

# Nuclear

## Nuclear chemistry & radioactivity

Chemistry normally is concerned with interaction of atoms and depends on the properties of electrons and only the charge and mass of the nucleus (location of protons and neutrons)

Physics studies the structure of the nucleus. For example, nuclear physics and particle physics study the nucleus.

But there is overlap of interest.

To understand atoms it is important to know something about the nucleus, radioactivity, transformations of matter, nuclear uses in chemistry, energy production from fusion and fission, kinetics of decay, etc.

### Particles in Atom (from chemistry standpoint)

Nuclei parts:	Protons	Neutrons	Electrons
Symbol:	p	n	e
Relative charge:	+1	0	-1
Mass (amu)	1.0073	1.0087	0.00055

amu = atomic mass units (amu or u can be used as symbol)  
 1 gram =  $6.02 \times 10^{23}$  amu

nucleus has protons and neutrons and gives atom its mass  
 orbitals around nucleus have electrons and give atom its size

### Isotopes

Isotopes are atoms with different number of neutrons but same number of protons

Symbols used are:

A = mass number = #p + #n

Z = atomic number = charge (in isotopes  $Z = \#p$ ) ( $A - Z = \#n$ )

X = element symbol



For example:

3p make atom lithium. Li and can have isotopes of 3n or 4 n.

A = 3+3=6 or A = 3+4=7 and Z=3 for both so



note on periodic table number of protons is integer above element symbol

average mass is decimal number below element symbol

### Mass average

on Periodic Table masses given below element symbol is average based on all isotopes of that element and their amounts found in nature

So 6.941 below Li is average of 6 and 7.

If only two isotopes can find amounts from average

$$(1-x)(6.00\text{amu}) + (x)(7.00\text{amu}) = 6.941$$

where x is fraction of mass 7.00 isotopes and 1-x is fraction of mass 6.00

(not quite exact but here we assume mass same as mass number)

Solve above and find  $x = 0.941$  and  $1-x = 0.059$  or

94.1%  ${}^7\text{Li}$  and 5.9%  ${}^6\text{Li}$

### Nucleus

Nucleus is most of the mass of the atom but in a very small space.

As shown below diameter of atom is about 100,000 greater than diameter of nucleus.

$$\frac{\text{diameter atom}}{\text{diameter nucleus}} = \frac{10^{-10}\text{m}}{10^{-15}\text{m}} = \frac{100000}{1}$$

Density of nucleus is  $2.4 * 10^{14} \text{ g/cm}^3$

$1\text{cm}^3$  of protons and neutrons would weigh 500 billion pounds!

roughly equivalent to the mass of all the cars in U.S

In some stars matter condensed to this value become neutron stars.

## Radioactivity

Unstable nuclei (natural or synthetic) undergo radioactive decay to move toward a zone of stability.

Decay means to throw off some particles from nucleus.

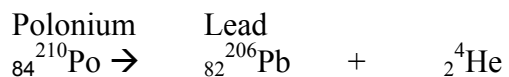
### Processes

$\alpha$	Alpha emission $\rightarrow$	${}_2^4\text{He}$	
$\gamma$	Gamma radiation $\rightarrow$	${}_0^0\gamma$	no mass and no charge
$\beta$	Beta emission $\rightarrow$	${}_{-1}^0\text{e}$	$n \rightarrow p + \text{e}^-$
$\beta^+$	Positron emission $\rightarrow$	${}_{+1}^0\text{e}$	$p \rightarrow n + \beta^+$
p	proton	${}_{+1}^1\text{p}$	
n	neutron	${}_0^1\text{n}$	

note For almost every particle there is an antiparticle particle and antiparticle have same mass but opposite charge example electron and positron

Balance for mass and charge,  $\gamma$  gamma radiation balances for energy only  
Only concerned with nuclear charge ignore the outer electrons

### Alpha emission $\alpha$



Balance superscripts and subscripts of above equation.

