Science is facts; just as houses are made of stone, so science is made of facts; but a pile of stones is not a house, and a collection of facts is not necessarily a science.

\- Jules Henri Poincare

Science is not belief, but the will to find out.

\- Anonymous

Energy and Work

Harder you have to work, the more *potential* energy you produce

Ex: lifting weights

Electrical potential energy:
proportional to the charges,
inversely proportional to
distance apart

$$U = k\frac{Q_1 Q_2}{d}$$

Potential energy is positive if
you have to force the objects together, *i.e.,* they repel each other

Potential energy is negative if
you have to use force to separate the objects, *i.e.,* they attract each other

Example: Make a rough estimate of how the electrical potential energy of two protons in a carbon nucleus compares to the electrical potential energy of the outermost electron orbiting outside the nucleus.

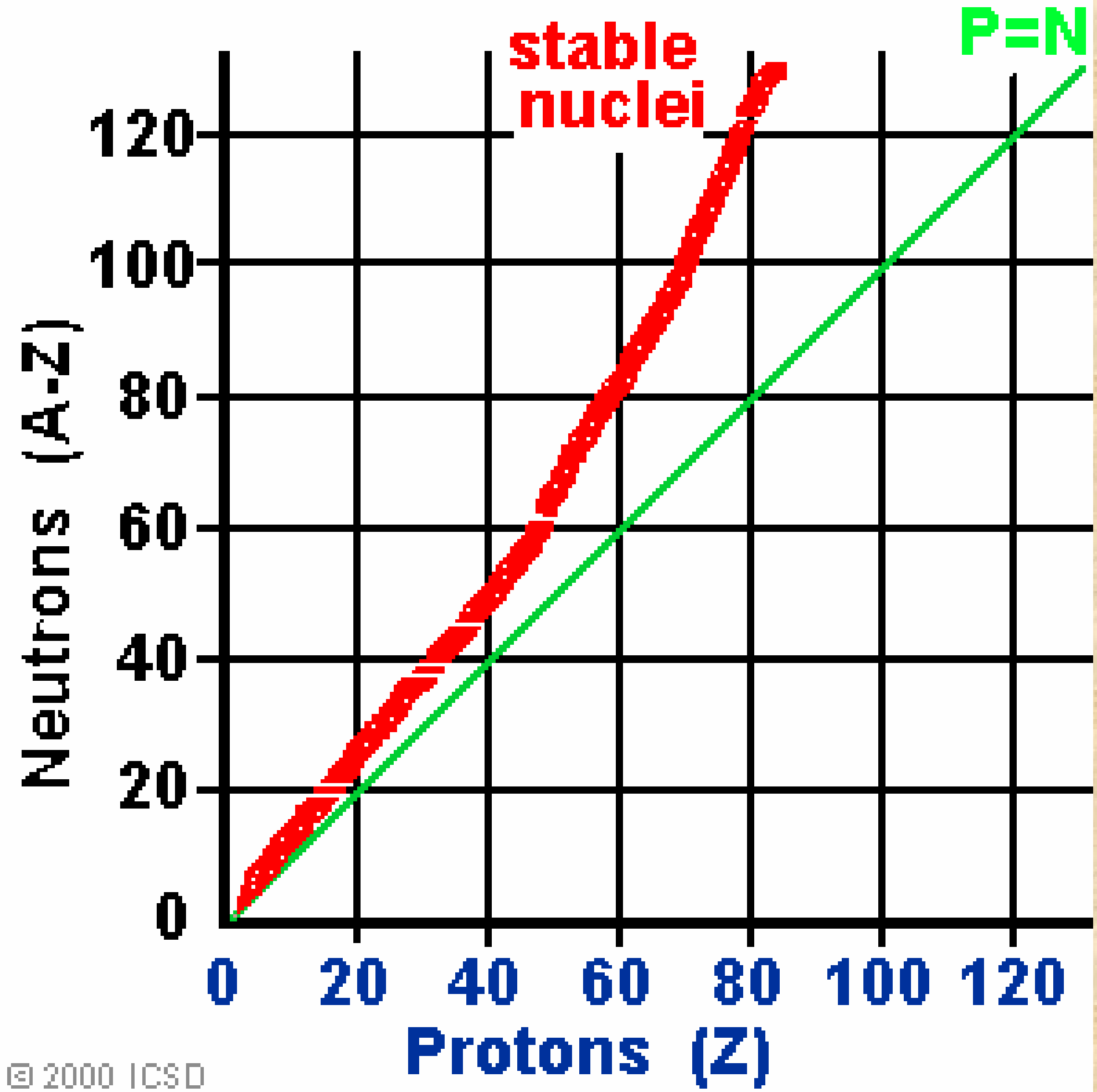
$$U = k\frac{Q_1 Q_2}{d}$$

The outermost electron has a charge of –*e* and the *effective* charge of the nucleus is +*e.* The two protons both have charge +*e.* So there is no difference in the *size* of the charges in the two cases. But an estimate of the distance between the proton and the electron is about 10^{-10} m while an estimate of the distance between the two protons is 10^{-13} m. So the electrical potential energy of the two protons is $(10^{-10}/10^{-13}) = 10^3 = 1000$ times the electrical potential energy of the proton and the electron.

