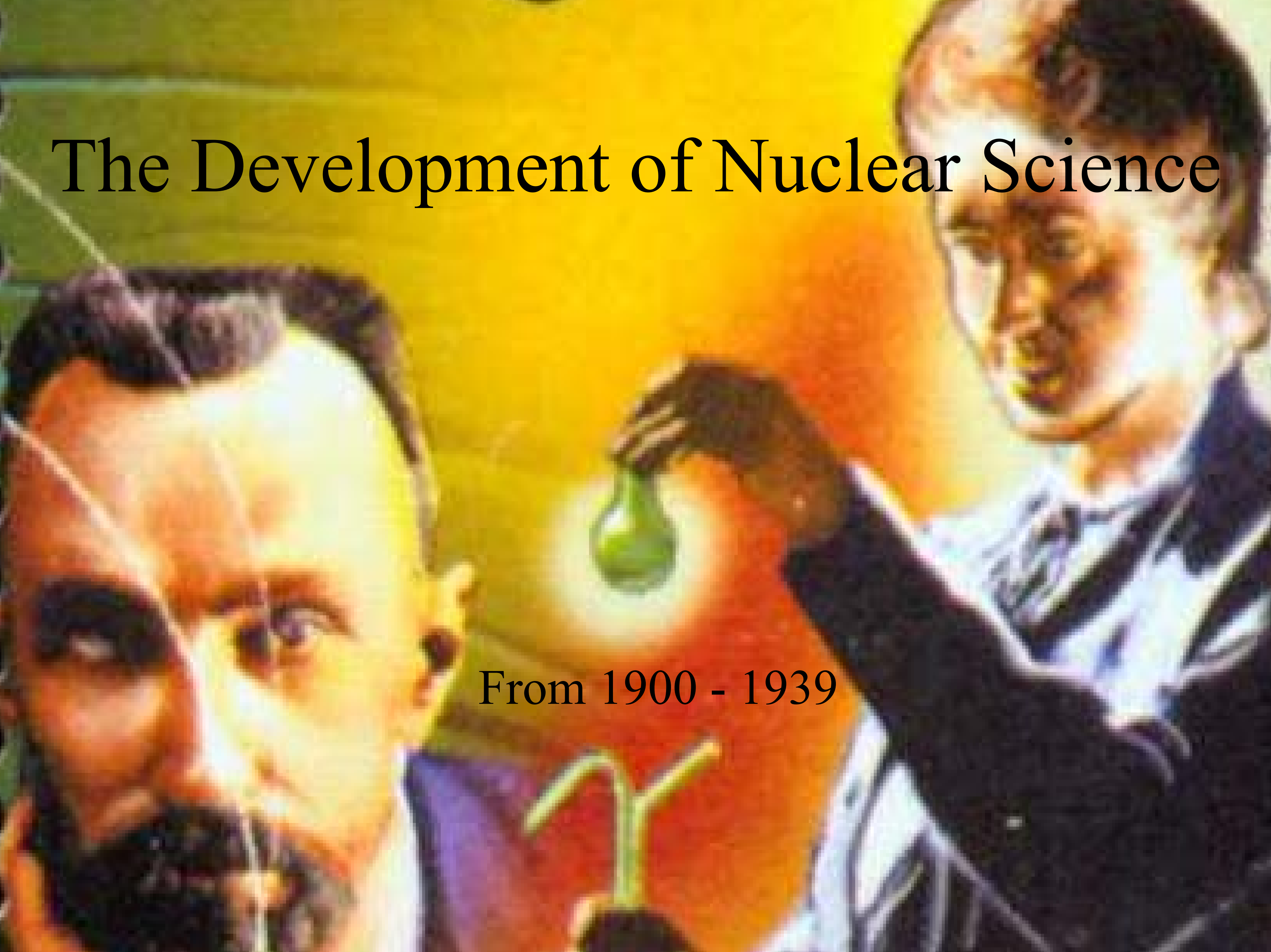
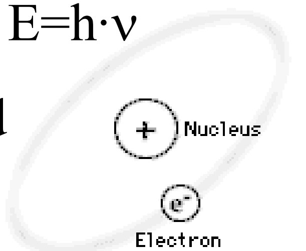
The Development of Nuclear Science

