SAND2007-3542P

Fundamental Principles of Radioactivity and Ionizing Radiation

KHNP Training Program

Module 1: Fundamental Principles of Radioactivity and Ionizing Radiation

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SAND 2007-P

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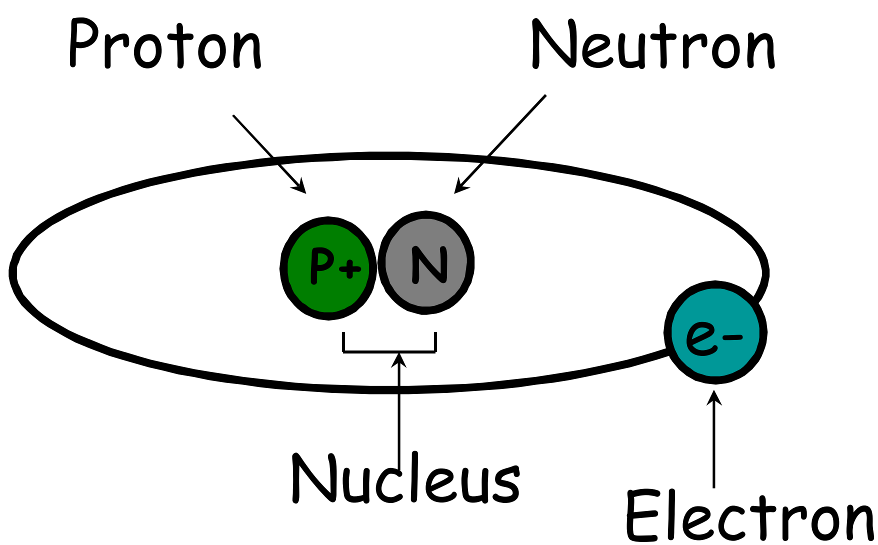
Atomic Structure Particles

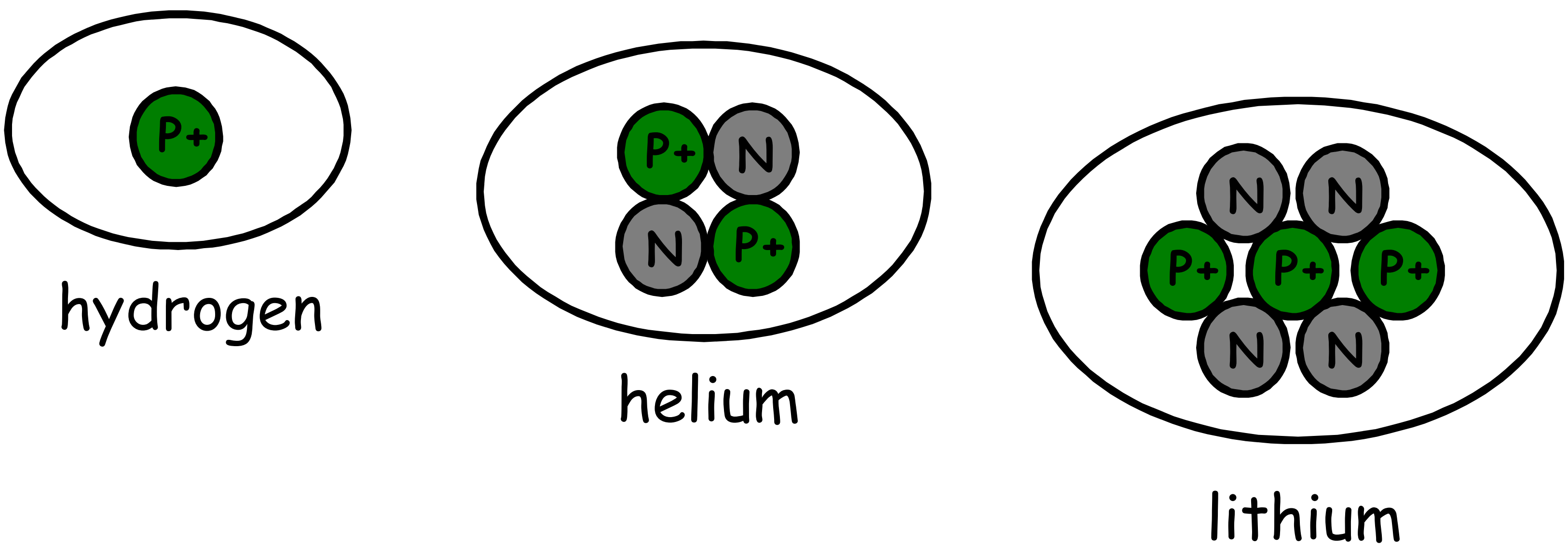
Protons (positive)
Neutrons (neutral)
Electrons (negative)

Nucleus



Elements

- **The number of protons in the nucleus determines the element**
- **If the number of protons changes, the element changes**



Periodic Table of the Elements

Transition Metals

I	II	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	III	IV	V	VI	VII	0
H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	57-71	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	89-103	Rf 104	Ha 105	106	107	108	109									

Lanthanides	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
Actinides	Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

Metal

Metalloid

Nonmetal

Some Nuclear Reactions

Reaction	Measured Q (MeV)	Reaction	Measured Q (MeV)
$^{2}H(n,\gamma)^{3}H$	6.257 +/- 0.004	$^{9}Be(p,\alpha)^{6}Li$	2.132 +/- 0.006
$^{2}H(d,p)^{3}H$	4.032 +/- 0.004	$^{10}B(n,\alpha)^{7}Li$	2.793 +/- 0.003
$^{6}Li(p,\alpha)^{3}H$	4.016 +/- 0.005	$^{10}B(p,\alpha)^{7}Be$	1.148 +/- 0.003
$^{6}Li(d,p)^{7}Li$	5.020 +/- 0.006	$^{12}C(n,\gamma)^{13}C$	4.948 +/- 0.004
$^{7}Li(p,n)^{7}Be$	-1.645 +/- 0.001	$^{13}C(p,n)^{13}N$	-3.003 +/- 0.002
$^{7}Li(p,\alpha)^{4}He$	17.337 +/- 0.007	* $^{14}N(p,n)^{14}C$	-0.627 +/- 0.001
$^{9}Be(n,\gamma)^{10}Be$	6.810 +/- 0.006	$^{14}N(n,\gamma)^{15}N$	10.833 +/- 0.007
$^{9}Be(\gamma,n)^{8}Be$	-1.666 +/- 0.002	$^{18}O(p,n)^{18}F$	-2.453 +/- 0.002
$^{9}Be(d,p)^{10}Be$	4.585 +/- 0.005	$^{19}F(p,\alpha)^{16}O$	8.124 +/- 0.007

* The nuclear reaction in the atmosphere which produces carbon-14 for radiocarbon dating.

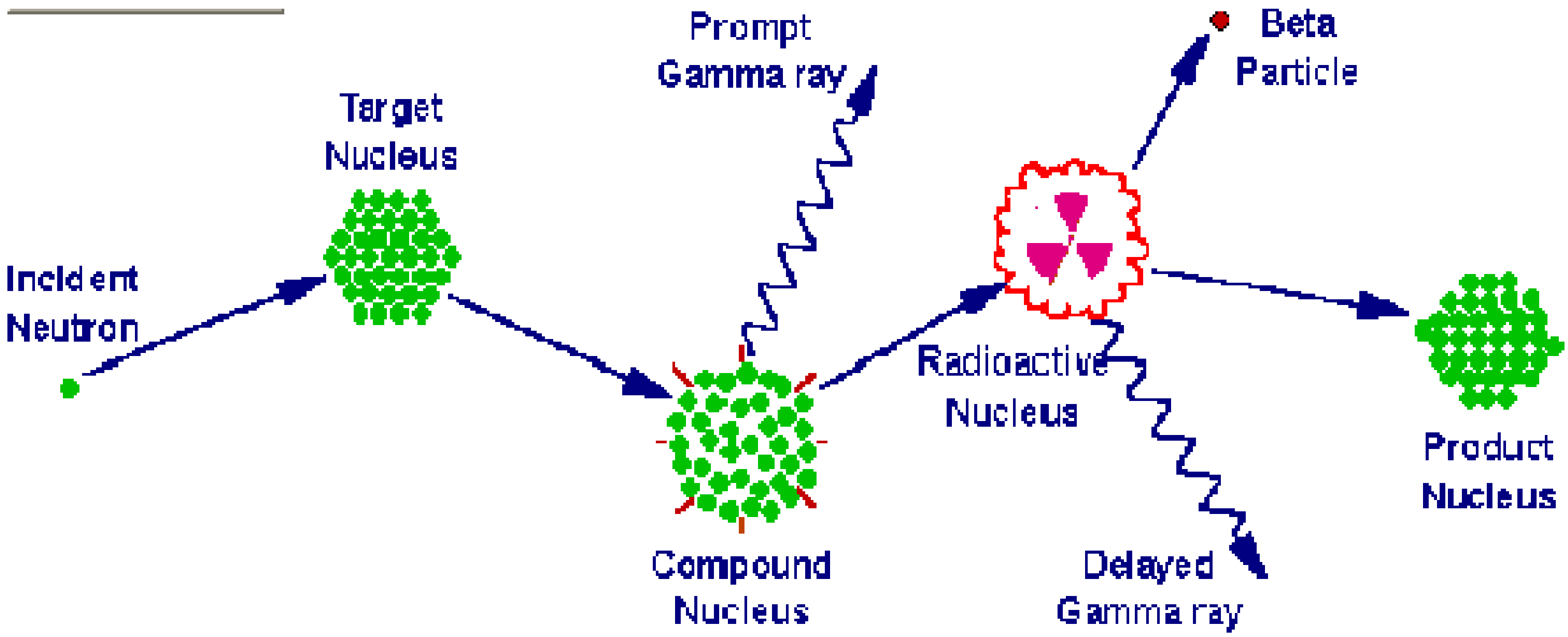
Another way to write a nuclear reaction:

$$_{0}n^{1} \quad + \quad _{2}H^{2} \quad = \quad _{2}H^{3} \quad + \quad \gamma$$

neutron + deuterium   tritium + gamma

$$Ni^{58} + n^{1} = Co^{58m} + H^{1} = Co^{58} + \gamma$$

Neutron activation reaction

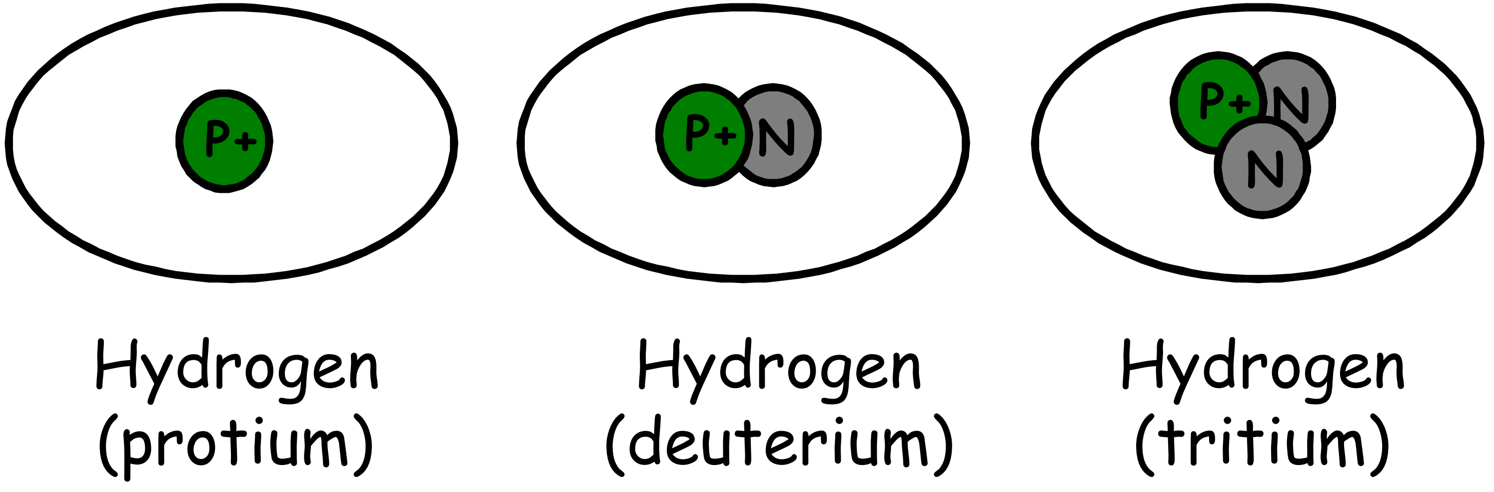


NEUTRON ACTIVATION

Isotopes

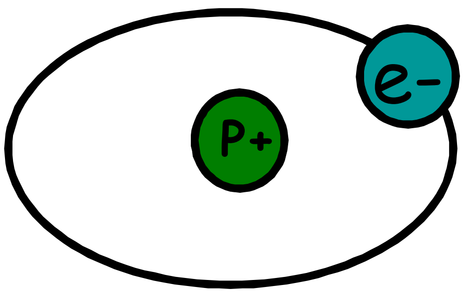
- **Isotopes - atoms of the same element which have the same number of protons, but a different number of neutrons**

- **Isotopes have the same chemical properties; however, the nuclear properties can be quite different**



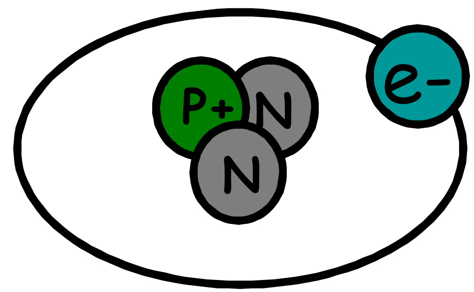
Stable vs. Unstable Atoms

If there are too many or too few neutrons for a given number of protons, the nucleus will not be stable



Hydrogen
(protium)

STABLE
"Non-Radioactive"

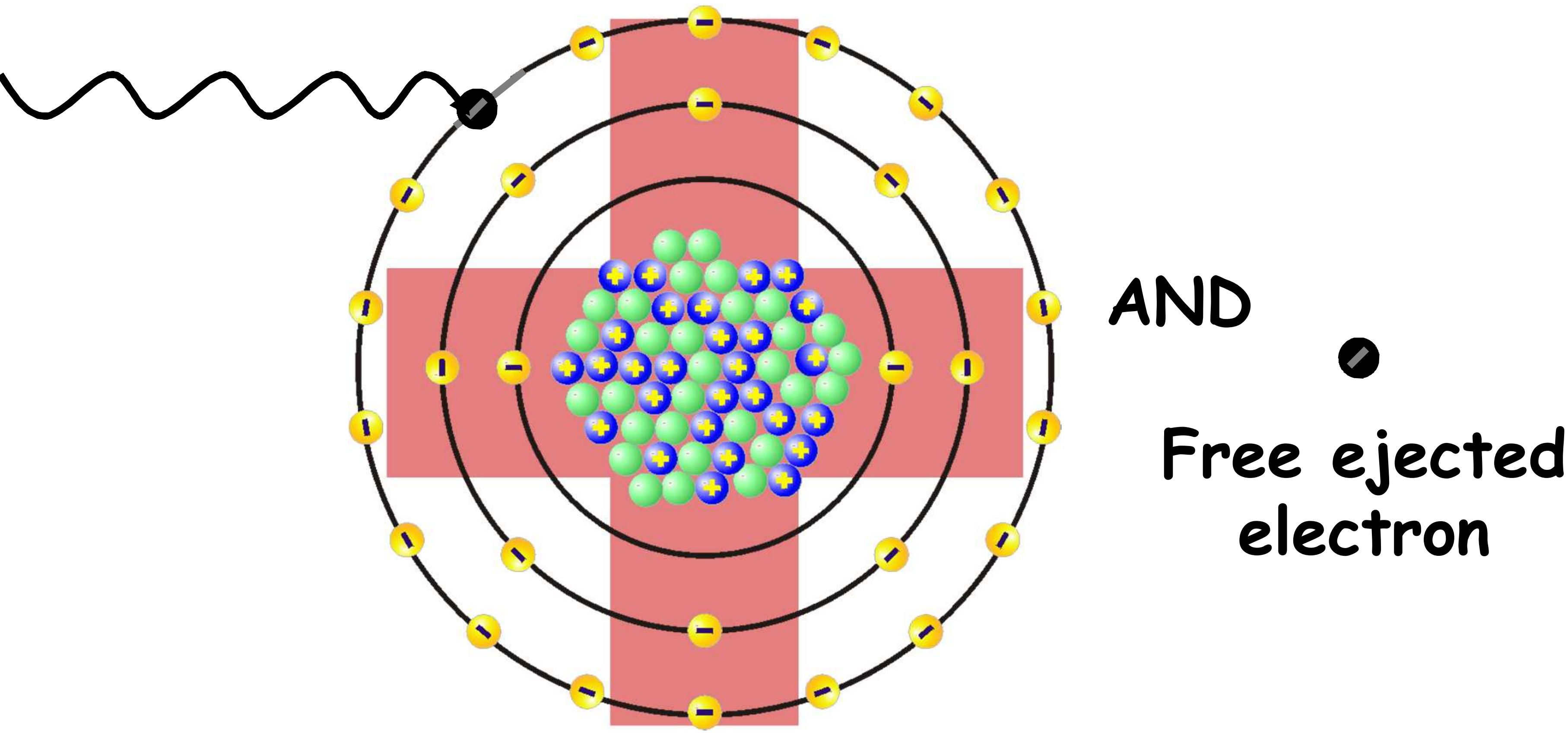


Hydrogen
(tritium)