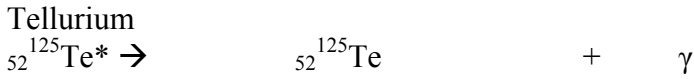
Do not worry about outer electrons:

There will be electron loss and gain to keep atoms neutral – only focus on nuclei

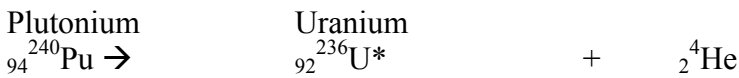
### Gamma radiation $\gamma$

Short wavelength, high energy electromagnetic radiation

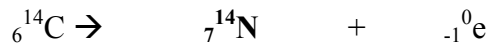
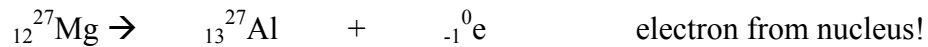
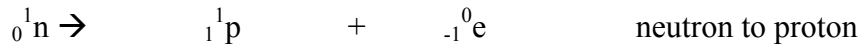
High energy  $\rightarrow$  lower energy state +  $\gamma$   
discrete values of energy  
quantized energy levels



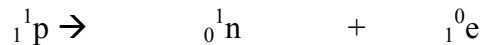
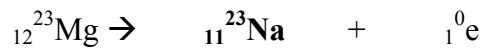
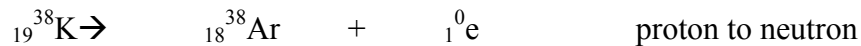
Frequently accompanies another type of radioactive decay



### Beta emission $\beta$



### Positron emission $\beta^+$



If any one part missing you can find by balancing top numbers and bottom numbers on left and right side

Example:



so  $23 = A + 0$  and  $A = 23$

$12 = Z + 1$  and  $Z = 11$  element with 11p is Na

so missing piece is  $_{11}^{23}\text{Na}$

Also particles captured by nucleus will lead to product predicted by balance of charge and mass.  $\beta$

### Strong Interaction

What hold p and n together in nucleus?

Expect electrostatic repulsion between protons (+1) so to counter this repulsion in the nucleus there must be another force. Strong interaction is different from gravitational and electromagnetic forces of nature

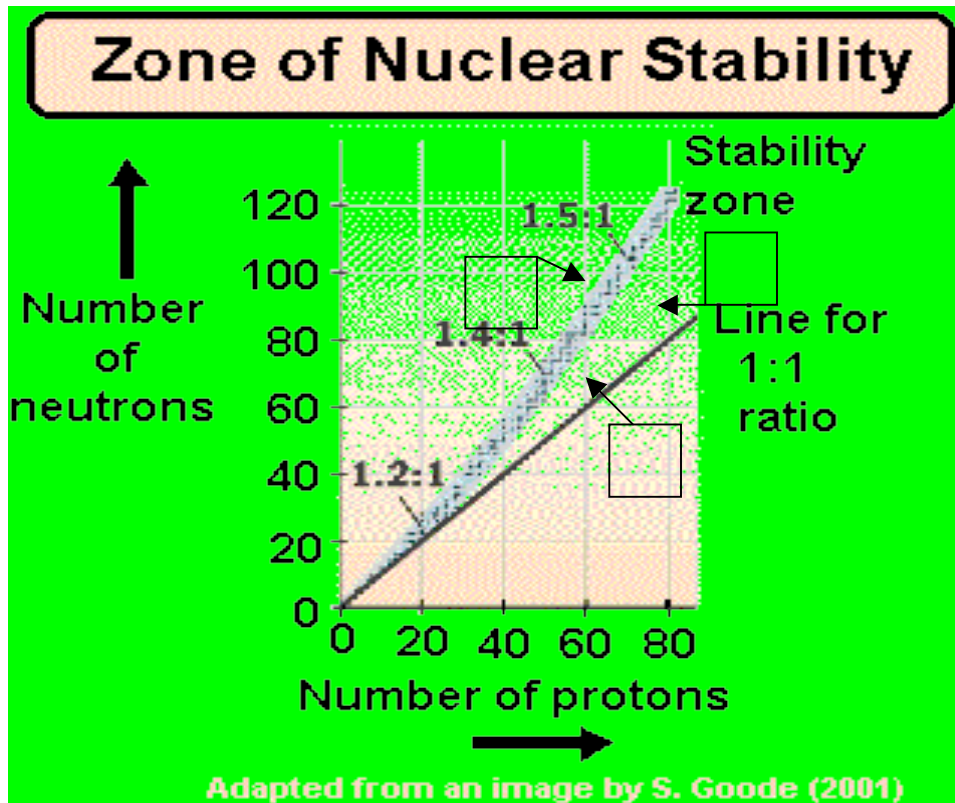
Force between n-n, n-p, and p-p are a kind of “nuclear glue.”

Short range  $2 \times 10^{-15}$  m and only if next to each other.

