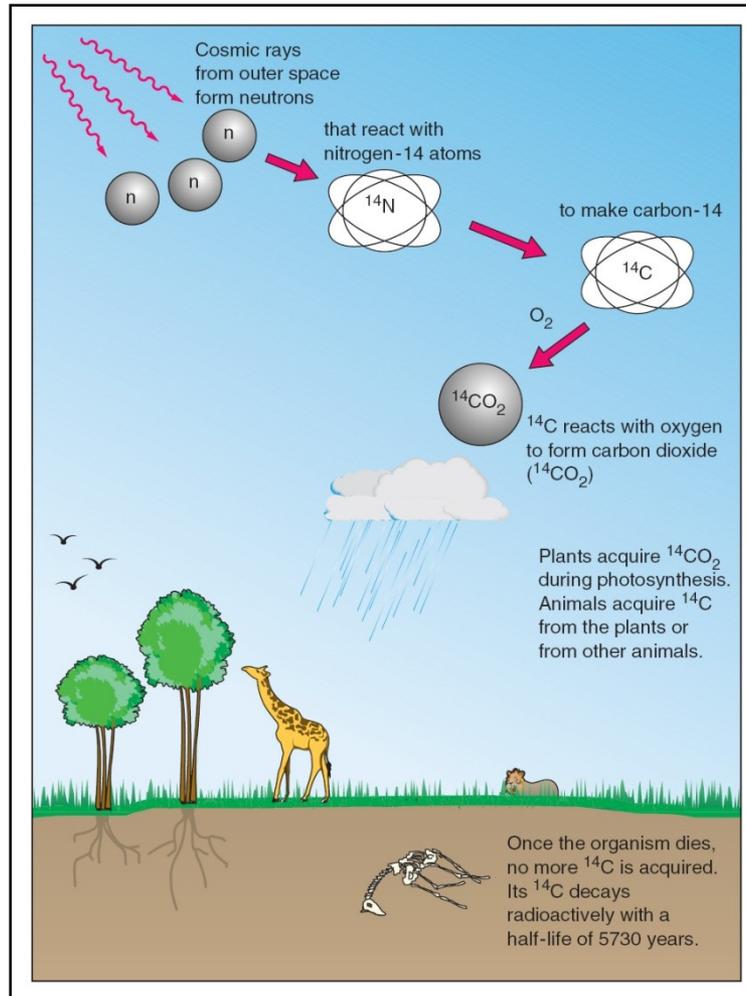
- An important dating procedure in archeology.
- Used on materials that were once part of living things – wood, bones, parchment, *etc.*
- ^{14}C is formed naturally in the upper atmosphere and is dispersed by atmospheric mixing
- All living matter contains about the same level of ^{14}C or an activity level of 16 counts/min per gram of total Carbon.

Carbon-14 Dating



- Once an organism dies, it ceases to take in ^{14}C , and the ^{14}C present at death starts to undergo radioactive decay.
- Therefore, the longer an organism has been dead, the lower is the radioactivity of each gram of carbon (the ^{12}C and ^{13}C is stable) in its remains.

Carbon-14 Dating



Limits to Carbon-14 Dating



- After about 10 half-lives, very little ^{14}C remains, and it is therefore barely measurable.
- The limit of radiocarbon dating depends on the ability to measure very low activity in old samples
- 40,000-50,000 years is the current limit of age-dating using ^{14}C .

Carbon 14 Dating Example



- An old scroll is found in a cave that has a carbon-14 activity of 4 counts/min per gram of total carbon. Approximately how old is the scroll?
- The plant from which the scroll was made originally had an activity level of 16 counts/min per gram of Carbon.
- To get to 4 cts/min
- $16\text{cts} \Rightarrow (t_{1/2}) 8\text{ cts} \Rightarrow (t_{1/2}) 4\text{ cts}$ or 2 half-lives
- ^{14}C has a half life of 5730 yrs
- $2 \times 5730 = 11,460$ yrs
- The scroll is between 11,000 and 12,000 years old.

Nuclear Reactions



- We know that radioactive nuclei can spontaneously change into nuclei of other elements, a process called transmutation.
- Scientists wondered if the reverse was possible.
- Could a particle (proton or neutron) be added to a nucleus to change it into another element?
- The answer is “yes,” and this process is called a nuclear reaction.

[Audio Link](#)

Nuclear Reactions

- In 1919 Ernest Rutherford produced the first nuclear reaction by bombarding ^{14}N with alpha (^4He) particles.

2

- The result was an artificial transmutation of a nitrogen isotope into an oxygen isotope.



Nuclear Reaction – General Form



- ${}^4_2\text{He} + {}^{14}_7\text{N} \rightarrow {}^{17}_8\text{O} + {}^1_1\text{H}$
- Note that the conservation of mass number and conservation of atomic number holds in nuclear reactions, just like in nuclear decay.
 - 18 = total mass # on each side
 - 9 = total atomic # on each side
- The general form for a nuclear reaction is
- $a + A \rightarrow B + b$
 - a is the particle that bombards A to form nucleus B and emitted particle b

Common Particles Encountered in Nuclear Reactions



- In addition to the particles in the table below, protons (${}^1_1\text{H}$), deuterons (${}^2_1\text{H}$), and tritons (${}^3_1\text{H}$) are commonly encountered in nuclear reactions.

Table 10.4 Nuclear Radiations

Name	Symbol	Charge	Mass Number
Alpha	${}^4_2\text{He}$	2+	4
Beta	${}^0_{-1}\text{e}$	1-	0
Gamma	γ	0	0
Positron	${}^0_{+1}\text{e}$	1+	0
Neutron	${}^1_0\text{n}$	0	1

Completing an Equation for a Nuclear Reaction – *an Example*



- *Complete the equation for the proton bombardment of lithium-7.*
- ${}^1_1\text{H} + {}^7_3\text{Li} \rightarrow \underline{\text{????}} + {}^1_0\text{n}$
- Note, the sum of the mass #'s on left = 8.
- The mass # on the right must also = 8, therefore the missing particle must have a mass # = 7.
- The sum of the atomic #'s on left = 4
- Therefore the sum of the atomic #'s on right must also equal 4.

Completing an Equation for a Nuclear Reaction – *an Example (cont.)*



- ${}^1_1\text{H} + {}^7_3\text{Li} \rightarrow \underline{\text{????}} + {}^1_0\text{n}$
- The missing particle must have an atomic number = 4
- Therefore the missing particle has a mass number of 7 and an atomic number of 4.
- This element is ${}^7_4\text{Be}$ (beryllium.)
- Completed equation \rightarrow
- ${}^1_1\text{H} + {}^7_3\text{Li} \rightarrow {}^7_4\text{Be} + {}^1_0\text{n}$

Confidence Exercise

- *Complete the equation for the deuteron bombardment of aluminum-27*
- ${}^2\text{H} + {}^{27}\text{Al} \rightarrow \underline{\text{????}} + {}^4\text{He}$
- Note the sum of the ¹mass #'s on left = 29
- The mass # on the right must also = 29, therefore the missing particle must have a mass # = 25
- The sum of the atomic #'s on left = 14
- Therefore the sum of the atomic #'s on right must also equal 14.

Confidence Exercise (*cont.*)



- ${}^2_1\text{H} + {}^{27}_{13}\text{Al} \rightarrow \underline{\text{????}} + {}^4_2\text{He}$
- The missing particle must have an atomic number = 12
- Therefore the missing particle has a mass number of 25 and an atomic number of 12.
- This element is ${}^{25}_{12}\text{Mg}$ (magnesium.)
- Completed equation \rightarrow
- ${}^2_1\text{H} + {}^{27}_{13}\text{Al} \rightarrow {}^{25}_{12}\text{Mg} + {}^4_2\text{He}$

Nuclear Reactions



- Rutherford's discovery of the transmutation of ^{14}N into ^{17}O was actually an accident!
 - But the implications of this discovery were enormous!
- One element could now be changed into another completely different element!