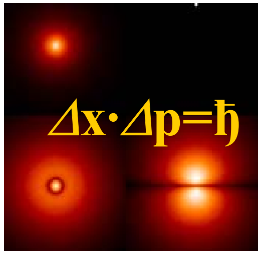
From 1900 - 1939



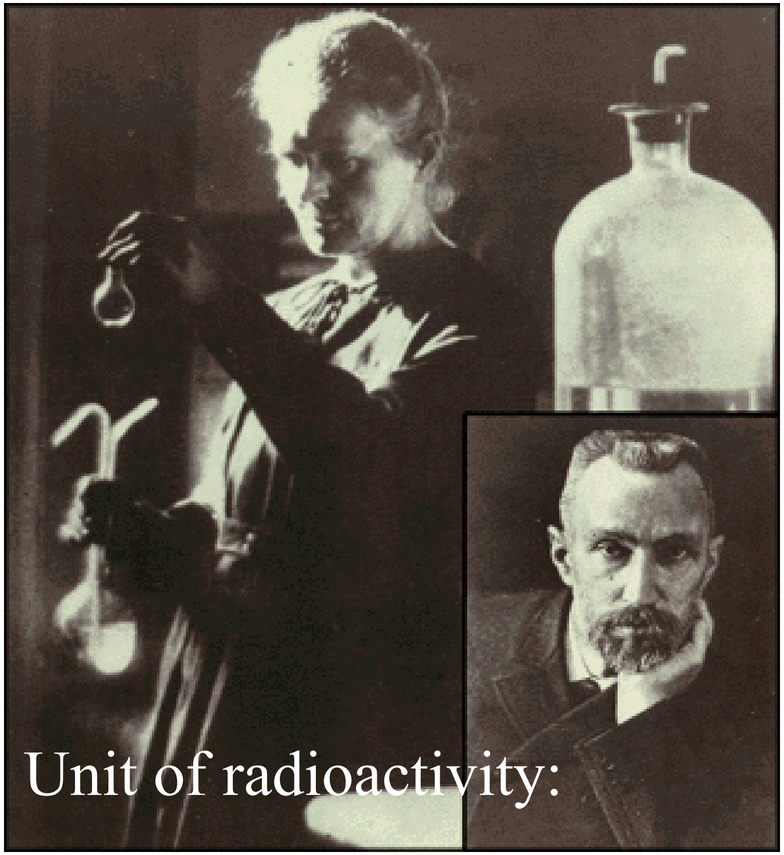
The Development of Scientific Thought in the 20th Century

Discovery & study of radioactivity	1898	Marie &.Pierre Curie	
Introduction of quantum concept	1900	Max Planck	h
Theory of special relativity	1905	Albert Einstein	$E=m\cdot c^2$
Quantization of light (photoelectric effect)	1905	Albert Einstein	$E=h\cdot\nu$
Discovery of atomic nucleus	1911	Ernest Rutherford	
Interpretation of atom structure	1913	Nils Bohr	
Particle waves	1924	Louis de Broglie	
Wave mechanics	1925	Erwin Schrödinger	
Uncertainty principle	1927	Werner Heisenberg	
Discovery of Neutron	1932	James Chadwick	
Artificial Radioactivity (Reactions)	1934	Frederic Joliot & Irene Curie	
Discovery of fission	1938	Otto Hahn, Fritz Strassmann	
Interpretation of fission	1938	Liese Meitner, Otto Frisch	
Prediction of thermonuclear fusion	1939	C.F. v. Weizsäcker, H. Bethe	





The new radiating material



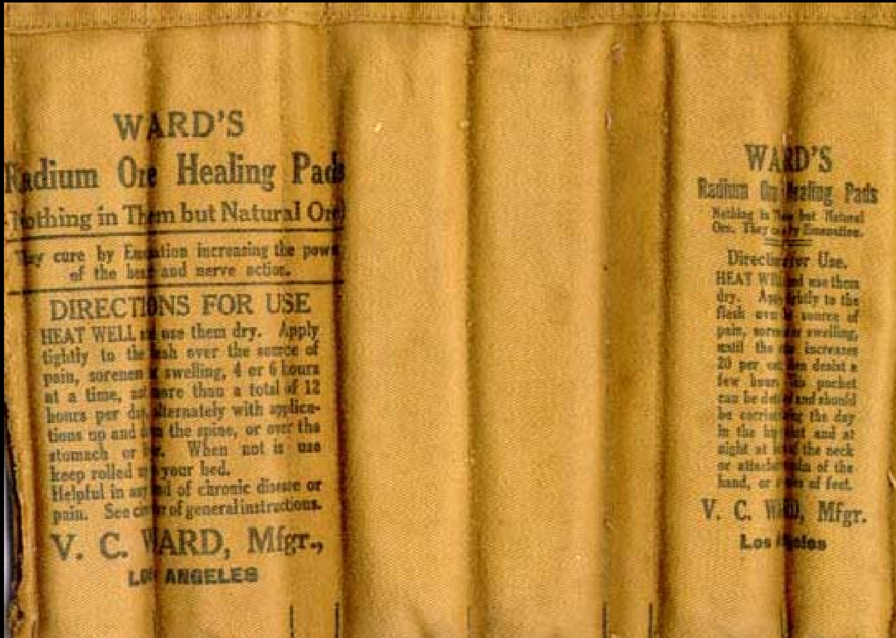
Radioactive material such as Uranium - first discovered by Henri Becquerel – was studied extensively by Marie and Pierre Curie. They discovered other natural radioactive elements such as Radium and Polonium.