1935 Yukawa proposed exchange of  $\pi$  meson (pion) between protons and neutrons (rapidly  $10^{24}$ /sec interchanged). Meson is another a subatomic particle.

Details are more a concern of nuclear physics but good to be aware that like electromagnetism and gravity strong interaction is another fundamental force of nature.

### Stable Nuclei and Zone of Stability



<http://www.cyberphysics.pwp.blueyonder.co.uk/topics/physics/radioact/why.htm>

Radioactive decay moves nuclei toward zone of stability by throwing off pieces to adjust ratio of protons and neutrons.

More neutrons are needed as you have higher number of protons.

Side note - A lot of stable nuclei are an even number of proton and neutrons. The even # is associated with stability. Periodic properties in Nucleus Numbers 2, 8, 20, 50, 82, and 126.

### Radioactive Disintegration Series

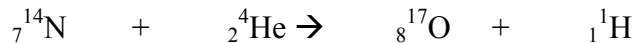
Series of decay steps where one unstable nuclei decays into another until final stable nuclei is reached.

Example age of some rock that is billions of years old determined by looking at relative amounts of  ${}_{92}^{238}\text{U}$  and  ${}_{82}^{206}\text{Pb}$ .

Note Linear accelerator or colliders causes nuclei and/or particles to collide and then see what products are produced as a way to study the nucleus and fundamental particles of nature.

### Transmutation of Matter (Alchemist's dream)

1915 Rutherford used  $\alpha$  particles from  ${}_{84}^{214}\text{Po}$  (polonium) to change N to O.



Transuranium elements (heavier than uranium and more protons) have all been produced artificially by nuclear reactions. They are not found in nature but have been made.

### Radioactive Decay

All radioactive decay is first order.

$N$  = # of atoms at time  $t$

$N_0$  = # of atoms at start of time  $t=0$

$k$  = rate constant

$dN$  = change in  $N$

$dt$  = change in time

$-dN/dt = kN$  the decrease in N is first order decay – it depends on amount of N

through calculus can change form of equation above to

$$\ln N = \ln N_0 - kt$$

$$\text{or } \ln (N_0/N) = kt$$

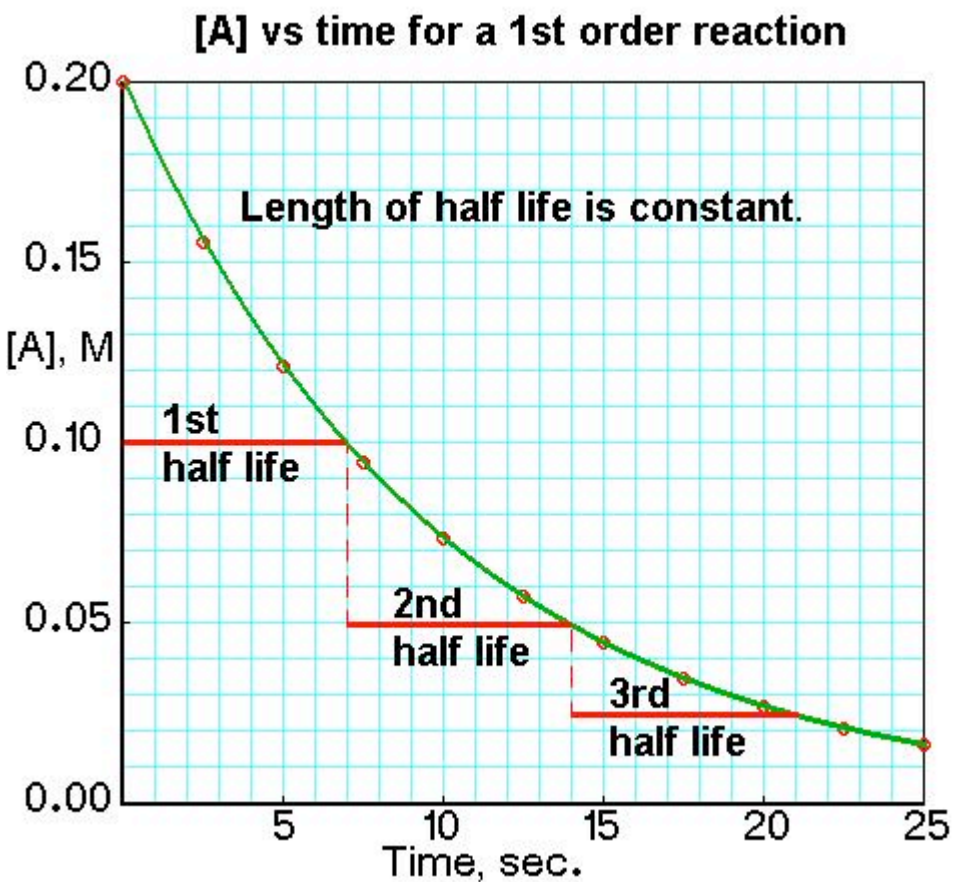
Length of time for half of sample to decay is **half-life** ( $t_{1/2}$ )