UNSTABLE
"Radioactive"

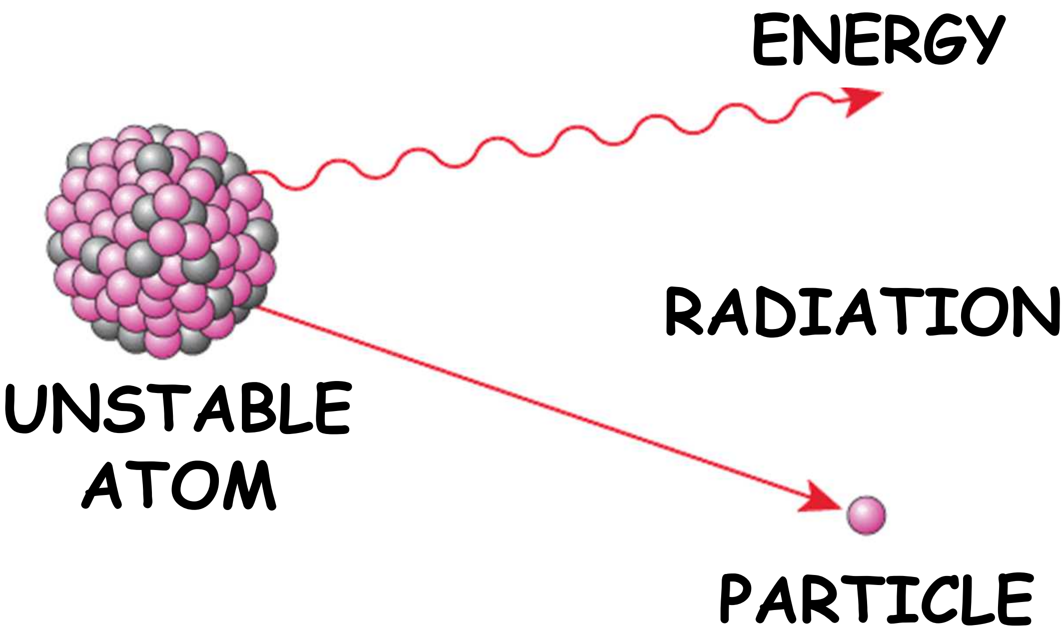
Ionization

The <u>process</u> of removing electrons from neutral atoms

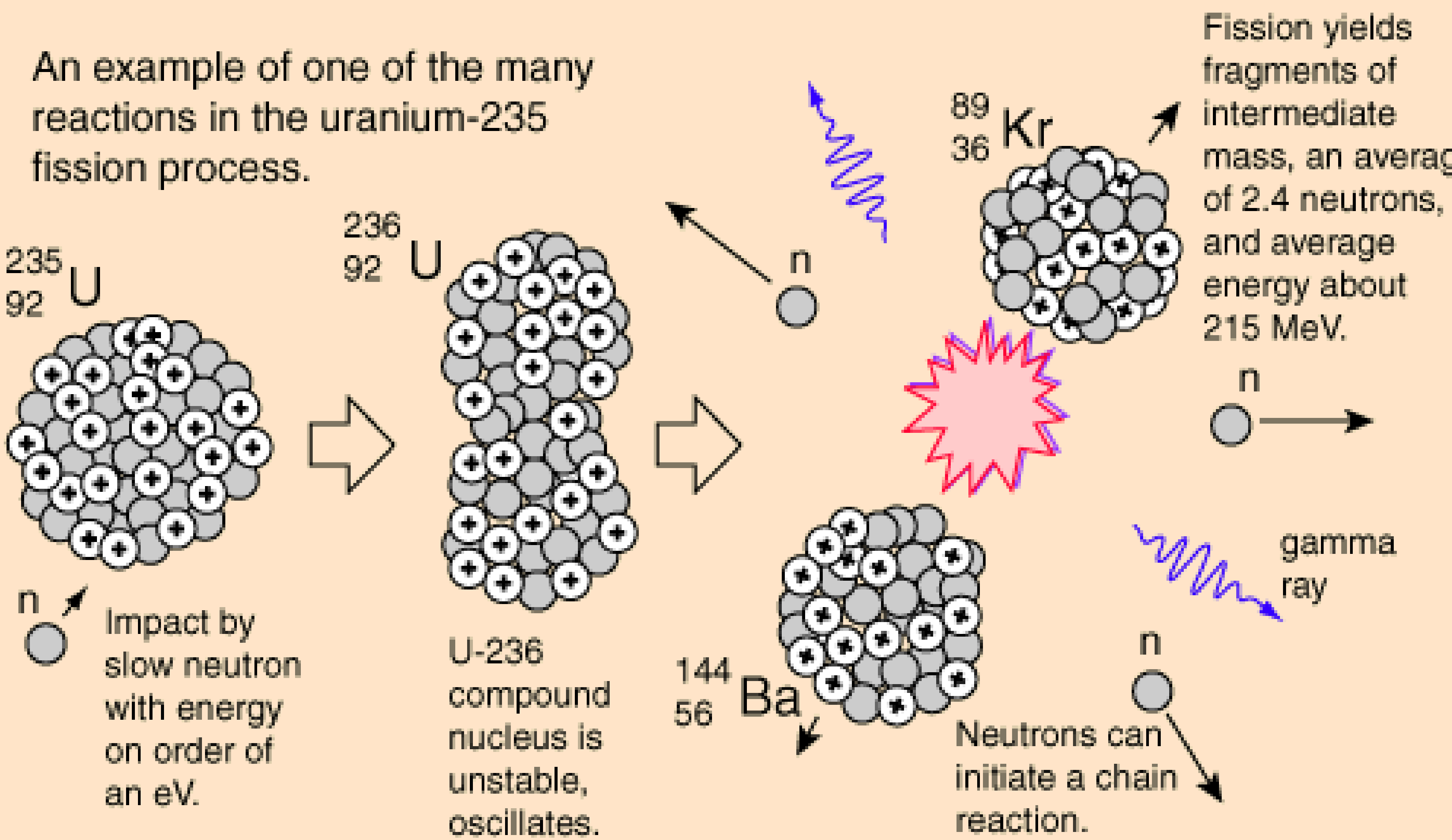


Radiation

- <u>Energy</u> released from unstable atoms and some devices in the form of rays or particles
- Can be either <u>ionizing</u> or <u>non-ionizing</u>