Nuclear Reactions



- The age-old dream of the alchemists had come true.
 - It was now possible to actually make gold (Au) from other more common elements!
- ${}^1_1\text{H} + {}^{200}_{80}\text{Hg} \rightarrow {}^{197}_{79}\text{Au} + {}^4_2\text{He}$
- Unfortunately, the above process to make gold is VERY expensive.
 - More than \$1,000,000 per ounce!

Nuclear Reactions

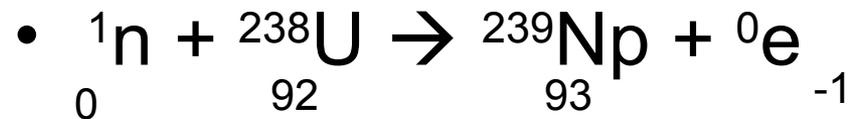


- Neutrons produced in nuclear reactions can be used to induce other nuclear reactions.
 - Hence, a “chain reaction” is possible.
- Since neutrons have an electrical charge, they are particularly efficient in penetrating the nucleus and inducing a reaction.
 - Without an electrical charge neutrons are not influenced by positive and negative atomic charges.

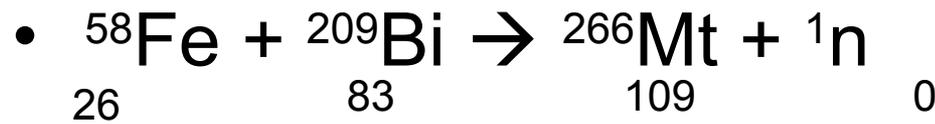
Transuranium Elements



- Transuranium Elements – those with atomic number greater than 92
 - All of these elements are synthetic.
 - Created in the lab by bombarding a lighter nucleus with alpha particles or neutrons
 - For Example ...



• *Or ...*



Nucleosynthesis



- H, He, and Li are thought to have formed in the Big Bang.
- Be up to Fe were likely made in the cores of stars by fusion.
- Atoms heavier than Fe are thought to have formed during supernova explosions of stars, when there was an abundance of neutrons and medium-sized atoms.

Uses of Radionuclides

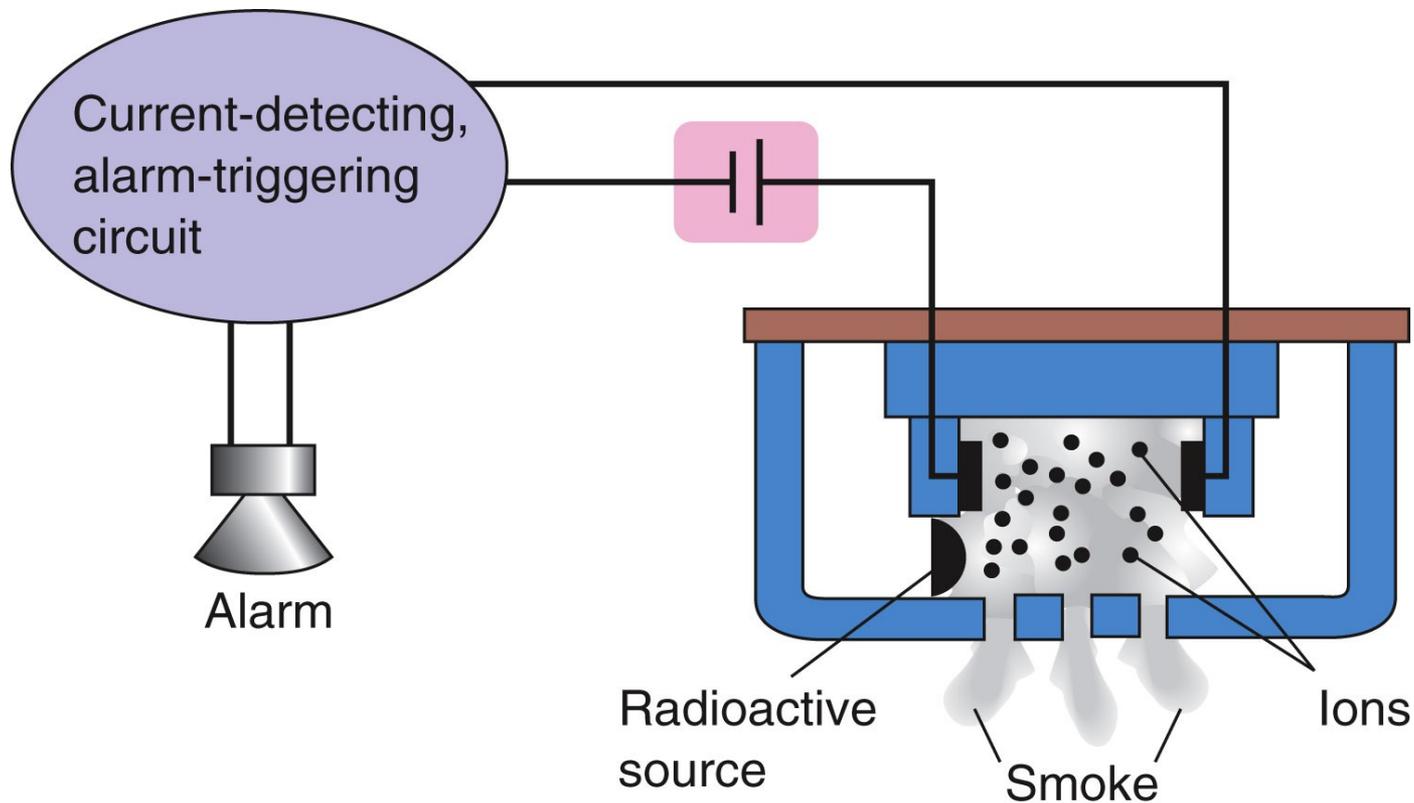


- Radionuclides have many uses in medicine, chemistry, biology, geology, agriculture, and industry.
- One medical use involves a radioactive isotope of iodine, ^{123}I , it is used in a diagnostic measurement of the thyroid gland.
- Americium-241, a synthetic transuranium radionuclide, is used in most common home smoke detectors.

Smoke Detector



- A weak radioactive source ionizes the air and sets up a small current. If smoke particles enter, the current is reduced, causing an alarm.



Uses of Radionuclides



- In both chemistry and biology, radioactive “tracers” (^{14}C & ^3H) are used to “tag” an atom within a molecule.
 - In this way the reaction pathways of drugs & hormones may be determined.
- In geology, the predictable decay rate of radioactive elements in rocks and minerals allow age determination.
- In industry, tracer radionuclides help manufacturers test durability.

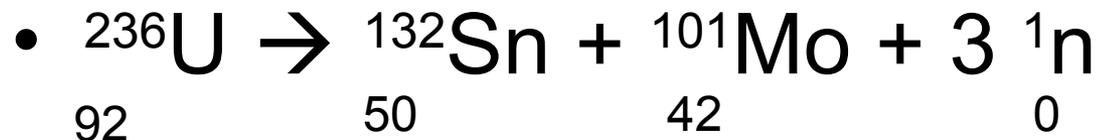
Nuclear Fission



- Fission – the process in which a large nucleus “splits” into two intermediate-size nuclei
 - With the emission of neutrons and ...
 - The conversion of mass into energy
- For example, ^{236}U fissions into two smaller nuclei, emits several neutrons, and releases energy.



- *Or ...*



[Audio Link](#)

Completing the Equation for Fission *an Example*



- *Complete the following equation for fission.*
- $${}_{92}^{236}\text{U} \rightarrow {}_{36}^{88}\text{Kr} + {}_{56}^{144}\text{Ba} + \underline{\text{????}}$$
- Atomic #'s are balanced, 92 on both sides
- Therefore the atomic # for the unknown is 0.
- Mass #'s are not balanced.
 - *236 on the left & 232 on the right*
- Therefore 4 additional units of mass are needed on the right.