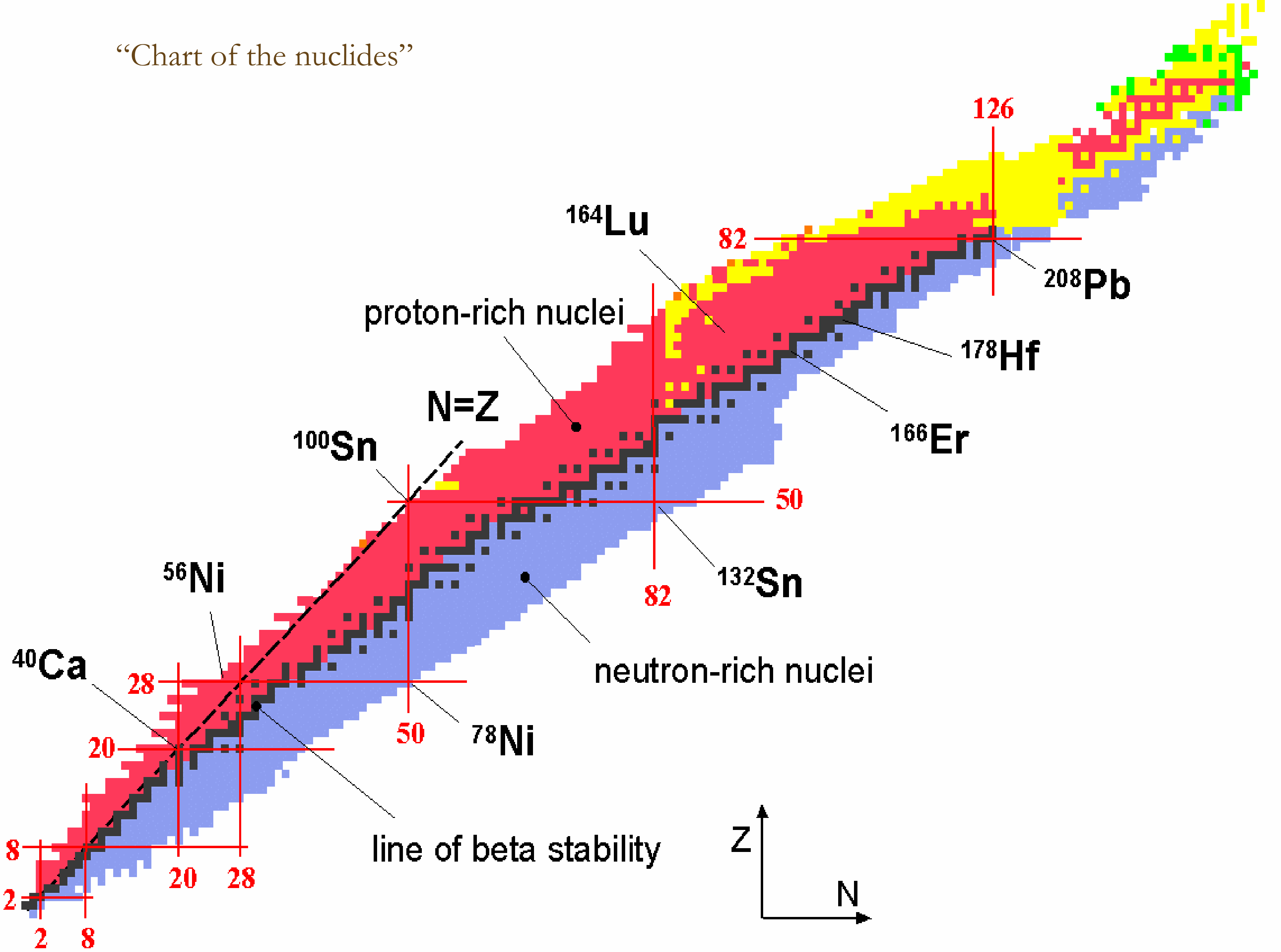
Potential energy can be converted into *kinetic energy* (energy of motion)of atoms. Often this is the first step to producing other forms of energy.

The average kinetic energy of atoms in a gas is proportional to its (absolute) temperature. So if you increase the kinetic energy of a gas by converting some of the potential energy of its atoms or molecules into kinetic energy, it gets hotter.

This is basically what happens in a coal burning power plant. Or in a nuclear power plant.


stable nuclei
P=N
Neutrons (A-Z)
120
100
80
60
40
20
0
0
20
40
60
80
100
120
Protons (Z)

“Chart of the nuclides”



Three primary modes of radioactive decay:

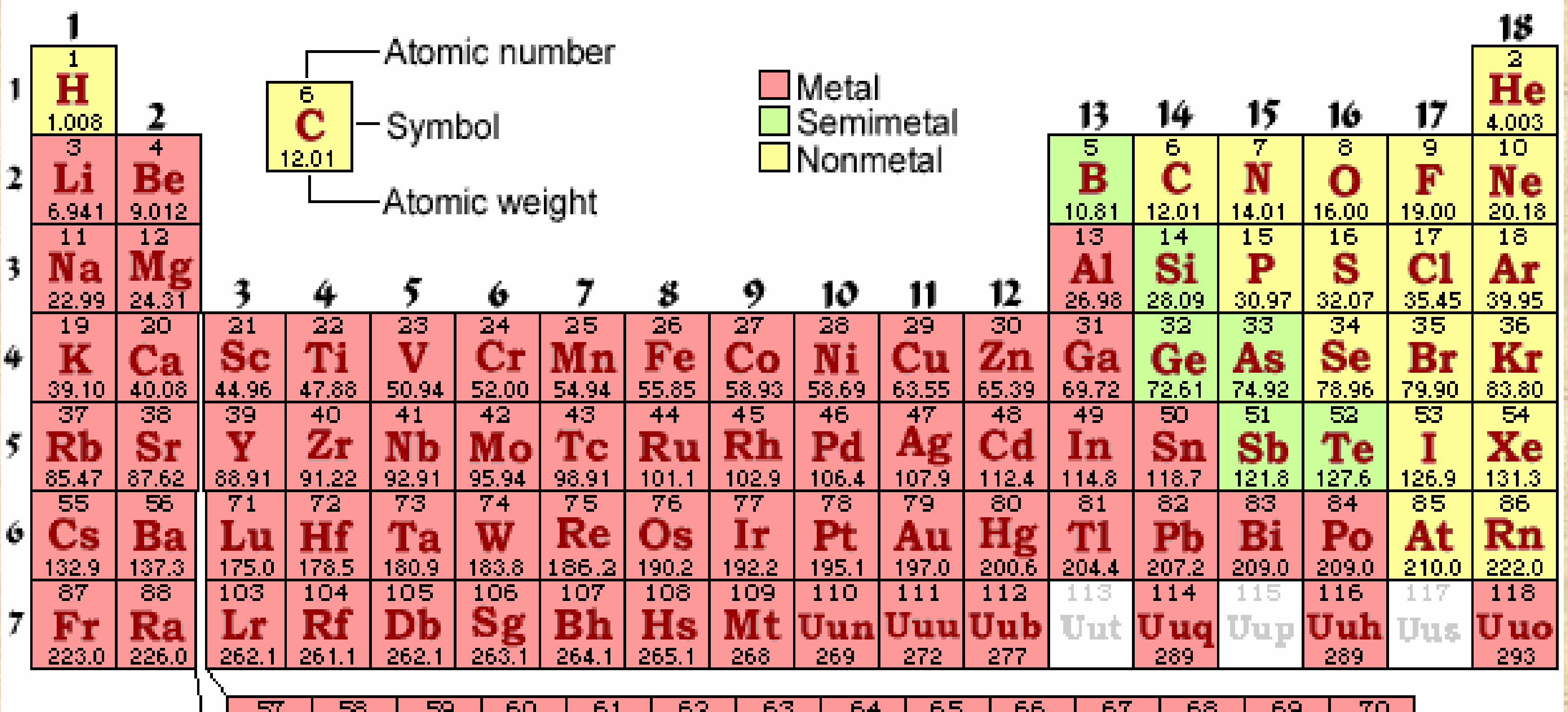
- alpha (α) decay
- beta (β) decay
- gamma (γ) decay

The solution to too many neutrons: beta (β) decay

Inside the nucleus: $$n^0 \rightarrow p^+ + e^- + \bar{\nu}_e^{\,0}$$

Upshot: neutron becomes proton (hence different element!) , electron and neutrino ejected with much energy, (electron anti)neutrino never heard from again, energetic electron *is* the beta radiation.

Example: $$^{137}_{55}\mathrm{Cs} \rightarrow {}^{137}_{56}\mathrm{Ba} + \beta^-$$



Atomic number
Symbol
Atomic weight
6
C
12.01

🟥 Metal
🟩 Semimetal
🟨 Nonmetal

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc 98.91	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	71 Lu 175.0	72 Hf 178.5	73 Ta 180.9	74 W 183.8	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po 209.0	85 At 210.0	86 Rn 222.0
7	87 Fr 223.0	88 Ra 226.0	103 Lr 262.1	104 Rf 261.1	105 Db 262.1	106 Sg 263.1	107 Bh 264.1	108 Hs 265.1	109 Mt 268	110 Uun 269	111 Uuu 272	112 Uub 277	113 Uut	114 Uuq 289	115 Uup	116 Uuh 289	117 Uus	118 Uuo 293