Uranium-235 Fission

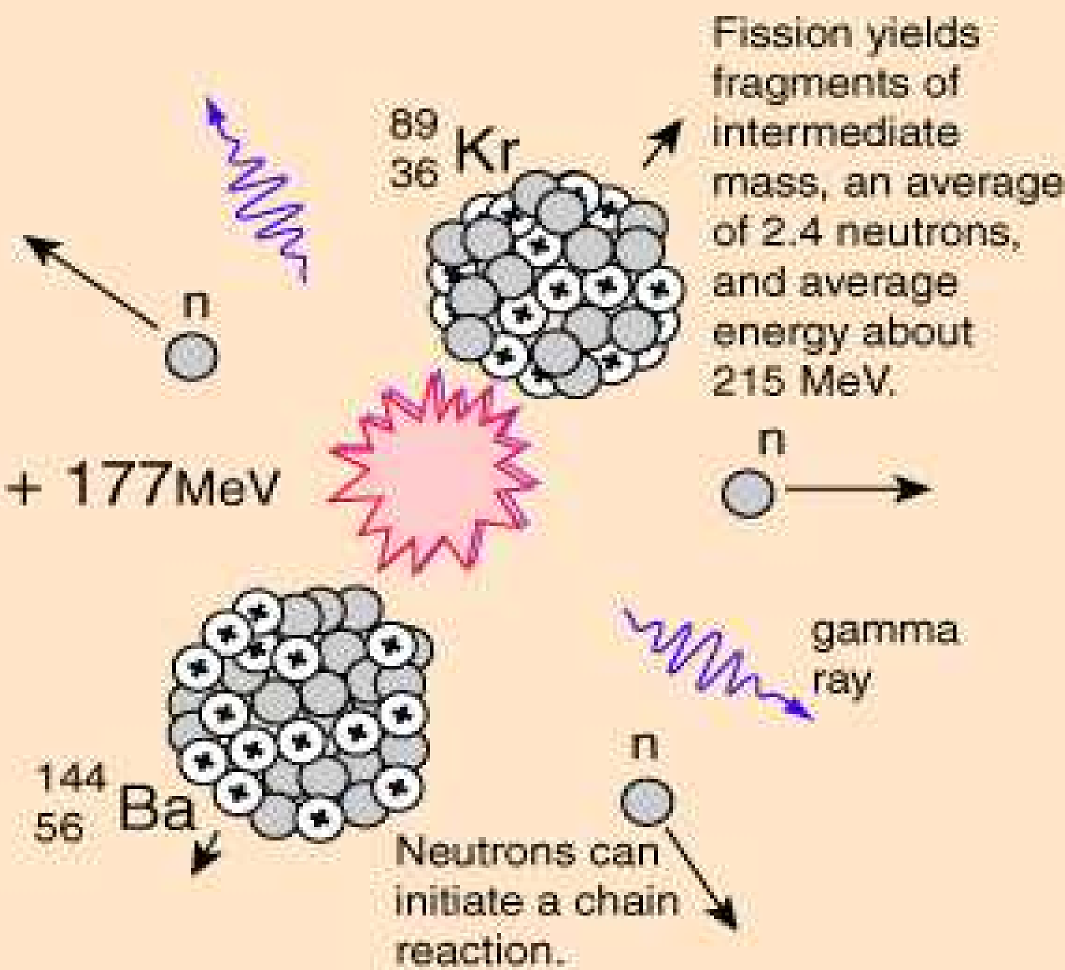


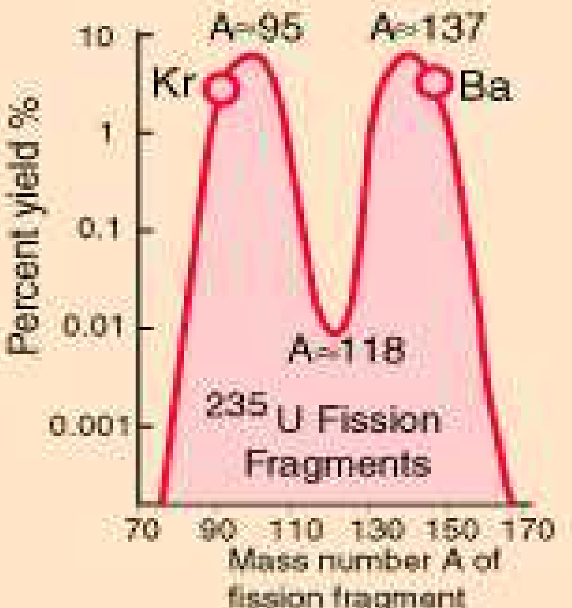
Uranium-235 Fission Example

...one of the many reactions in the uranium-235 fission process.

$$n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U$$

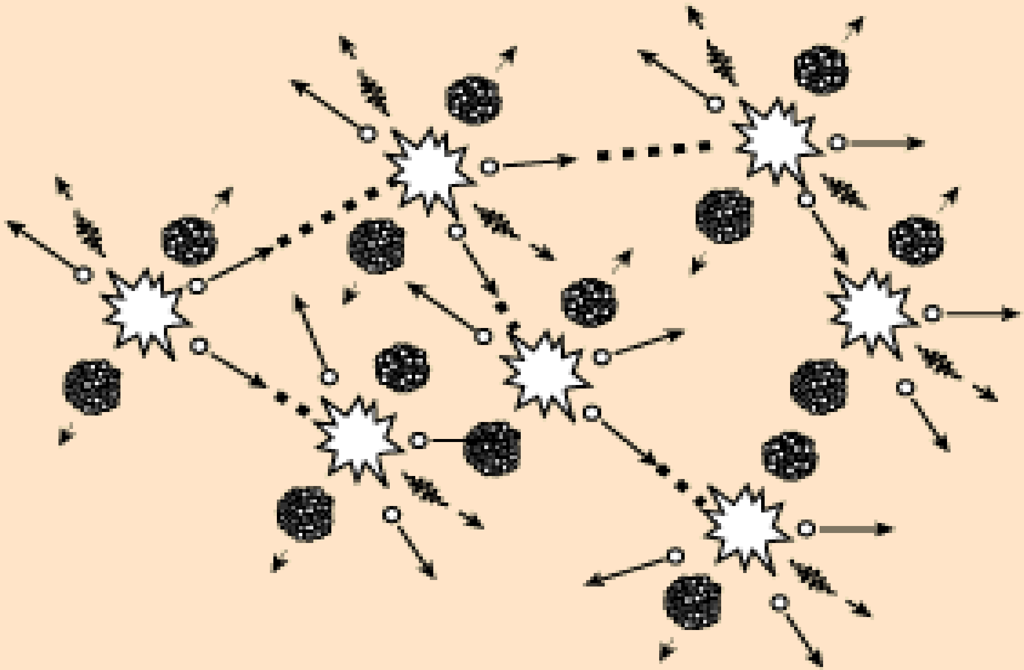
$${}^{236}_{92}U \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3n + 177\,\text{MeV}$$





Uranium-235 Chain Reaction

If an least one neutron from U-235 fission strikes another nucleus and causes it to fission, then the chain reaction will continue. If the reaction will sustain itself, it is said to be "critical", and the mass of U-235 required to produced the critical condition is said to be a "critical mass". A critical chain reaction can be achieved at low concentrations of U-235 if the neutrons from fission are moderated to lower their speed, since the probability for fission with slow neutrons is greater.



A fission chain reaction produces intermediate mass fragments which are highly radioactive and produce further energy by their radioactive decay. Some of them produce neutrons, called delayed neutrons, which contribute to the fission chain reaction.

Ionizing Radiation

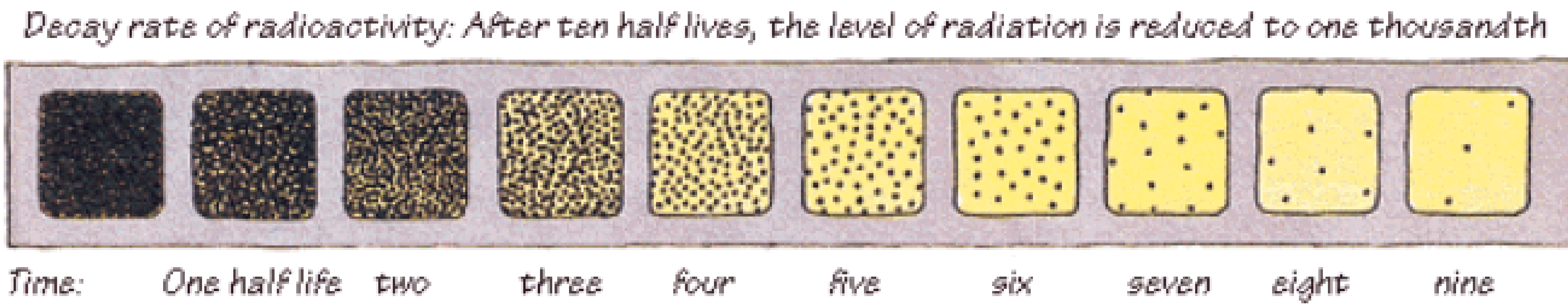
- Radiation that possesses enough energy to cause ionization in the atoms with which it interacts
- Released from unstable atoms and some devices in the form of rays or particles
  - alpha α
  - beta β
  - gamma/x-ray γ
  - neutron ${}_0n^1$

URANIUM 238 (U238) RADIOACTIVE DECAY

type of radiation	nuclide	half-life
α	uranium-238	4.47 billion years
β	thorium-234	24.1 days
β	protactinium-234m	1.17 minutes
α	uranium-234	245000 years
α	thorium-230	8000 years
α	radium-226	1600 years
α	radon-222	3.823 days
α	polonium-218	3.05 minutes
β	lead-214	26.8 minutes
β	bismuth-214	19.7 minutes
α	polonium-214	0.000164 seconds
β	lead-210	22.3 years
β	bismuth-210	5.01 days
α	polonium-210	138.4 days
	lead-206	stable