Completing the Equation for Fission *an Example (cont.)*

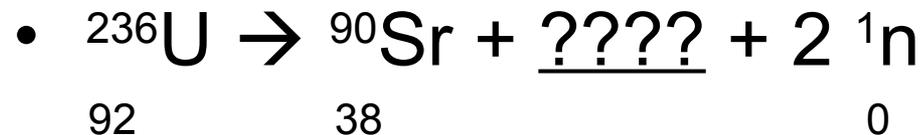


- ${}_{92}^{236}\text{U} \rightarrow {}_{36}^{88}\text{Kr} + {}_{56}^{144}\text{Ba} + \underline{\text{????}}$
- The missing particle must have:
 - An atomic number of 0
 - A mass number of 4
- But no single particle exists with those properties
- Therefore the missing “particle” is actually 4 neutrons.
- ${}_{92}^{236}\text{U} \rightarrow {}_{36}^{88}\text{Kr} + {}_{56}^{144}\text{Ba} + 4 {}_0^1\text{n}$

Completing the Equation for Fission *Confidence Exercise*



- *Complete the following equation for fission*



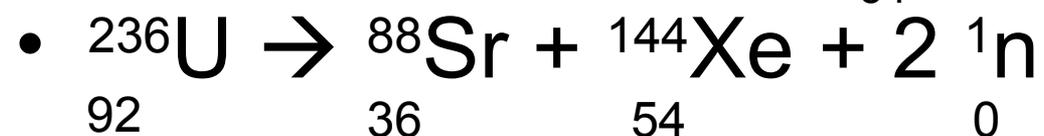
- Atomic #'s are not balanced.

- The atomic # for the unknown must be 54.

- Mass #'s are not balanced.

- The mass # for the unknown must be 144.

- The unknown must be ${}_{54}^{144}\text{Xe}$.



Nuclear Fission – Three Important Features



- The products of fission are always radioactive.
 - Some of the products have half-lives of thousands of years.
 - Nuclear waste disposal problems
- Relatively large amounts of energy are produced.
- Neutrons are released.

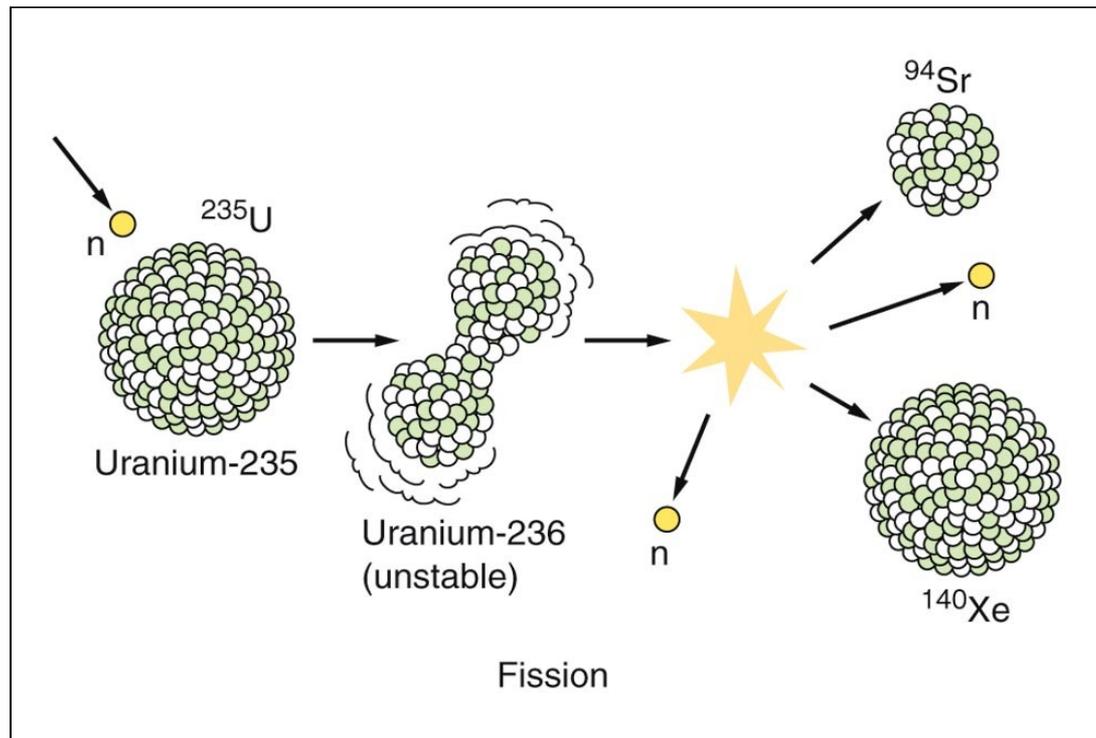
Chain Reaction



- In an expanding chain reaction, one initial reaction triggers a growing number of subsequent reactions.
- In the case of ^{235}U each fission emits two neutrons.
 - Each of these two neutrons can hit another ^{235}U , resulting in the fission of two additional ^{235}U nuclei and the release of energy and four neutrons.
- As the chain expands, the number of neutrons emitted and the energy output increases.

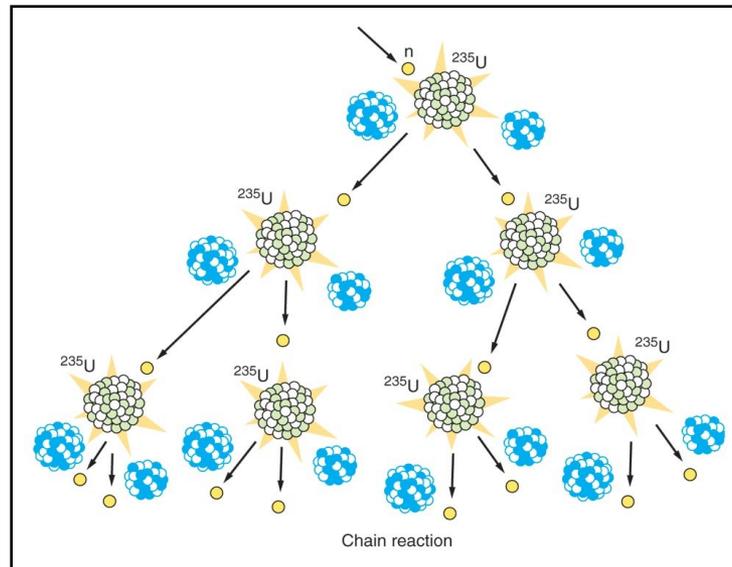
Fission

- ^{235}U absorbs a neutron, initially changes into ^{236}U and then immediately undergoes fission, releasing two neutrons and energy.



Chain Reaction

- If all of the emitted neutrons hit another ^{235}U nucleus, this results in an increasing number of emitted neutrons, fission reactions, and energy release.
- An expanding chain reaction occurs.