$$\ln (N_0/N) = kt$$

$$\ln (2) = k t_{1/2}$$

$$0.693 = k t_{1/2} \quad \text{Convert half life to rate constant } k$$

First Order



<http://www.chem.purdue.edu/gchelp/howtosolveit/Kinetics/Halflife.html>

Each half-life, the radioactivity is cut in half.

## Radiocarbon dating



CO<sub>2</sub> is used in photosynthesis

So ratio of <sup>14</sup>C to <sup>12</sup>C in plant is the same as the atmosphere. The plant dies, <sup>14</sup>C decays and amount decreases.

Older dead plant then has lower percent of <sup>14</sup>C.

$$t_{1/2}({}^{14}\text{C}) = 5770 \text{ years} \quad \text{half life of carbon-14 decay is 5770 years}$$

Example (exact method):

Wood just cut	15.3 counts/ g min	disintegrations
Old wood	7.0	

Find rate constant.

$$k = 0.693 / t_{1/2} = 0.693 / 5770 \text{ years}$$

$$k = 1.20 \times 10^{-4} \text{ yr}^{-1}$$

then find time t that solves equation

$$\ln N = \ln N_0 - kt$$

$$\ln (7.0) = \ln (15.3) - 1.20 \times 10^{-4} \text{ yr}^{-1} (t)$$

$$1.946 = 2.728 - 1.20 \times 10^{-4} \text{ yr}^{-1} (t)$$

$$-0.728 / -1.20 \times 10^{-4} \text{ yr}^{-1} = t$$

$$6520 \text{ years} = t$$

t = 6520 years so wood from tree that died this many years ago

Example (simple method):

An initial amount of radioactivity has changed from N<sub>0</sub>=16 to N=2 so how much time has passed – each halving of amount is one half-life

$$16 \text{ count/ g min} \xrightarrow{t_{1/2}} 8 \text{ counts} \xrightarrow{t_{1/2}} 4 \xrightarrow{t_{1/2}} 2$$

$$3 t_{1/2} = 3 ( 5770 \text{ years}) = t$$

$$t = 17310 \text{ years}$$

Problems with radioactive decay.

Find  $k$  from  $t_{1/2}$   
Or find  $t_{1/2}$  from  $k$

Four values  $N$   $N_0$   $k$   $t$  if you know three of them then you can find the fourth

Radioactive Decay

$$\ln N = \ln N_0 - kt \quad \text{or } \ln (N/N_0) = -kt$$
$$\ln (2) = 0.693 = k t_{1/2} \quad \text{use } t_{1/2} \text{ find } k$$

Then use  $k$ ,  $N_0$ , and  $N$  to find  $t$ .

Ex. (exact)

$$t_{1/2} = 20 \text{ hr.} \rightarrow 0.0347 \text{ hr}^{-1} = k \quad \text{from } 0.0347 \text{ hr}^{-1} = 0.693/20.0 \text{ hr}$$

$$N_0 = 100$$

$$N = 25$$

$$\ln (25) = \ln (100) - 0.0347 \text{ hr}^{-1} (t)$$

$$\ln (25) - \ln (100) = -0.0347 \text{ hr}^{-1} t$$

$$-1.3863 = 0.0347 \text{ hr}^{-1} t$$

$$t = 39.95 \text{ or round off to } t = 40 \text{ hr.}$$

Ex. (quick)

Level radioactivity

Changed from 100 to 25

Example using  $t_{1/2}$  quick calculation

$$N_0 = 100$$

$$N = 25 \quad \text{have many half lives have passed}$$

$100 \rightarrow 50 \rightarrow 25$  so two half-lives

$$2 t_{1/2} = 2 (20 \text{ hours}) = t$$

$$t = 40 \text{ hr.}$$

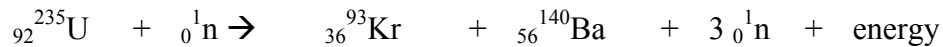
## Fission and Fusion

Fission heavy nucleus → split lighter nuclei and neutrons and energy

Fusion light nuclei → fused heavier nucleus and energy  
(occurs in sun and is the means by which stars release energy)