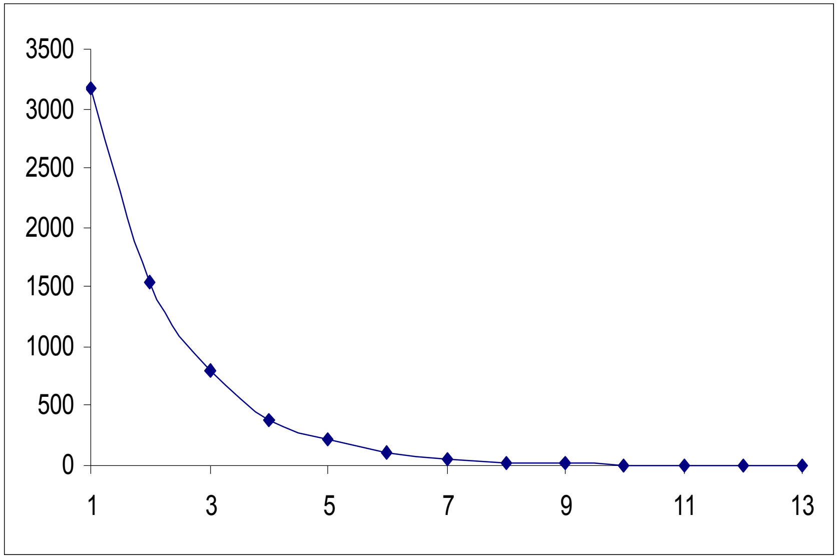
Radioactive Half-Life

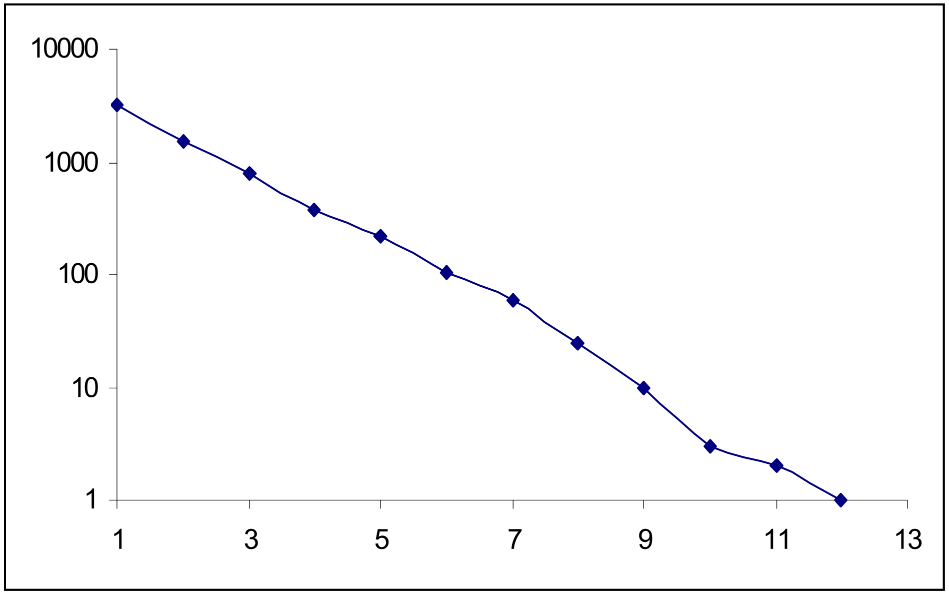
The time it takes for one half of the radioactive atoms present to decay



$$N = N_0 e^{-\lambda t}$$

$$\lambda = \ln 2 / t_{1/2}$$





Derivation of the Radioactive Decay Law

- Define

$$\text{Activity} \equiv \text{Rate of Decay} = A$$

$$A \equiv \frac{dN(t)}{dt} \propto N(t)$$

Where N(t) is the number of *radioactive* nuclei present at time t

$$\lambda = \text{Radioactiv e Decay Constant}$$

$$A \equiv \frac{dN(t)}{dt} \propto N(t) = -\lambda N(t)$$

- Why do we have a minus sign in the formula?

Activity (Continued)

$$A \equiv \frac{dN(t)}{dt} \propto N(t) = -\lambda N(t)$$

$$A \equiv \frac{dN(t)}{dt} = -\lambda N(t)$$

$$\frac{dN(t)}{N(t)} = -\lambda dt \Rightarrow \frac{dN}{N} = -\lambda dt \Rightarrow \int_{N_o}^{N(t)} \frac{dN}{N} = -\lambda \int_0^t dt$$

$$\ln \frac{N(t)}{N_o} = -\lambda t \Rightarrow \frac{N(t)}{N_o} = e^{-\lambda t} \Rightarrow \boxed{N(t) = N_o\, e^{-\lambda t}}$$

Relationship Between Activity and Mass

$$A = \frac{(\ln 2)(6.02\ \mathrm{x}\ 10^{23})\left(\dfrac{m}{at.wt}\right)}{t_{1/2}}$$

- A = activity in Bq (sec^{-1})
- $t_{1/2}$ = half-life in seconds
- m = mass in grams
- at.wt = gram atomic weight
- 6.20 x 10^{23} is Avogadro's number: the number of atoms in one gram atomic weight

$$A \equiv \frac{dN(t)}{dt} = -\lambda N(t)$$

Units of Activity

- Curie
  - The traditional unit of activity
  - 1 Ci = 3.7×10^{10} disintegrations/second
  - Based on the disintegration rate of 1 gm of Ra-226
- Becquerel
  - SI Unit
  - 1 Bq = 1 dis/sec

Half-life

- Half Life Definition

$$\equiv \text{The average amount of time required for the sample size or activity to decrease to 1/2 of its initial amount.}$$

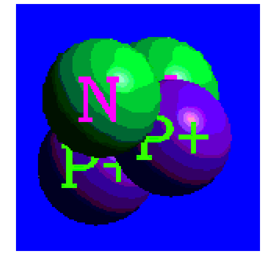
- Derivation => initial conditions: $N(t) = \frac{N_o}{2} : t = t_{½}$

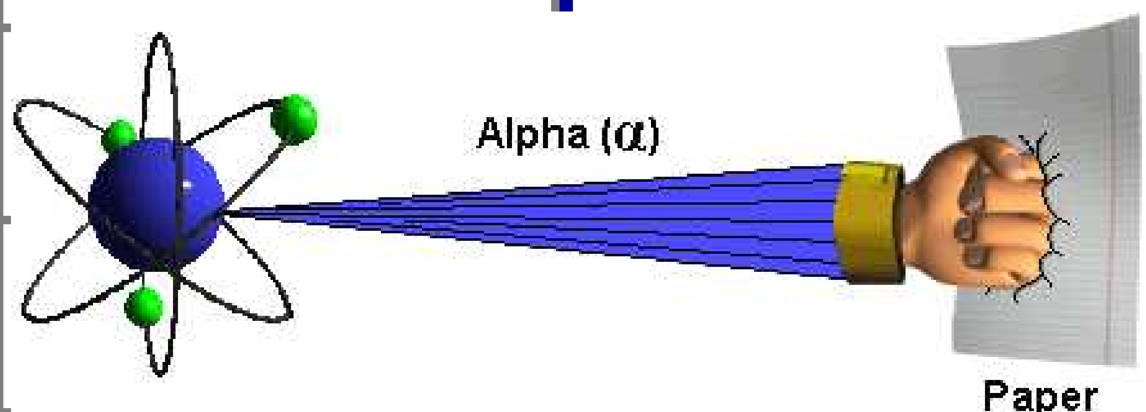
$$\frac{N_o}{2} = N_o e^{-\lambda t_{1/2}} \Rightarrow \frac{1}{2} = e^{-\lambda t_{1/2}} \Rightarrow -\ln(2) = -\lambda t_{1/2}$$

$$\lambda = \frac{\ln(2)}{t_{1/2}} = \frac{0.693}{t_{1/2}} \quad \Rightarrow \quad \boxed{t_{1/2} = \frac{0.693}{\lambda}}$$

Alpha Radiation (α)

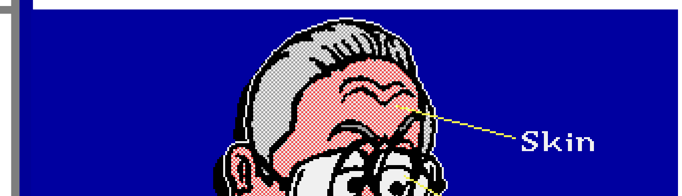
Characteristics	**Particle, Large Mass, +2 Charge**
Range	**Very Short 1 - 2" in air**
Shielding	**Paper Outer layer of skin**
Hazards	
Sources	