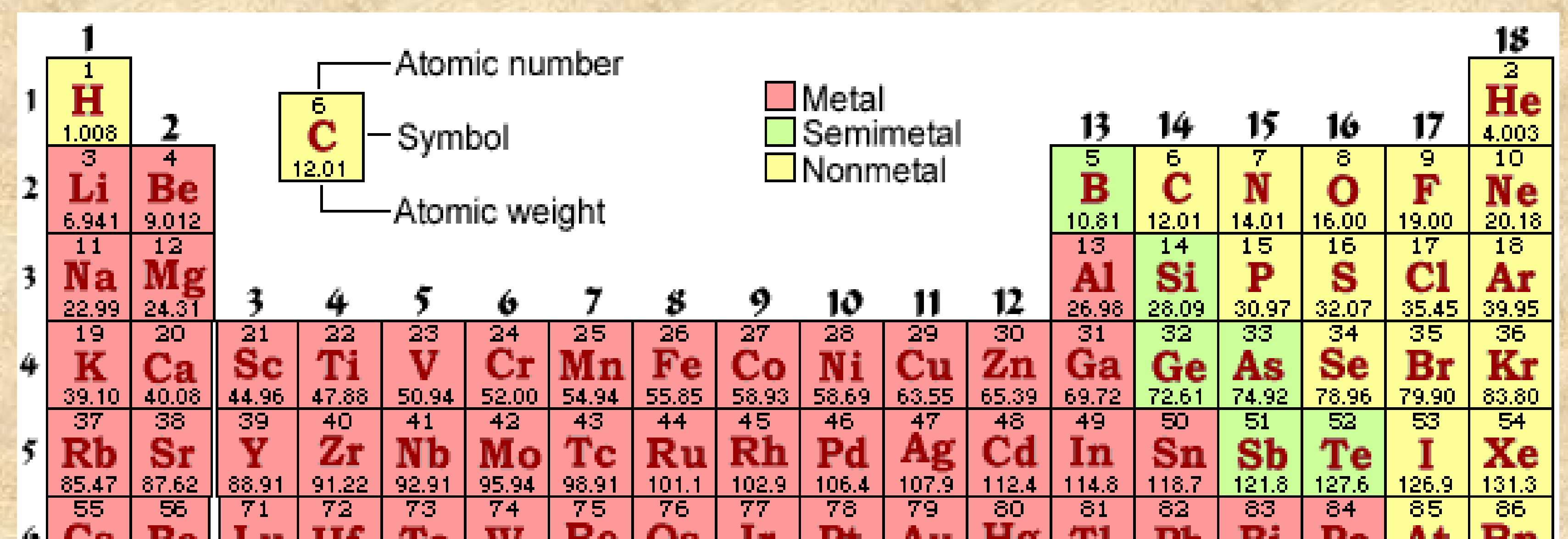
57	58	59	60	61	62	63	64	65	66	67	68	69	70

One solution to too many protons: also beta decay, but with a twist.

Inside the nucleus: $$p^{+} \rightarrow n^{0} + e^{+} + \nu_{e}{}^{0}$$

Upshot: proton turns into neutron (hence different element!), positive version of the electron (the *positron)* and the (electron) neutrino go off with high energy, the neutrino is never heard from again, energetic positron *is* the beta radiation.

Example: $${}^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + \beta^{+}$$



Atomic number 6
Symbol C
Atomic weight 12.01

🟥 Metal
🟩 Semimetal
🟨 Nonmetal

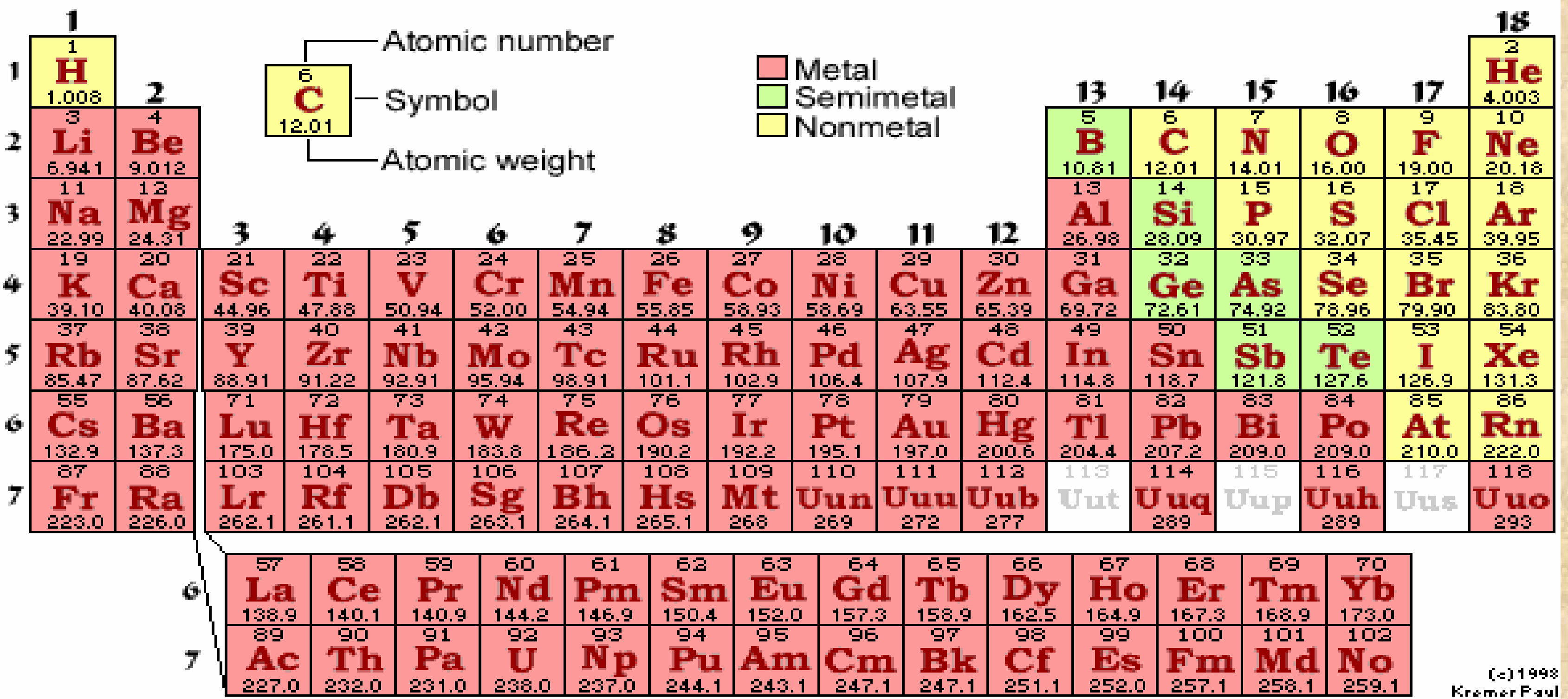
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc 98.91	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55	56	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86