Nobel Prize 1903 and 1911!

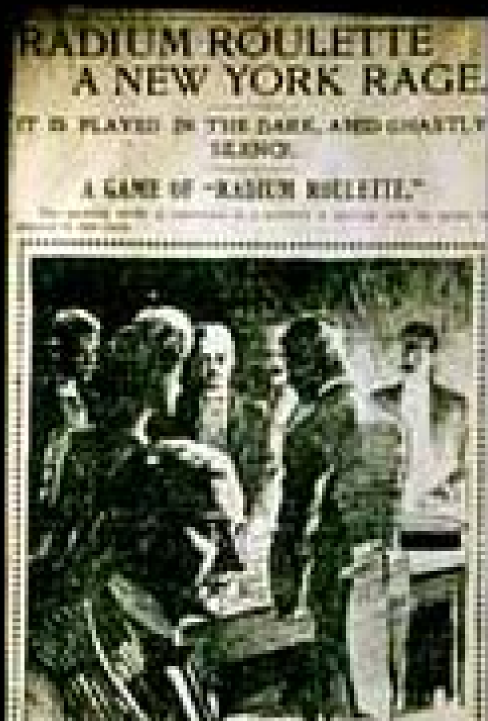
Unit of radioactivity:

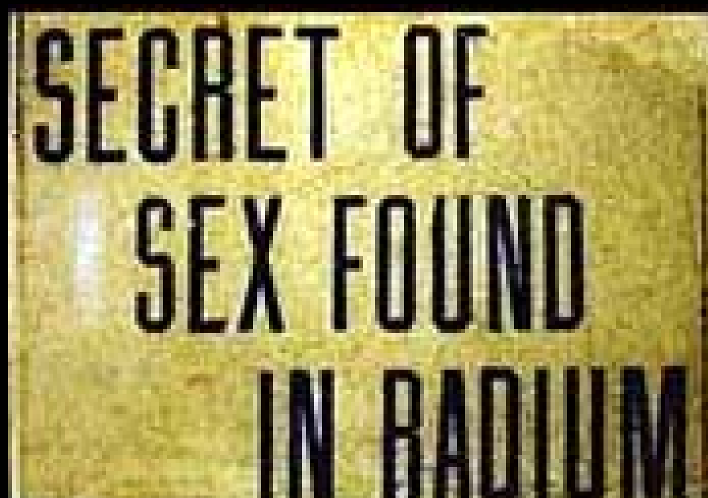
The activity of 1g Ra = 1Ci = $3.7 \cdot 10^{10}$ decays/s   1Bq = 1 decay/s

Discovery triggered a unbounded enthusiasm and led to a large number of medical and industrial applications