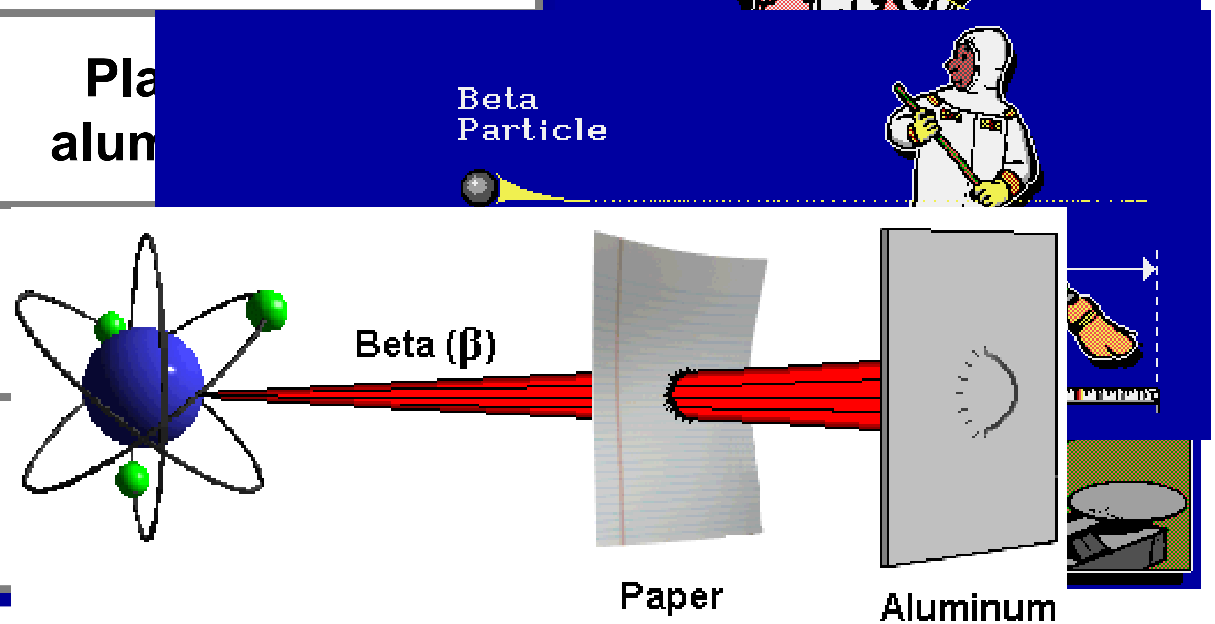




Beta Radiation (β)

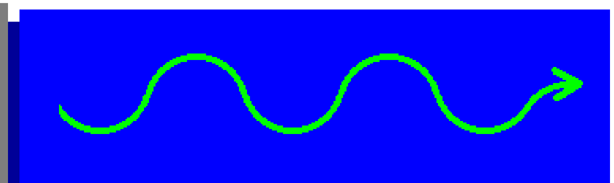
Characteristics	Particle, Small Mass, -1 Charge
Range	12ft / MeV in air
Shielding	Pla alum
Hazards	
Sources	

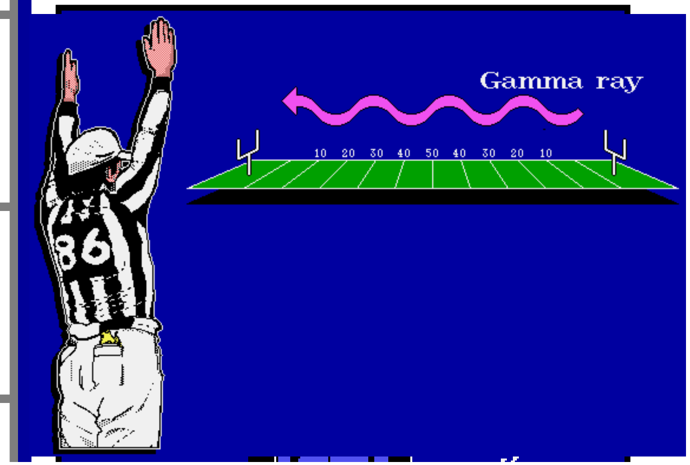


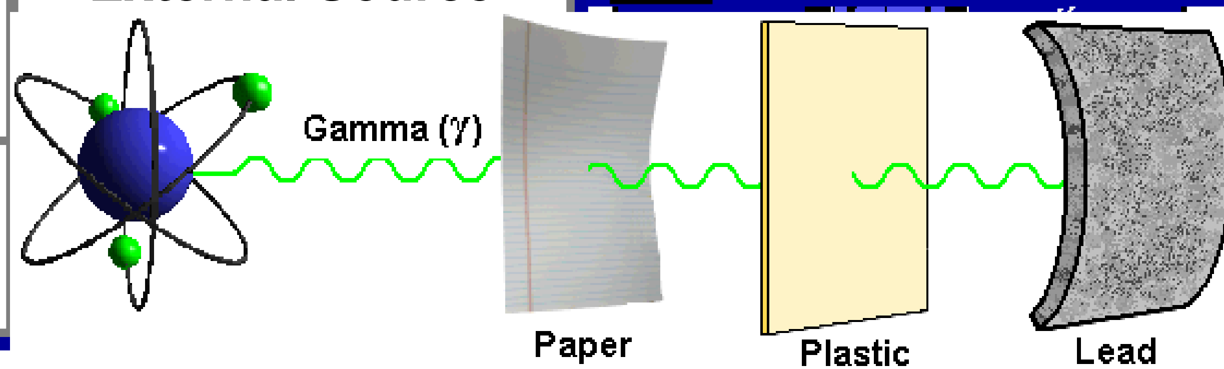


Gamma Rays (γ) and X-Rays

Characteristics	No mass, no charge electromagnetic
Range	Hundreds of feet in air
Shielding	Lead, Steel Concrete
Hazards	External Source
Sources	

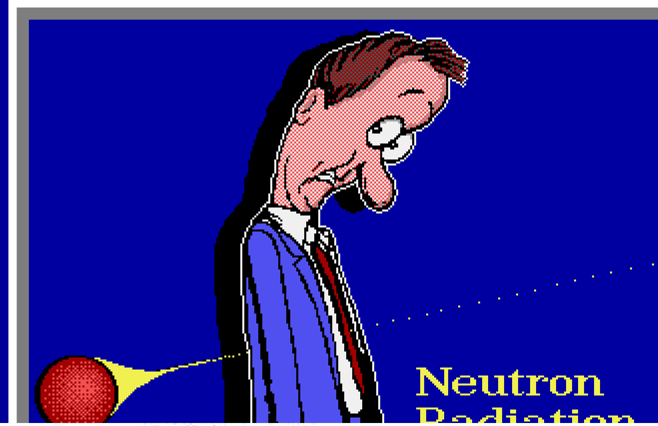


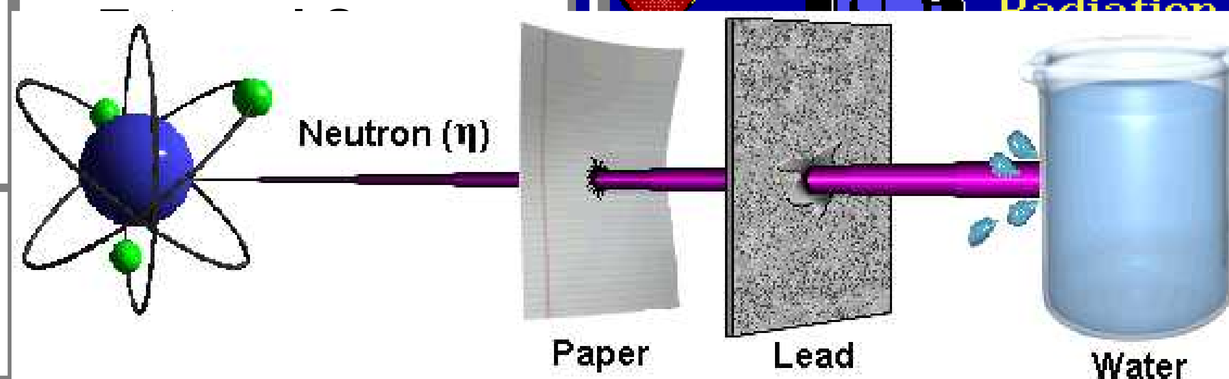




Neutron Radiation (η)

Characteristics	Particle with no charge
Range	Hundreds of feet in air
Shielding	Hydrogenous material - water, polyethylene
Hazards	
Sources	





RAD or GRAY(Gy)

- **Units of absorbed energy in any material**
- **1 Gy = 1 joule/kilogram of absorber**
- **1 rad = 1 erg/gram of absorber**
- **1 Gy = 100 rad**
- **Does not take into account the potential effect that different types of radiation have on the body**