Another solution to too many protons: alpha (α) decay

Nucleus spits out the nucleus of a helium-four atom, $^{4}_{2}\text{He}$ (a.k.a. an *alpha* particle).

Upshot: Alpha particle shoots out of nucleus carrying two protons and two neutrons (hence changing element!), the energetic alpha particle *is* the radiation.

Example: $^{241}_{95}\text{Am} \rightarrow {}^{237}_{93}\text{Np} + \alpha$



Atomic number
Symbol
Atomic weight

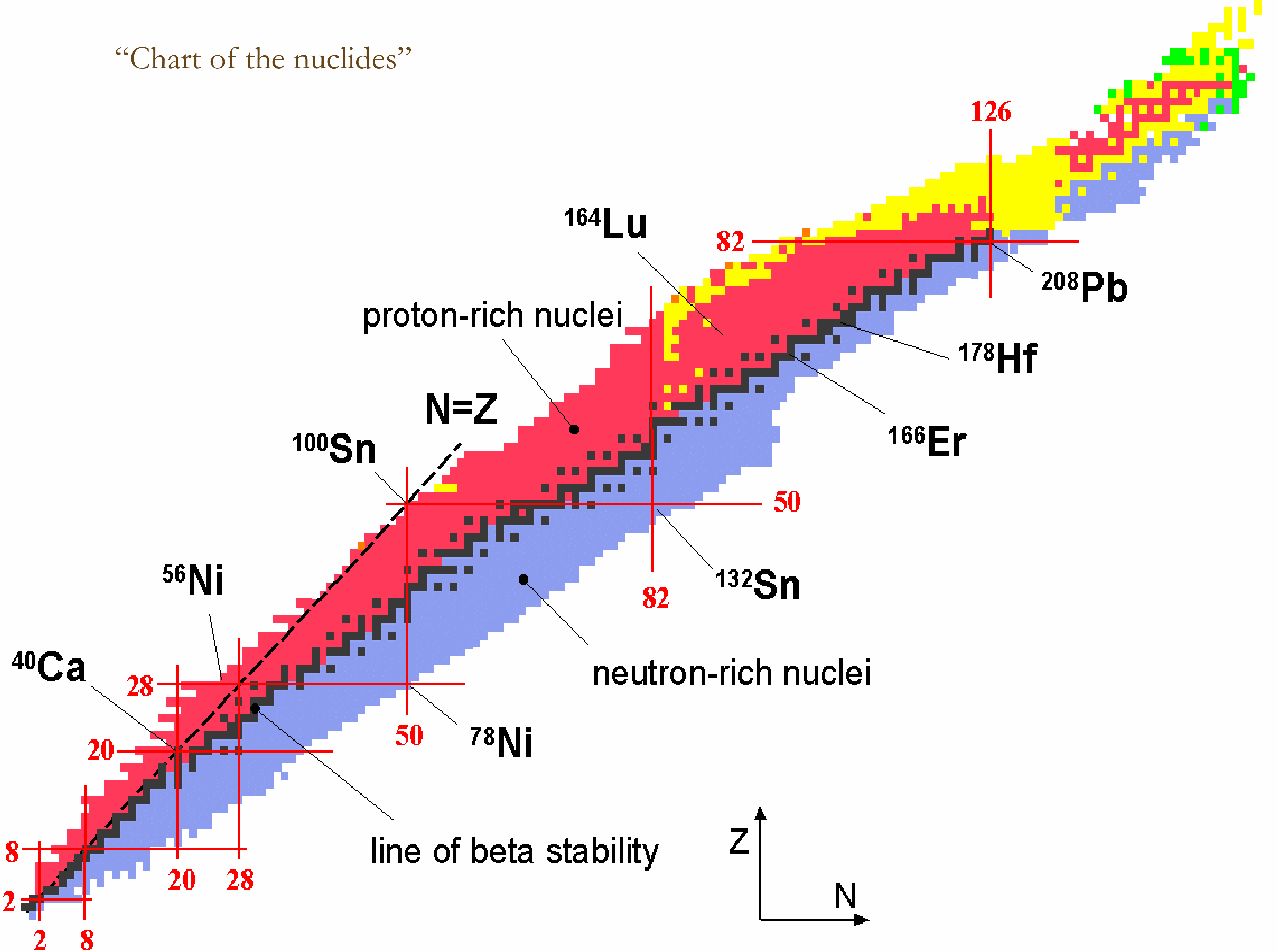
	6 **C** 12.01

🟥 Metal
🟩 Semimetal
🟨 Nonmetal

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 **H** 1.008																	2 **He** 4.003
2	3 **Li** 6.941	4 **Be** 9.012											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
3	11 **Na** 22.99	12 **Mg** 24.31											13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.07	17 **Cl** 35.45	18 **Ar** 39.95
4	19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.88	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.85	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.39	31 **Ga** 69.72	32 **Ge** 72.61	33 **As** 74.92	34 **Se** 78.96	35 **Br** 79.90	36 **Kr** 83.80
5	37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.94	43 **Tc** 98.91	44 **Ru** 101.1	45 **Rh** 102.9	46 **Pd** 106.4	47 **Ag** 107.9	48 **Cd** 112.4	49 **In** 114.8	50 **Sn** 118.7	51 **Sb** 121.8	52 **Te** 127.6	53 **I** 126.9	54 **Xe** 131.3
6	55 **Cs** 132.9	56 **Ba** 137.3	71 **Lu** 175.0	72 **Hf** 178.5	73 **Ta** 180.9	74 **W** 183.8	75 **Re** 186.2	76 **Os** 190.2	77 **Ir** 192.2	78 **Pt** 195.1	79 **Au** 197.0	80 **Hg** 200.6	81 **Tl** 204.4	82 **Pb** 207.2	83 **Bi** 209.0	84 **Po** 209.0	85 **At** 210.0	86 **Rn** 222.0
7	87 **Fr** 223.0	88 **Ra** 226.0	103 **Lr** 262.1	104 **Rf** 261.1	105 **Db** 262.1	106 **Sg** 263.1	107 **Bh** 264.1	108 **Hs** 265.1	109 **Mt** 268	110 **Uun** 269	111 **Uuu** 272	112 **Uub** 277	113 **Uut**	114 **Uuq** 289	115 **Uup**	116 **Uuh** 289	117 **Uus**	118 **Uuo** 293