Self-Sustaining Chain Reaction



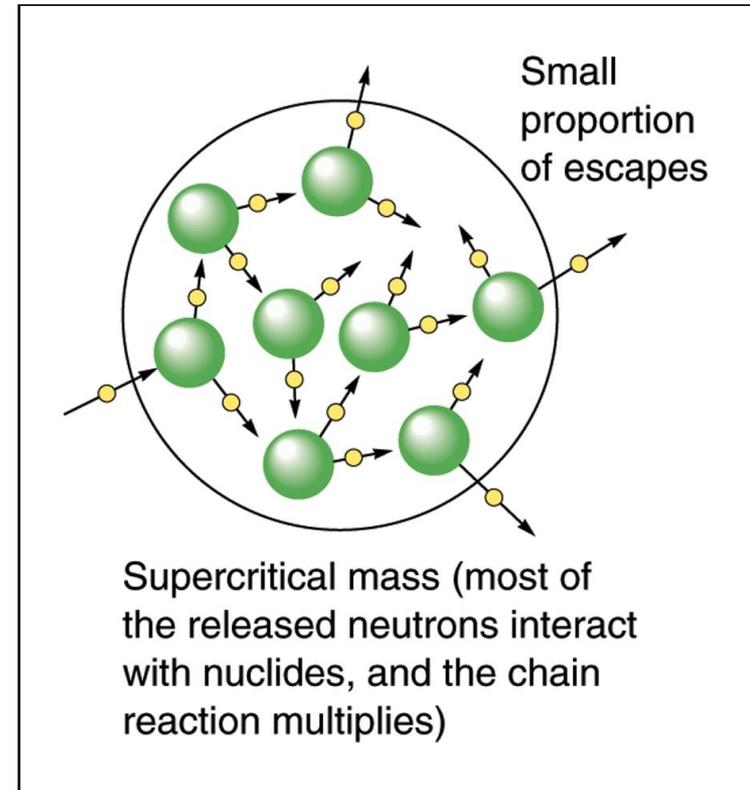
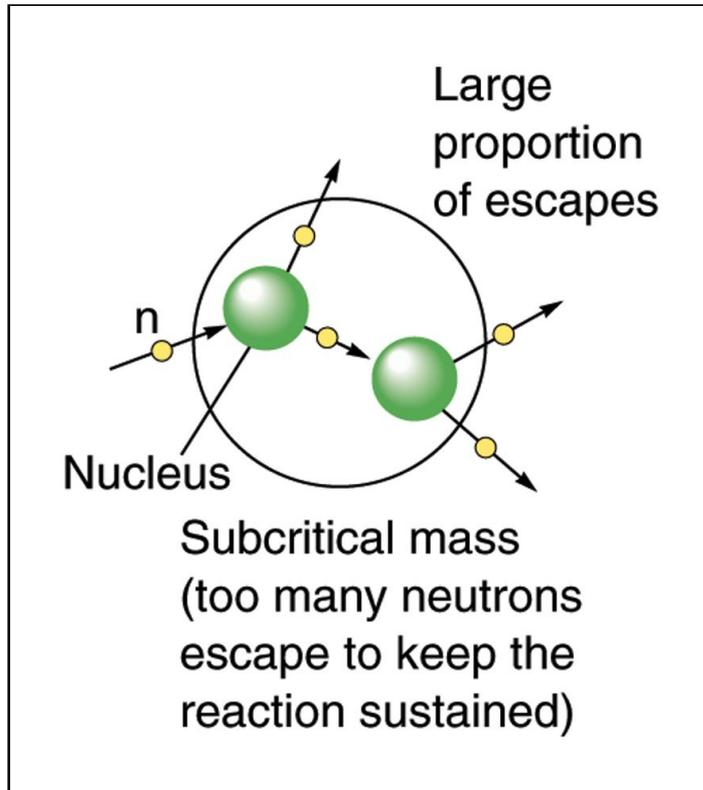
- A steady release of energy can be attained when each fission event causes only one more fission event - a self-sustaining chain reaction
- For a self-sustaining chain reaction to proceed, the correct amount and concentration of fissionable material (^{235}U) must be present.
- If there is too much fissionable material present an expanding chain reaction occurs.
- If there is too little fissionable material present the chain reaction will stop .

Critical Mass



- Critical Mass – the minimum amount of fissionable material necessary to sustain a chain reaction
 - About 4kg (baseball size) of pure ^{235}U
- Subcritical Mass – no chain reaction occurs
- Supercritical Mass – an expanding chain reaction occurs

Subcritical and Supercritical Masses



Uranium



- Natural uranium contains 99.3% ^{238}U and only 0.7% is the fissionable ^{235}U isotope.
- Therefore, the ^{235}U must be concentrated or “enriched” in order to create either a self-sustaining or expanding chain reaction.
- In U.S. nuclear reactors the ^{235}U has been enriched to about 3%, enough for a self-sustaining chain reaction.
- In contrast, nuclear weapons require an enrichment of 90% or more ^{235}U , enough for a sudden release of energy

Atomic Bomb



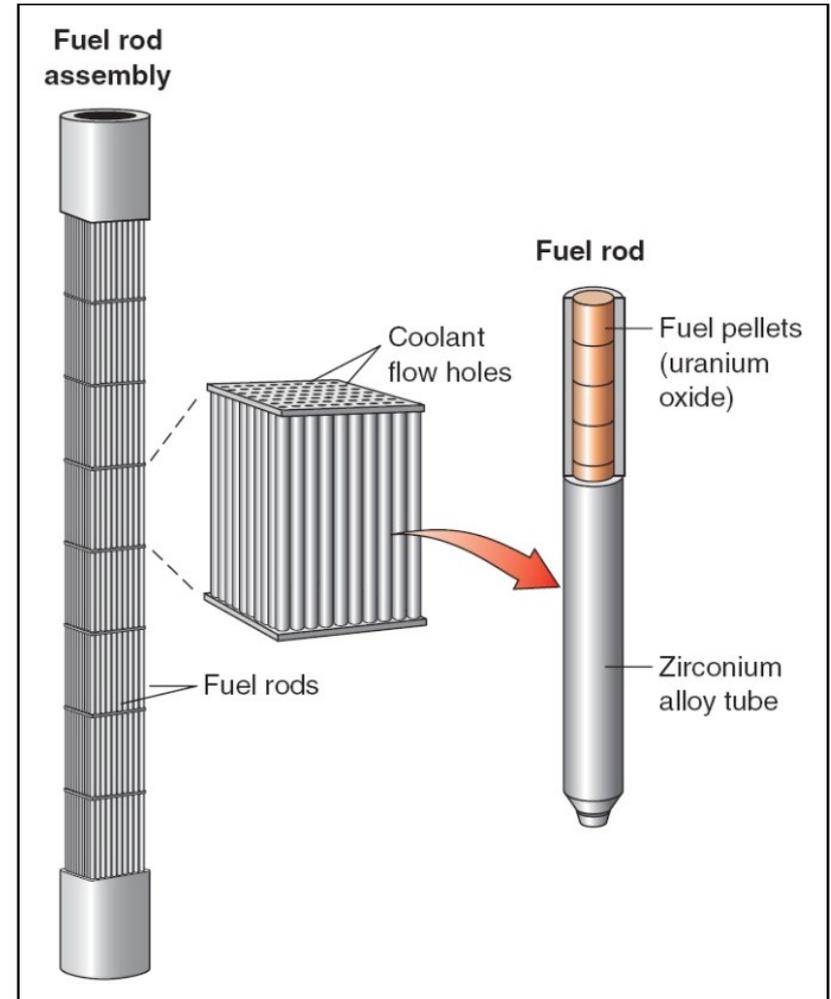
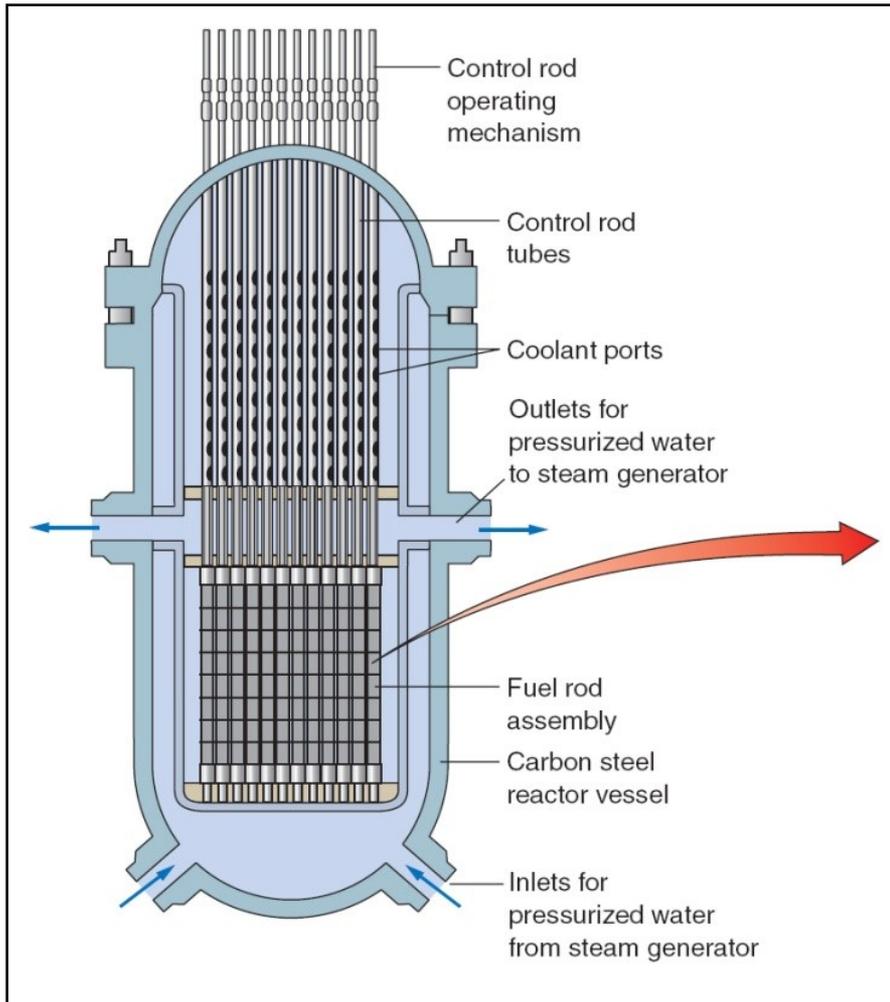
- In order to create a fission bomb (“atomic bomb”), a supercritical mass of fissionable material must be formed and held together.
- Subcritical portions of the fissionable material are held apart until detonation.
- A conventional explosion brings the subcritical segments together to create a supercritical mass capable of a explosive release of energy.
 - This energy sudden energy release is due to an expanding chain reaction of the fissionable material.