Examples:

Fission

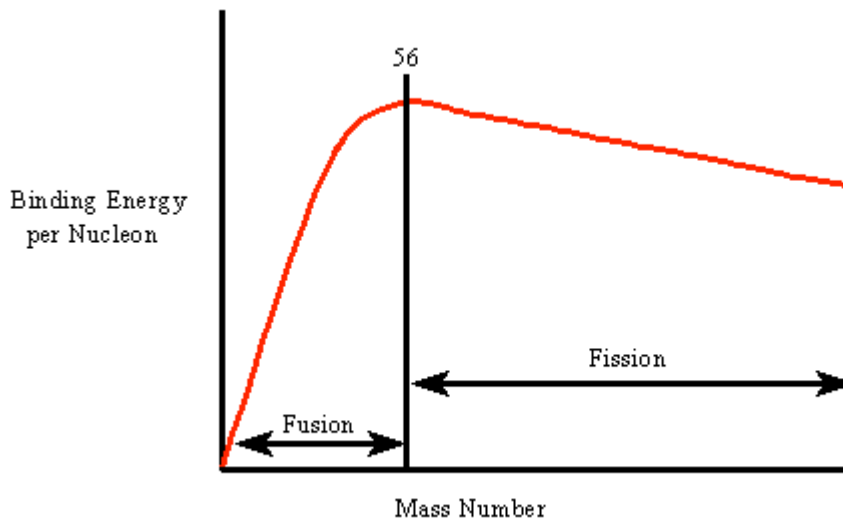


Fusion



requires high temperature so small nuclei can collide together at high energy

Binding energy- higher binding energy more mass is converted to energy



<http://www.bcpl.net/~kdrews/nuclearchem/nuclear.html>

Processes that move up on the graph creating more binding energy are exothermic and can release tremendous energy

The peak is the sum of masses less the loss of mass converted to energy.

Binding energy = energy released by formation of nucleus

Mass is lost when nuclei put together

Nucleons  $\rightarrow$  nuclei + binding energy (accounts for loss of mass)

Higher binding energy per nucleon (BEPN) is in intermediate mass.

Carry out fission or fusion to produces higher BEPN. That is an exothermic process (gives off energy).

### Fission

Neutron causes fission of  $^{235}\text{U}$ .

Average release of 2.5 neutrons per U atom

Rapid process

Nuclear weapon

Small amount of U then neutrons lost to surroundings

Above critical mass, where atoms are closer than normal, then neutrons captured by other U atoms and explosive chain reaction results

0.7% of U is  $^{235}\text{U}$  most  $^{238}\text{U}$

$\text{UF}_6$  produced by separated gaseous diffusion plant (Oak Ridge)

Nuclear reactor cylinders containing radioactive material  $^{235}\text{U}$  surrounded by heavy water, graphite rods (to capture neutrons).

Control rods are used to control rate of neutron production. (kept close to 1)

### Fusion

In stars and in hydrogen bomb

Hydrogen bomb, high temperature generated by fission bomb and much more energy given off.

Controlled fusion reaction (energy source of future – not yet possible)

The by product is  $^2_4\text{He}$  and uses water to produce H for fuel

High Temp = 100 million degrees and requires magnetic container

### Energy Sources

Wood, coal, oil, gas, and hydroelectric → CO<sub>2</sub> production

Fission → radioactive by products stored long time (used in nuclear power plants)

Fusion → needs work to control

Solar → needs space, direct to electrocute (break water to hydrogen and oxygen)

### Energy- Matter

Einstein theorized the interconversion of mass and energy

$$E = mc^2 \quad \text{or} \quad \Delta E = (\Delta m) c^2$$

c = speed of light =  $3 \times 10^8$  m/s

Mass	Mass (kg)	E (J)
1u	$1.66 \times 10^{-27}$	$1.5 \times 10^{-10}$
1g	$1.0 \times 10^{-3}$	$9 \times 10^{13}$
1kg	1.0	$9 \times 10^{16}$

1 g of mass has the equivalent energy ( $9 \times 10^{13}$ ) of 3000 tons of coal (1 train load)