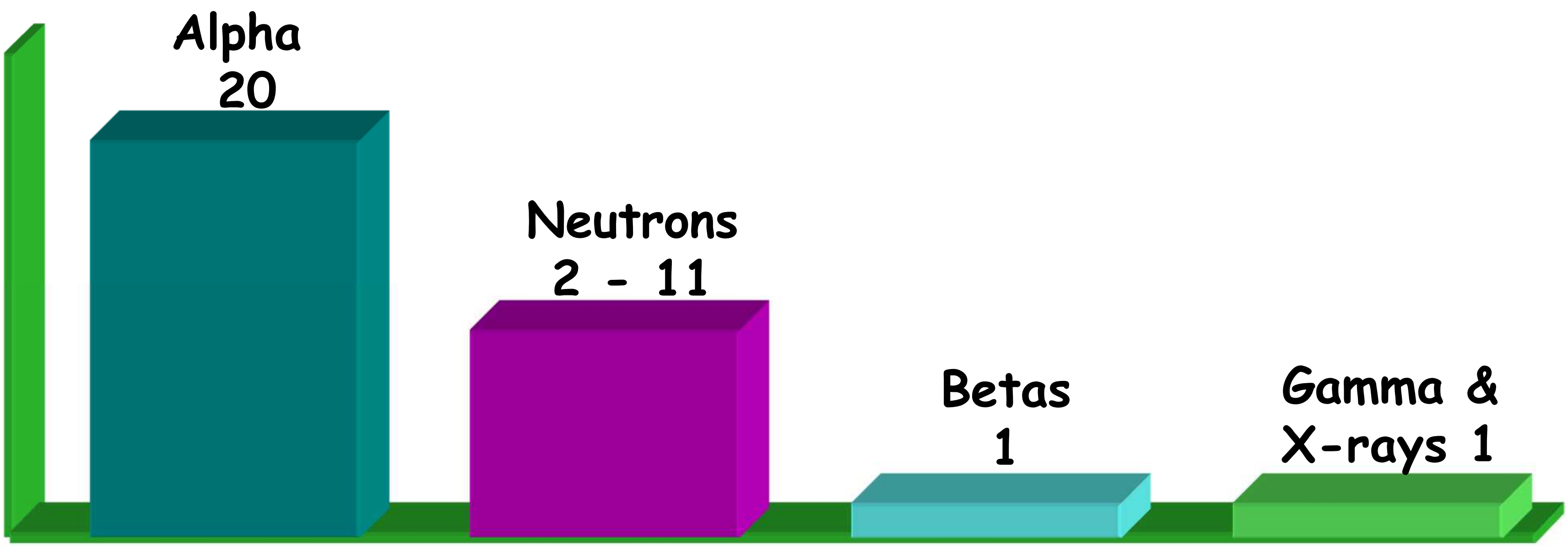
Sievert (Sv) or rem (roentgen equivalent man)

- **A measure of biological damage**
- **1 Sv = 100 rem**
- **Takes into account the energy absorbed and the biological effect on the body of that absorbed dose**

Quality Factor (QF)

The QF is used as a multiplier to reflect the relative amount of biological damage caused by the same amount of energy deposited in cells by the different types of ionizing radiation.

$$Gy \times QF = Sv$$



Radioactivity Units

Basic unit: Bequerel (Bq)

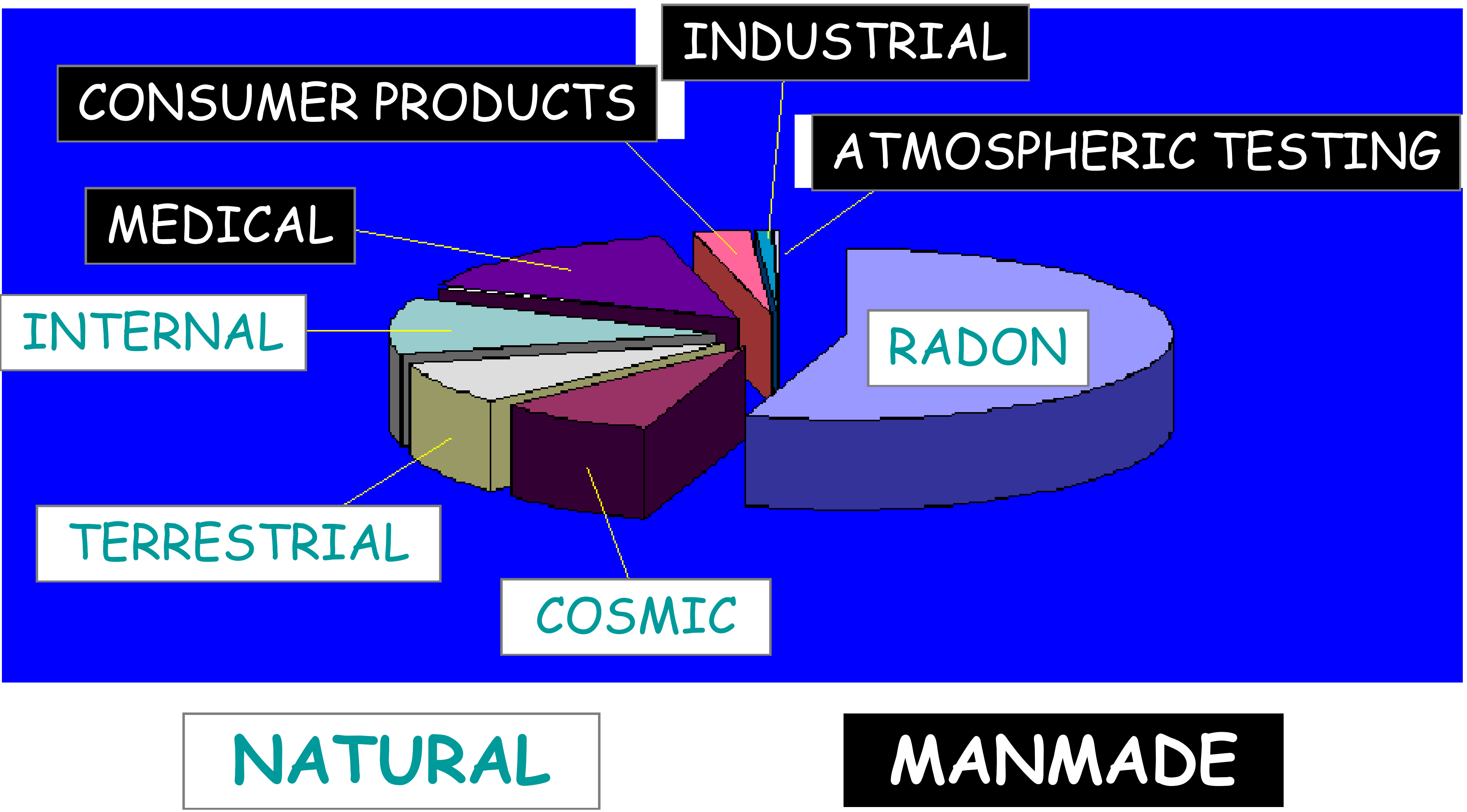
- One disintegration per minute (dpm)
- derived from the number of counts measured by instrument

Marie Curie
1867 - 1934
Discovered radium & polonium

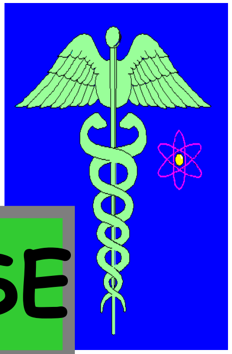
Traditional unit

- Curie (Ci)
- 1 Ci = 3.7×10^{10} Bq

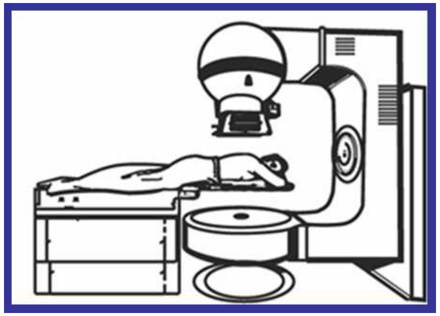
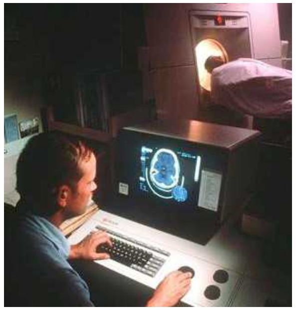
Background Radiation Sources