6	57 **La** 138.9	58 **Ce** 140.1	59 **Pr** 140.9	60 **Nd** 144.2	61 **Pm** 146.9	62 **Sm** 150.4	63 **Eu** 152.0	64 **Gd** 157.3	65 **Tb** 158.9	66 **Dy** 162.5	67 **Ho** 164.9	68 **Er** 167.3	69 **Tm** 168.9	70 **Yb** 173.0
7	89 **Ac** 227.0	90 **Th** 232.0	91 **Pa** 231.0	92 **U** 238.0	93 **Np** 237.0	94 **Pu** 244.1	95 **Am** 243.1	96 **Cm** 247.1	97 **Bk** 247.1	98 **Cf** 251.1	99 **Es** 252.0	100 **Fm** 257.1	101 **Md** 258.1	102 **No** 259.1

“Chart of the nuclides”



Nuclei are composite objects, hence can be set into vibration. This excitation is often the result of alpha or beta decay. The excitation energy is emitted in the form of very energetic light called gamma (γ) radiation. So γ radiation often accompanies alpha or beta decay.

Example:

$$^{22}_{11}\mathrm{Na} \rightarrow ^{22}_{10}\mathrm{Ne}^{*} + \mathrm{e}^{+} + \nu_e{}^{0}$$

$$^{22}_{10}\mathrm{Ne}^{*} \rightarrow ^{22}_{10}\mathrm{Ne} + \gamma^{0}$$

Upshot: Beta same as before, ejecting energetic electron, but now we see that energetic gamma is also produced. Note that γ radiation does *not* change the identity of the element. Also note that gamma rays are not charged nor do they have mass.

Another source of γ radiation is *matter-antimatter annihilation*. When a particle meets its antiparticle they both disappear (annihilate) and their energy is converted into two gamma rays.

Example:

$$\mathrm{e}^{-} + \mathrm{e}^{+} \rightarrow \gamma^{0} + \gamma^{0}$$

All three forms of radiation are very energetic. Around 10^6X more energy than it takes to break chemical bonds or strip electrons from molecules. Hence, *ionizing radiation*.

Alpha particles are doubly positively charged and the highest mass. It turns out this means that it interacts the most strongly with materials. Can be stopped by a piece of paper.

Beta particles are singly charged and have small mass. This means it interacts fairly strongly with materials, but not as much as alpha particles. Can be stopped by metal foil or 1/8" thick piece of plastic.

Gammas are not charged and so interact even less strongly with materials. So very penetrating radiation