## EXTRA MATERIAL – NOT COVERED IN CLASS

### Energy Units

$$\begin{aligned} \text{Electron volt } 1\text{eV} &= 1.6 \times 10^{-19} \\ &= (1.60 \times 10^{-18} \text{C}) \frac{(1\text{V})}{\text{coulomb}} \end{aligned}$$

energy equivalent  $1\mu = 9.31\text{MeV}$

### Rate of Decay

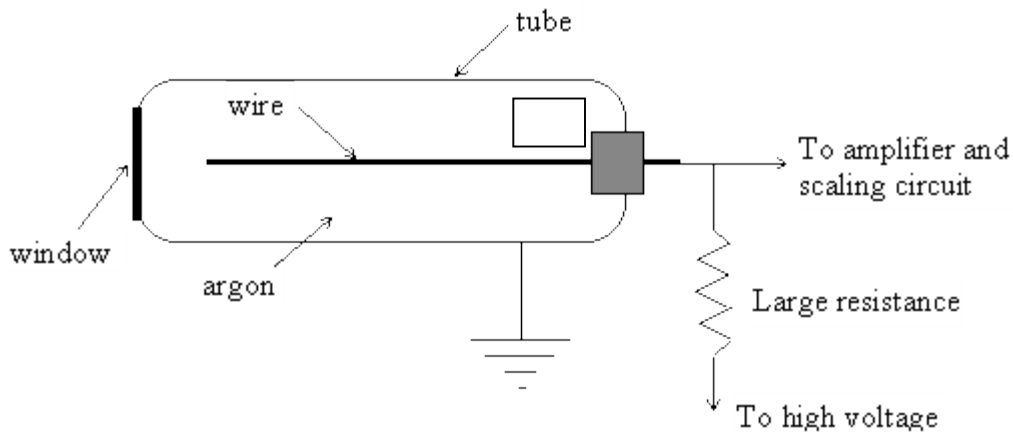
Detection of Radiation – count particles given off by radioactive substance or gamma rays

**Scintillation counter-** (quantitative) Particle strikes ZnS and is converted into a flash of light. The light is detected by the photoelectric tube. In the tube, the photon strikes the metal and gives off an electron. The electron signal is amplified and measured.

+

**Wilson cloud chamber** – Ions formed by particle moving through chamber water droplets condense on ions and see cloud path.

**Geiger- Muller counter** – (quantitative) Radiation particle forms  $Ar^+$ .  $Ar^+$  goes to the cathode and pulse of electricity flow amplified and detected as a click or operate counting device.



<http://www.gla.ac.uk/ibls/US/L4/options/optionsa/bip.html>

**Film** – changes in color by light or radiation

### Sources of radiation and Units

Radiation- high energy radiation or subatomic particles

rem (person/ year amount)	Sources
0.045	cosmic radiations- high energy particles from outer space cause secondary radiation from atoms in the atmosphere
0.60	earth- radioactive isotopes in with stable atoms in everything
0.025	from atoms in our body
0.070	x-rays
0.140	10,000 ft altitude
0.35	sea level
0.325	airline crew
0.100	granite building

## Units

Curie – rate of  $3.7 \times 10^{10}$  disintegrations/ sec  
Millicurie -  $10^{-3}$  curie

Rem for safety standards and biological damage.

Rem is beta or gamma radiation that transfers 0.01 J of energy to 1kg of matter.

Sudden exposure to 300 rem causes a 50% chance of death within 30 days.

50 rem exposure does not produce any observable effects.

Problem with extrapolation to 0 not necessarily effect.

Example:

1g of matter complete converted to energy would supply energy for how many homes per year?

Watt (W) = J/s  
100 W light bulb

A house uses at least 1000kWhr of electricity per month.

$$1\text{kWhr} = (\text{kWhr}) (10^3\text{W} / \text{kW}) (J/(\text{s} * \text{W})) (3600\text{s} / \text{hr}) = 3.6 \times 10^6 \text{ J}$$

$(3.6 \times 10^6\text{J} / \text{kWhr}) (12 \text{ months}) (1000 \text{ kWhr} / \text{ month})$  house per year =  $4.3 \times 10^{10}\text{J}$   
of energy

1g of matter completely converted to energy provides  $9 \times 10^{13}$  J or about 2000 homes see  $E = m c^2$

OR burn 3000 tons of coal to generate same energy.