Nuclear Reactors



- Nuclear reactors must have a controlled and continual release of fission energy.
- Within the reactor core, long fuel rods and control rods are placed.
- The fuel rods contain the fissionable material.
 - This is the heat source.
- The control rods contain neutron-absorbing material, such as B or Cd.
 - These rods “control” the rate of nuclear fission and thereby the amount of heat produced.

Nuclear Reactor Vessel

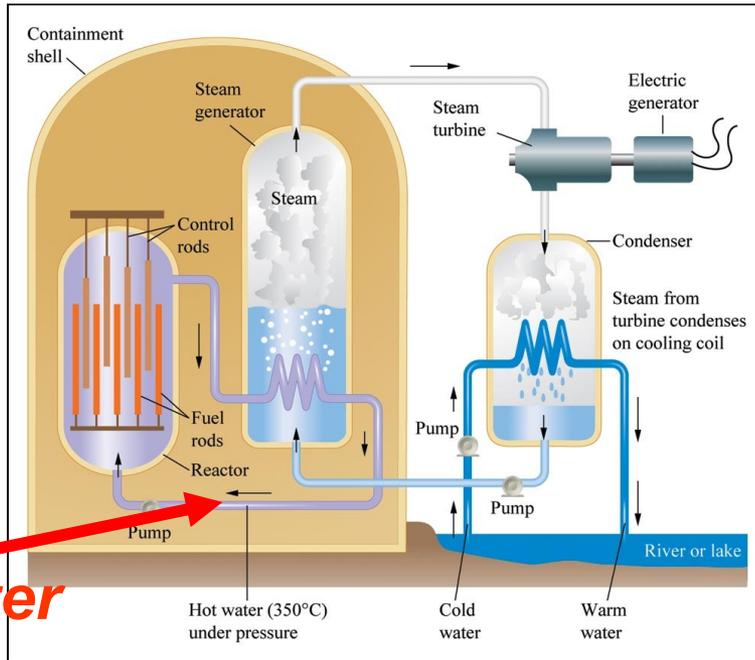


Nuclear Reactors



- Since the fission rate in the fuel rods cannot be directly controlled ...
- The control rods are inserted or withdrawn from between the fuel rods to control the number of neutrons being absorbed
- The reactor core is basically a heat source
 - The heat is continually removed by the coolant (H_2O) flowing through the core
- This heat is used to generate steam in the steam generator
 - The steam turns a generator – producing electricity

Nuclear Reactor



Hot water circuit

Note that the hot water circuit is completely “contained,” thereby allowing no radioactive contamination.

Nuclear Reactors – Coolant



- The reactor's coolant (H_2O) performs two critical functions:
- 1) The coolant transfers the heat from the reactor core to the steam generator.
- 2) The coolant serves as a moderator.
 - The neutrons that are initially emitted from the fuel rods are moving too fast to cause ^{235}U fission efficiently.
 - After colliding with several H_2O molecules the neutrons have slowed enough to induce ^{235}U fission more efficiently.

Nuclear Reactors – Potential Dangers



- Potential dangers exist with a continuous-fission chain reaction.
- The amount of heat generated must be controlled.
 - The fission rate is controlled through the insertion (slow down) or withdrawal (speed up) of the control rods between the fuel rods.
- The heat generated must be continually removed from the core.
 - The heat is removed by the circulation of the coolant.

Nuclear Reactors – Potential Dangers



- Improper control or removal of core generated heat can result in the fusing or “meltdown” of the fuel rods.
- The uncontrolled fissioning mass will become extremely hot and will literally melt through the floor of the containment structure.
 - At this point, the extremely hot and uncontrollable radioactive material will enter the outside environment (ground, water, atmosphere.)

Nuclear Accidents



- Two major nuclear accidents have occurred:
 - Three Mile Island (TMI) Pennsylvania in 1979
 - Chernobyl, Ukraine in 1986
- At TMI, an accidental shutdown of the coolant led to a partial meltdown.
 - This resulted in very little escape of radioactive gases.
- At Chernobyl, a complete meltdown occurred due to poor human judgment and design problems.
 - This resulted in an explosion & fire in the reactor core and significant regional contamination.

Breeder Reactor



- Besides ^{235}U , another fissionable nuclide is ^{239}Pu .
- ^{239}Pu is produced by the bombardment of ^{238}U (the non-fissionable U) with “fast” neutrons during the normal operation of a nuclear reactor.
- In a breeder reactor the production of ^{239}Pu is promoted.
- The ^{239}Pu is later separated and may be used in an ordinary nuclear reactor or in weapons.

Breeder Reactor

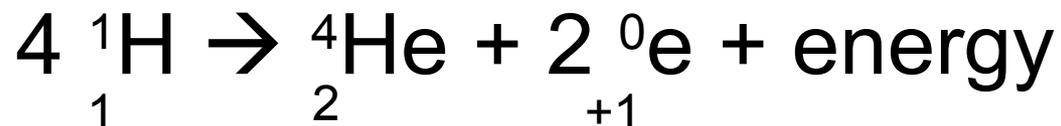


- Therefore ^{239}Pu is a natural by-product of a nuclear reactor.
- 20 breeder reactors running for a full year produce enough ^{239}Pu to run another reactor for a full year.
- Breeder reactors run at a higher temperature than conventional reactors and use liquid sodium as a coolant.

Nuclear Fusion



- Fusion – the process in which smaller nuclei combine to form larger nuclei
 - Along with the release of energy
 - Does not require a critical mass
- Fusion is the source of energy for the Sun and other stars.
- In the Sun, the fusion process produces a helium nucleus from four protons (hydrogen nuclei.)