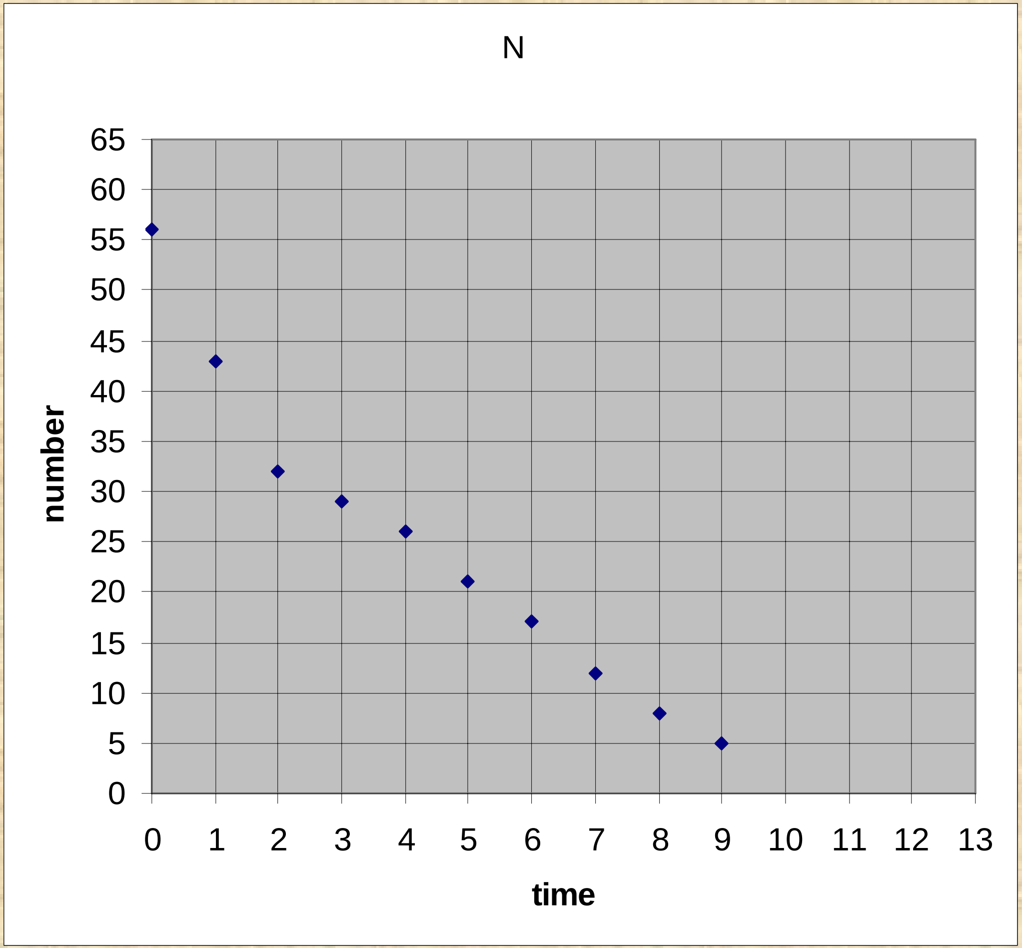
None of this radiation generates significant residual radioactivity.

A collection of a given radioactive nuclei gets less radioactive with time. We say that the radiation *decays* with time.

Fundamental rule: in any fixed time interval, there is an constant probability that a given nucleus will emit radiation.

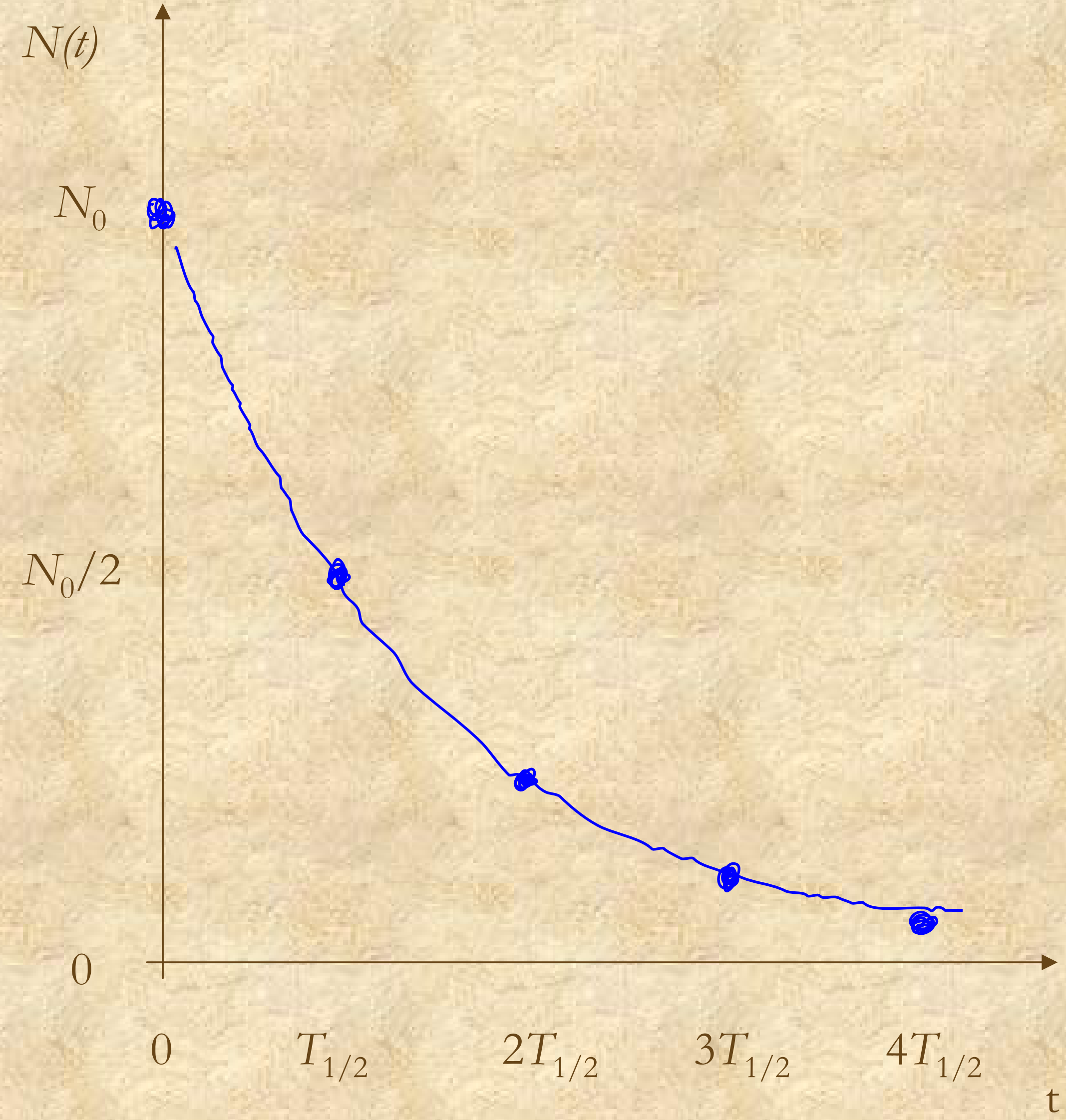
(Demo with dice)