Medical Procedures

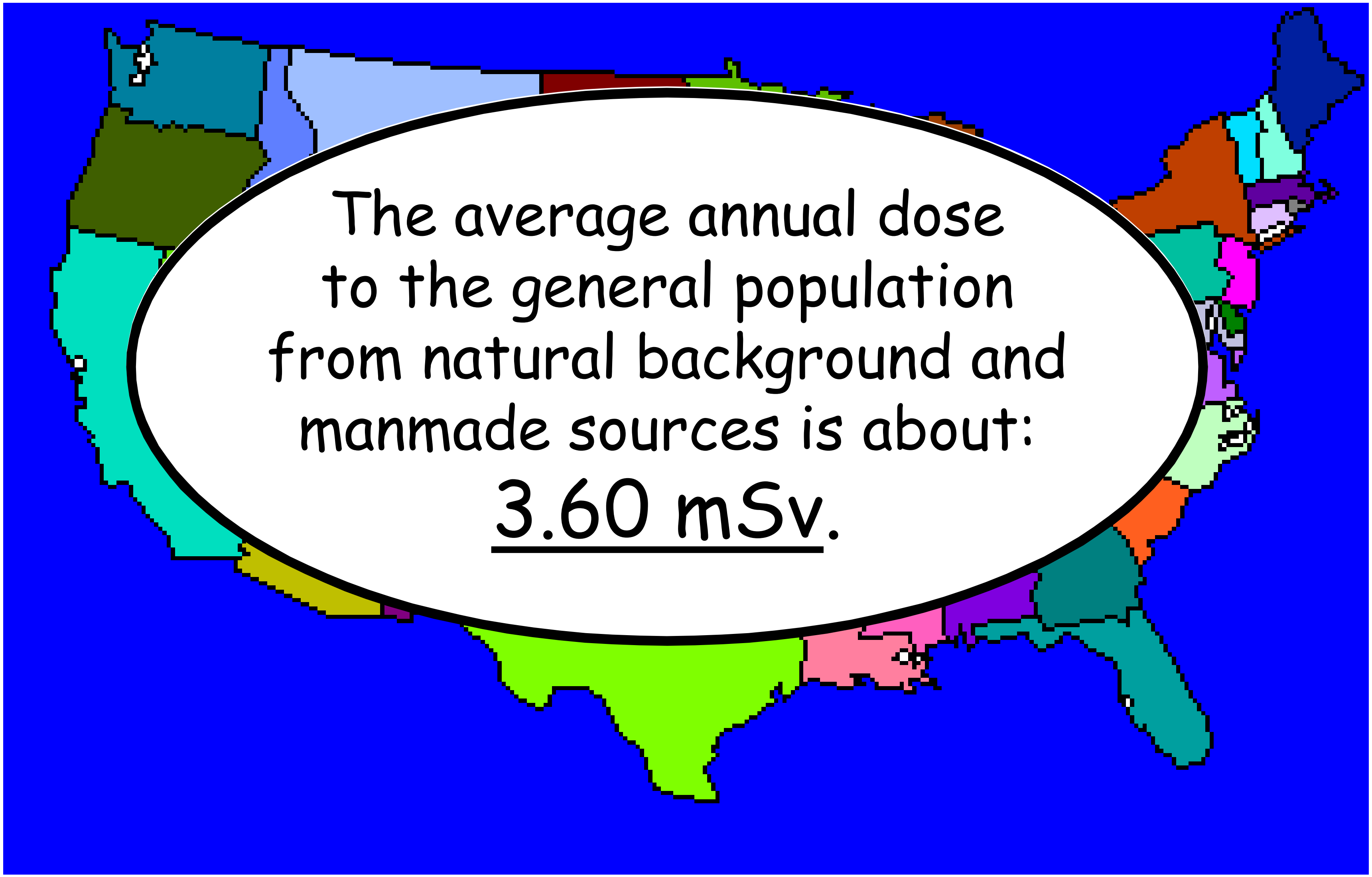


PROCEDURE	AVERAGE DOSE
THERAPY	6 Sv to tumor
CAT SCAN	0.058 Sv to head
MAMMOGRAM	4 mSv to breast
CHEST X-RAY	0.1 mSv

Radium Dial Factory

U.S. Average

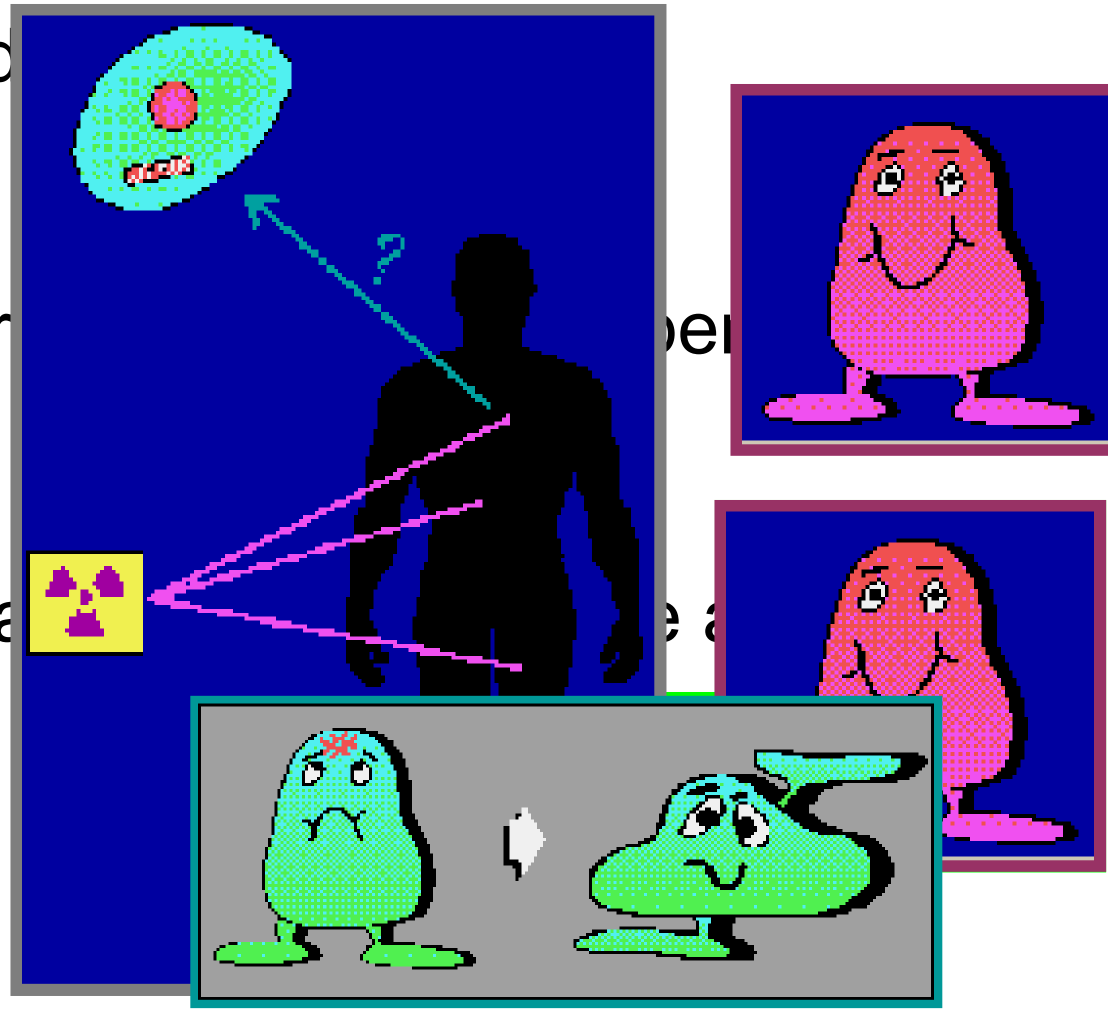


The average annual dose to the general population from natural background and manmade sources is about:

3.60 mSv.

Possible Effects of Radiation on Cells

- There is no d
- Cells repair ... per ... y
- Cells are da ... e a
- Cells die



Acute Exposure Effects

AVG DOSE	DAMAGE
> 50 Sv	Death Within 2 -3 Days
> 5 Sv	Gastrointestinal Damage
4.5 - 6 Sv	LD 50-60
2 - 5 Sv	Blood System Damaged
1 - 2 Sv	Radiation Sickness
0.25 – 0.50Sv	Slight Blood Changes
0.05 Sv	Annual Limit

Cancer Risk

- Current rate of cancer death among Americans is about 20%.
- An individual who receives 250 mSv over a working life increases his/her risk of cancer by 1% to about 21%.
- The average annual dose to DOE workers is less than 1 mSv.

Comparison of Health Risks

Health Risk	Days Lost
Unmarried Male	3500
Tobacco User	2250
Unmarried Female	1600
Overweight Individual	777
Alcohol Consumer	365
Motor Vehicle Driver	207
1 mSv/yr for 70 yrs	**10**

Comparison of Occupational Risk

EO9

Industry	Days Lost
Coal Miner	328
Farmer	277
Transportation Worker	164
U.S. Average	74
Manufacturer	43
Radiological Worker	**40**
Trades Employee	30

The Nuclear Fuel Cycle