[Audio Link](#)

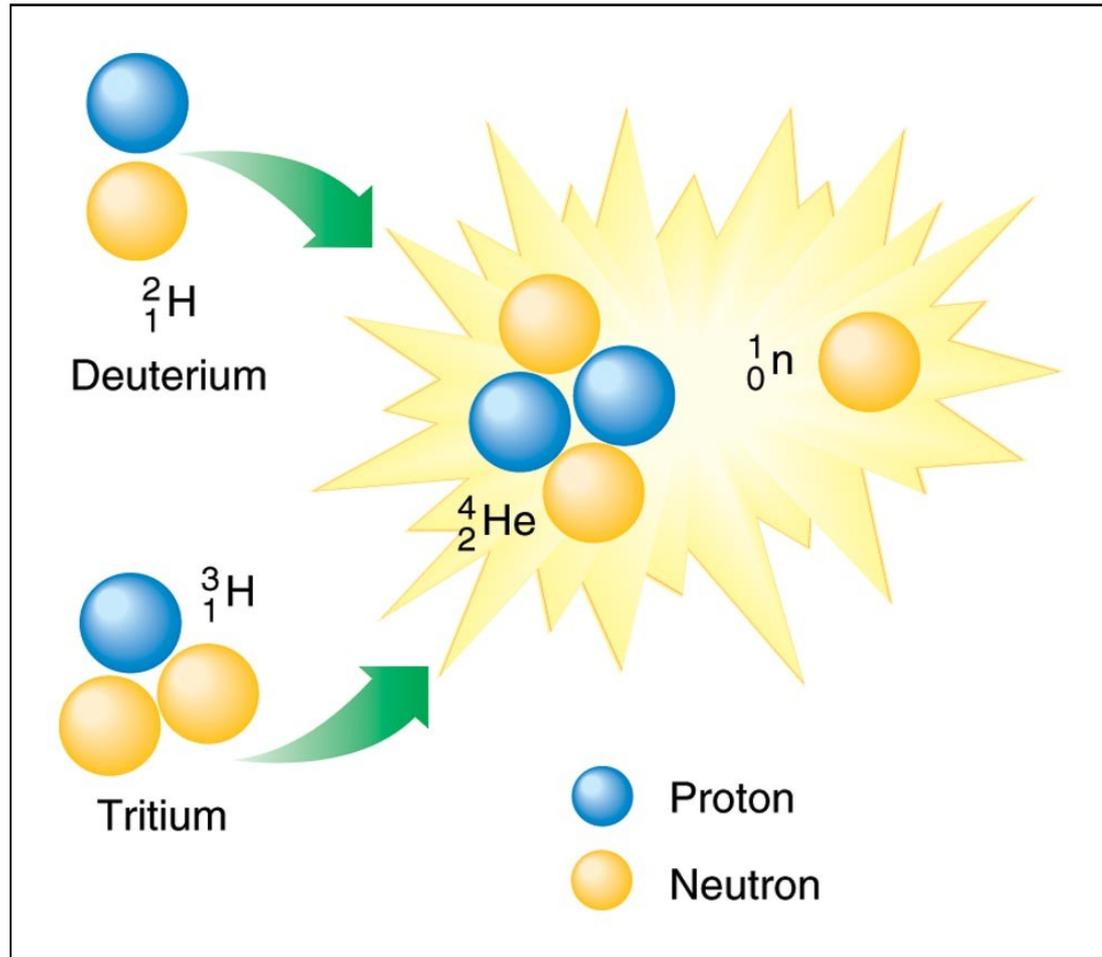
Examples of Fusion Reactions



- ${}^2_1\text{H} + {}^2_1\text{H} \rightarrow {}^3_1\text{H} + {}^1_1\text{H}$
- Two deuterons fuse to form a triton and a proton.
 - Termed a D-D (deuteron-deuteron) reaction

- ${}^2_1\text{H} + {}^3_1\text{H} \rightarrow {}^4_2\text{He} + {}^1_0\text{n}$
- One deuteron and a tritium form an alpha particle and a neutron.
 - Termed a D-T (deuteron-tritium) reaction

D-T Fusion Reaction



Nuclear Fusion – Technical Hurdles



- The repulsive force between two positively charged nuclei is very great.
- To overcome these strong repulsive forces and initiate fusion, the particles must be heated to extreme temperatures (100 million K.)
- At these extreme temperatures the H atoms exist as a plasma .
 - A plasma is gas of electrons and nucleons.

Nuclear Fusion – Technical Hurdles



- The plasma must also be confined at a high enough density for protons to frequently collide.
- Even with today's technology, it is a significant challenge to reach the necessary temperature and confinement requirements.

Nuclear Fusion - Inertial Confinement



- Inertial Confinement – simultaneous high-energy laser pulses from all sides cause a fuel pellet of D & T to implode, resulting in compression and high temperatures
- If the pellet can be made to stay intact for a sufficient time, fusion is initiated.
- Research into this method is being conducted at Los Alamos and Lawrence Livermore labs.

Nuclear Fusion – Magnetic Confinement



- Magnetic Confinement – a doughnut-shaped magnetic field holds the plasma, while electric currents raise the temperature of the plasma
- Magnetic and electric fields are useful since a plasma gas is a gas of charged particles.
 - Charged particles can be controlled and manipulated with electric and magnetic fields.
- The leading labs for fusion research using magnetic confinement are MIT and Princeton.

Fusion Advantages over Fission



- Low cost and abundance of deuterium
 - Deuterium can be extracted inexpensively from water.
- Dramatically reduced nuclear waste disposal
 - Relatively few radioactive by-products with relatively short half-lives
- Fusion reactors cannot get out of control
 - In the event of a system failure, quick cool down
 - Not dependent on a critical mass

Nuclear Reaction and Energy



- In 1905 Einstein published his special theory of relativity.
- This work deals with the changes that occur in mass, length, and time as an object's speed approaches the speed of light (c).
- This theory predicts the mass (m) and energy (E) are not separate entities but rather related by his famous equation $E = mc^2$.

Nuclear Reaction and Energy



- Einstein's predictions have proved correct.
- Scientists have been able to change mass into energy and on a very small scale, energy into mass.
- For example, using Einstein's equation what is the equivalent energy of 1 gram mass?
- $E = mc^2 = (0.001 \text{ kg})(3.00 \times 10^8 \text{ m/s}^2)$
- $= 90 \times 10^{12} \text{ J} = \underline{90 \text{ trillion joules}}$
- 90 trillion joules = same amount of energy released by 20,000 tons of TNT

Nuclear Reaction and Energy



- Calculations with Einstein's formula, $E=mc^2$, have convinced many scientists that small amounts of mass that are "lost" in nuclear reactions could be a tremendous source of energy.
- To determine the change in mass in a nuclear reaction, we simply add up the masses of all the reactants and subtract the masses of all the products.
- Generally during a nuclear reaction mass is either gained or lost.

Mass Defect

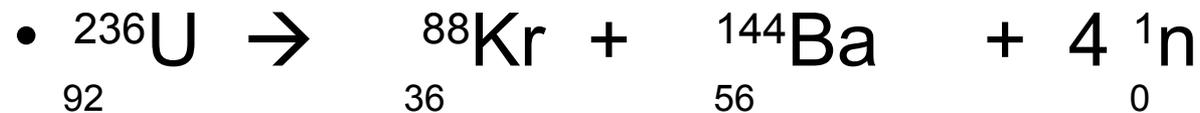


- MeV = Mega electron volts = 1.60×10^{-13} J
- Endoergic – an increase in mass has taken place during the reaction
 - Absorbs energy by the number of atomic mass units times 931 MeV/u
- Exoergic – a decrease in mass has taken place during the reaction
 - Releases energy by the number of atomic mass units times 931 MeV/u

Calculating Mass and Energy Changes in Nuclear Reactions – *An Example*



- *Calculate the mass defect and the corresponding energy released during this typical fission reaction (using the masses of the atoms.)*