"t"	N	A
0	56	
1	43	13
2	32	11
3	29	3
4	26	3
5	21	5
6	17	4
7	12	5
8	8	4
9	5	3



Half-life

t	N
0	N_0
$T_{1/2}$	$N_0/2$
$2T_{1/2}$	$N_0/4$
$3T_{1/2}$	$N_0/8$
$4T_{1/2}$	$N_0/16$
$\vdots$	$\vdots$
$nT_{1/2}$	$N_0/2^n$



Equation for radioactive decay:

$$N(t) = \frac{N_0}{2^{\left(\frac{t}{T_{1/2}}\right)}}$$

Activity (rate of decay, decays per second)

This is what we usually can measure. Usually symbolized by *A*.

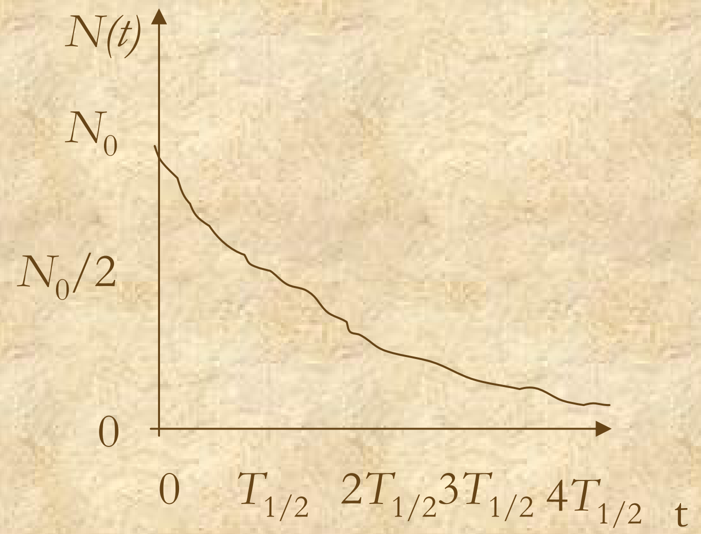
Note property of *N(t)* curve that number of Decays increases with *N*. In fact, *A* is proportional to *N*.

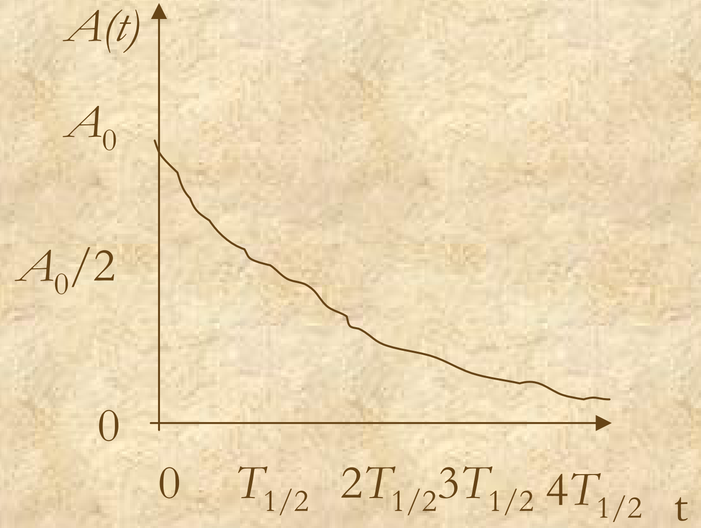
$$A = \lambda N$$

λ is called the *decay constant.*

λ and $T_{1/2}$ are related.

$$\lambda = \frac{\ln 2}{T_{1/2}}$$





Decay constant gives alternate formulas:

$$N = N_0 e^{-\lambda t} \qquad A = A_0 e^{-\lambda t}$$

One decay each second is called a *becquerel (Bq).*

$3.7\text{x}10^{10}$ decays each second is called a *curie (Ci).*

1 μCi (10^{-6} Ci) generally unregulated

1 mCi (10^{-3} Ci) is generally regulated, needs to be handled cautiously

1 Ci generally requires government inspections, protocols