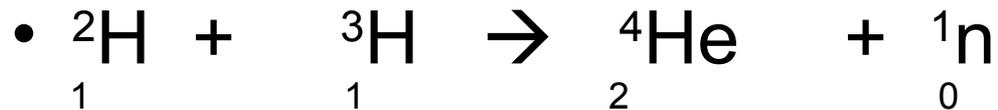


- $(236.04556 \text{ u}) \rightarrow (87.91445 \text{ u}) + (143.92284 \text{ u}) + (4 \times 1.00867 \text{ u})$
- Total mass on left side = 236.04556 u
- Total mass on right side = 235.87197 u
- Difference of 0.17359 u = mass defect
- $(0.17359 \text{ u})(931 \text{ MeV/u}) = 162 \text{ MeV}$ of energy released

Calculating Mass and Energy Changes in D-T Fusion Reaction – *Confidence Exercise*



- *Calculate the mass defect and the corresponding energy released during a D-T fusion reaction.*



- $(2.0140 \text{ u}) + (3.0161 \text{ u}) \rightarrow (4.0026 \text{ u}) + (1.0087 \text{ u})$
- Total mass on left side = 5.0301 u
- Total mass on right side = 5.0113 u
- Difference of 0.0188 u = mass defect
- $(0.0188 \text{ u})(931 \text{ MeV/u}) = 17.5 \text{ MeV}$ of energy released

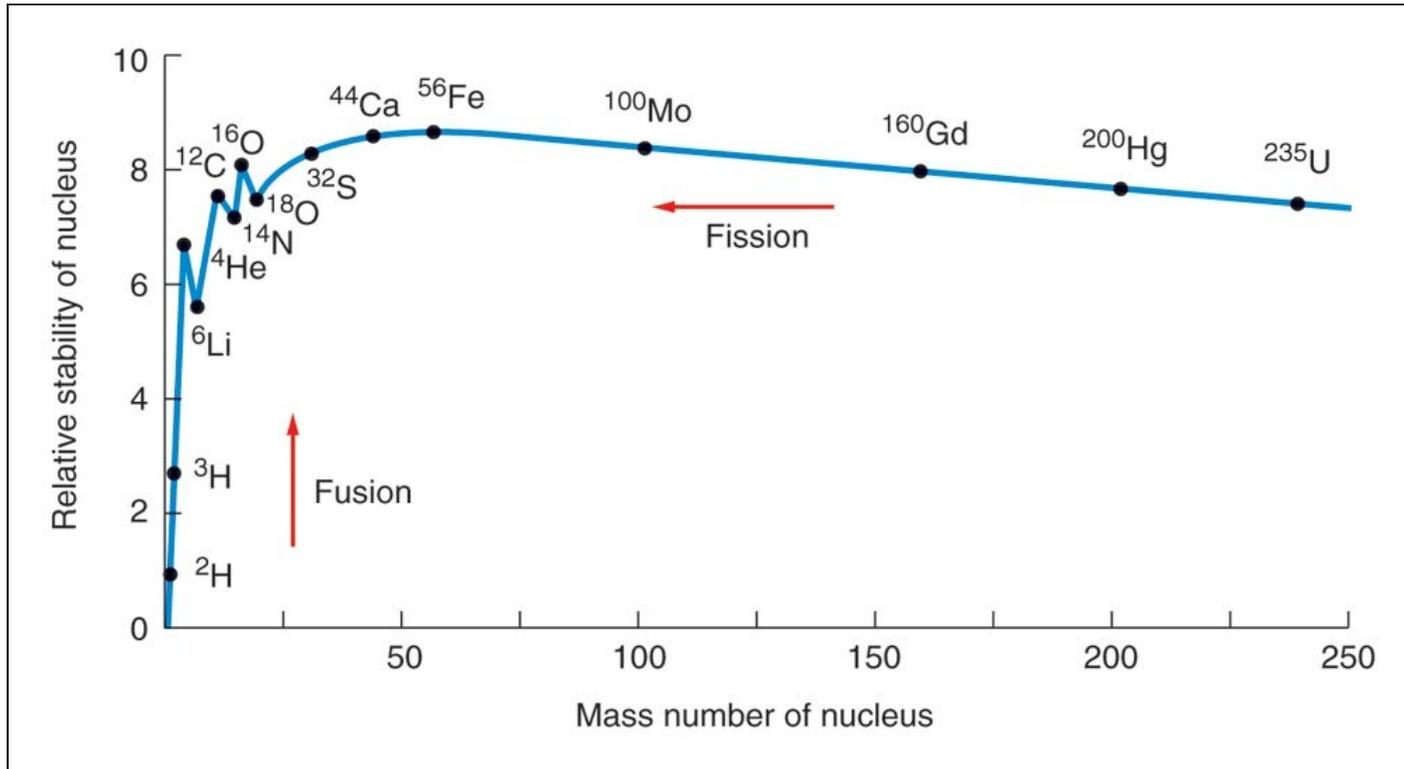
Fusion vs. Fission



- On a kilogram for kilogram comparison, more energy comes from fusion than from fission.
- The fission of 1 kg of ^{235}U provides energy equal to the burning of 2 million kg of coal.
- The fusion of 1 kg of deuterium releases energy equal to the burning of 40 million kg of coal.

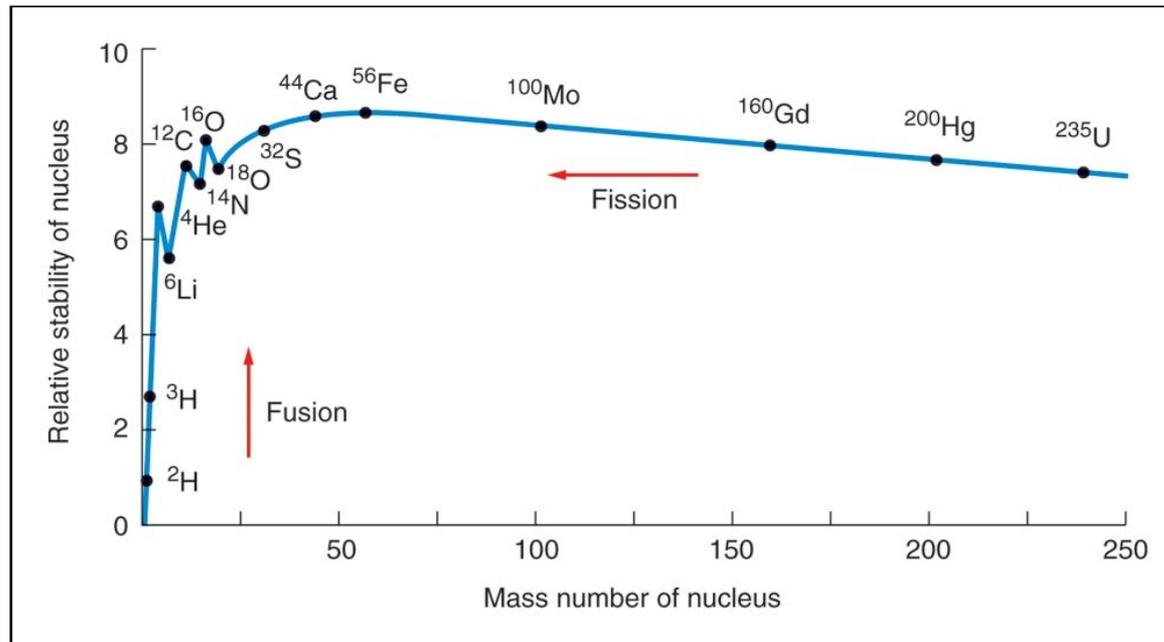
[Audio Link](#)

Energy Release in Both Nuclear Fission and Fusion



Any reaction that leads upward on the curve releases energy because such a reaction is accompanied by a mass defect.

Energy Release in Both Nuclear Fission and Fusion (*cont.*)



- Fission proceeds from right to left.
- Fusion proceeds from left to right.
- *Note that at the top of the curve is ^{56}Fe . No net energy will be released by either splitting ^{56}Fe or by fusing several ^{56}Fe .*

Biological Effects of Radiation



- Ionizing Radiation – radiation that is strong enough to knock electrons off atoms and form ions
- Ionizing Radiation includes; alpha particles, beta particles, gamma particles, neutrons, gamma rays, and X-rays
- These types of radiation can also harm or kill living cells, and are especially harmful if they affect molecules involved in cell reproduction

Effects of Radiation on Living Organisms



- Ionizing radiation cannot be seen, smelled, felt, or tasted
- Film badges worn by workers is commonly used to measure radiation exposure
- The effects of radiation on living organisms can be classified into two categories:
- Somatic Effects – short- and long-term effects on the recipient of the radiation
- Genetic Effects – defects in the recipient's subsequent offspring

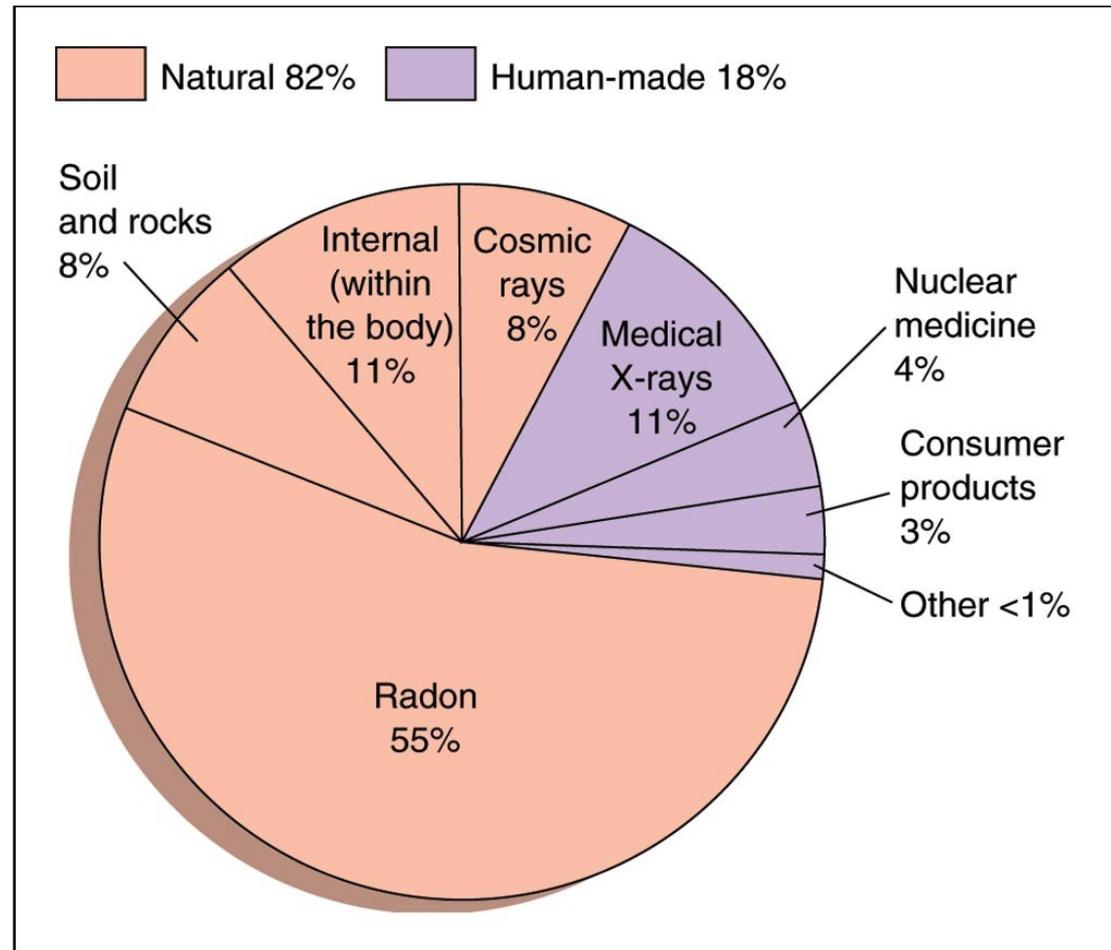
Radiation Units



- The *rem* (roentgen equivalent for man) is the unit used to discuss biological effects of radiation
- This unit takes into consideration the relative ionizing power of each type of radiation and its affects on humans
- The average U.S. citizens receives 0.2 rem per year, from a number of different sources (both natural and anthropogenic)

Sources of Exposure to Radiation

- 0.2 rem – average annual radiation exposure for person in U.S.



Radiation Sources



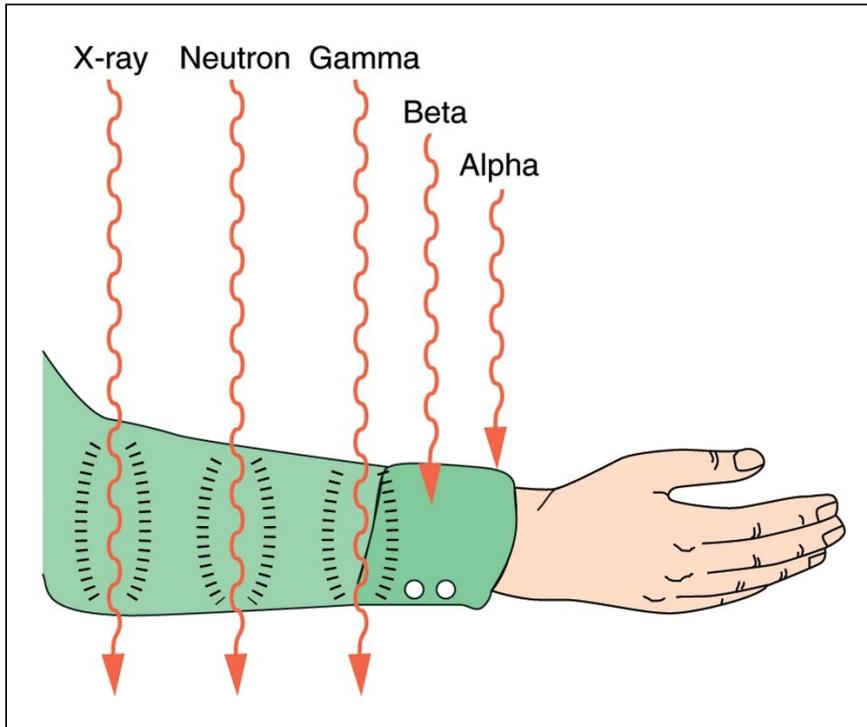
- Natural Sources – cosmic radiation (high altitude areas), bedrock, radionuclides that are ingested (carbon-14, potassium-40)
 - Radon gas, from bedrock, varies greatly with location, but is thought to cause from 10,000 to 130,000 lung cancers deaths per year in the U.S.
- Anthropogenic Sources – medical X-rays and treatment, TV's, tobacco smoke, nuclear waste, certain household products

Long-Term Somatic Effects



- Long-term cumulative effects of radiation exposure are not fully understood
- Without a doubt the most common long-term somatic effect is an increased likelihood of developing cancer
- Many early workers of radionuclides died of cancer – these scientists were generally exposed to small doses for many years

Penetration of Radiation



- But – there does not appear to be any lower limit, below which the effects are negligible
- \therefore any exposure to radiation should be taken seriously.

- Alpha and Beta particles are electrically charged and can be easily stopped. Gamma rays, X-rays, and neutrons are more difficult to stop because they are not charged particles.

Elementary Particles



- 4 fundamental building blocks: electron, proton, neutron, photon
- More than 200 elementary particles – mostly from within the nucleus
- Example: exchange particles responsible for the 4 fundamental forces: gravity, Electromagnetic, strong nuclear, weak nuclear

Particle Accelerators

- Study elementary particles
- LHC – Large Hadron Collider – near Geneva



Antimatter



- Every particle has its antiparticle
- The antiparticle for the electron is the positron
 $+e$
- When particles and antiparticles mix they annihilate each other and release energy.

Chapter 10 - Important Equations



- $N = A - Z$ Neutron Number = Mass Number – Atomic Number
- $E = mc^2$ Mass Energy