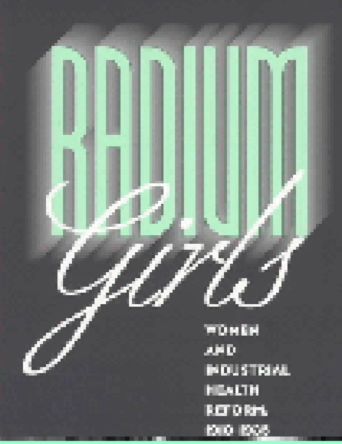
Applications for Radioactivity





Applications

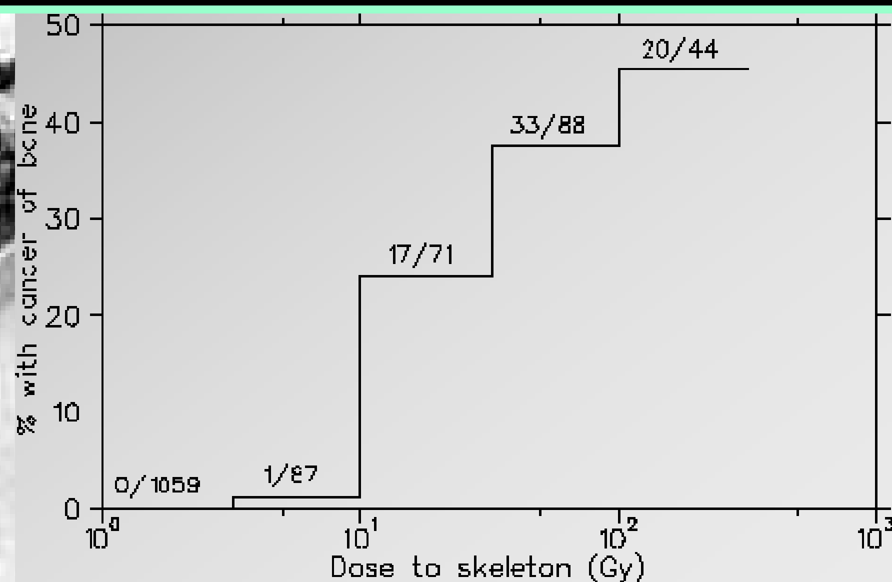
Popular products included radioactive toothpaste for cleaner teeth and better digestion, face cream to lighten the skin; radioactive hair tonic, suppositories, and radium-laced chocolate bars marketed in Germany as a "rejuvenator." In the U.S, hundreds of thousands of people began drinking bottled water laced with radium, as a general elixir known popularly as "liquid sunshine." As recently as 1952 LIFE magazine wrote about the beneficial effects of inhaling radioactive radon gas in deep mines. As late as 1953, a company in Denver was promoting a radium-based contraceptive jelly.



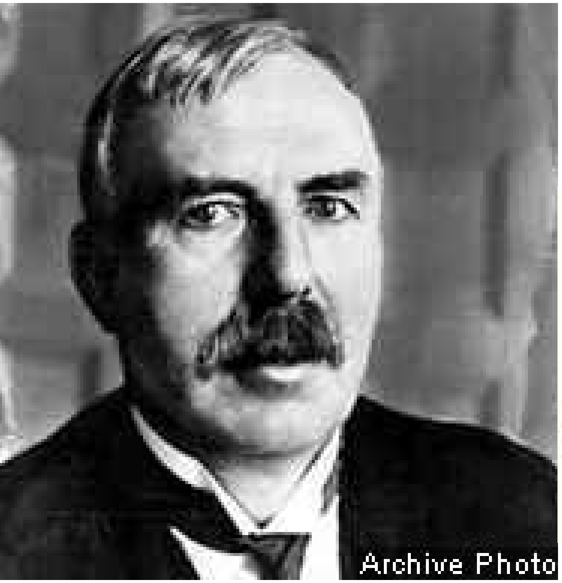
Radium Dials

Increase in cancer (tongue – bone) due to extensive radium exposure

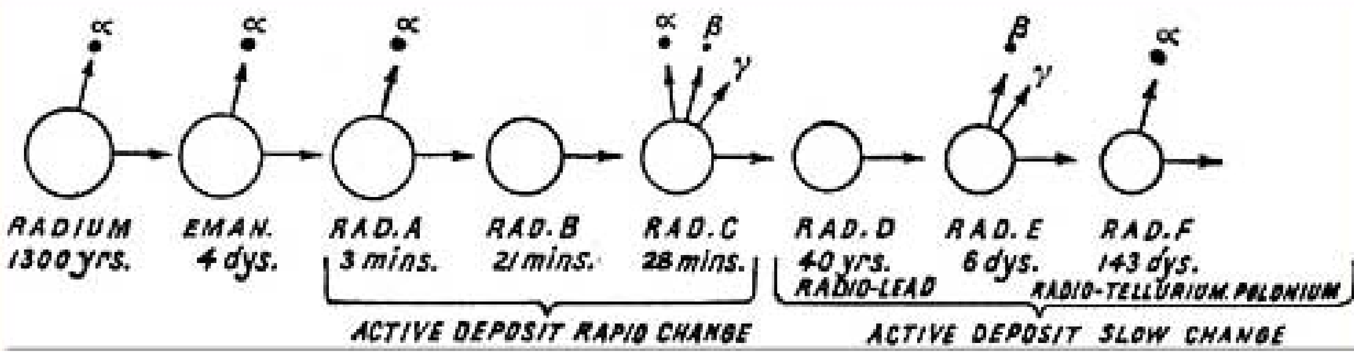
According to a Department of Commerce Information Circular from 1930, the radium paint might contain "from 0.7 to 3 and even 4 milligrams of radium”; this corresponds to a radioactivity level of 0.7 to 4 mCi or 26-150 GBq in modern units.



Explanation of natural radioactivity



Radioactivity comes in three forms α, β, γ

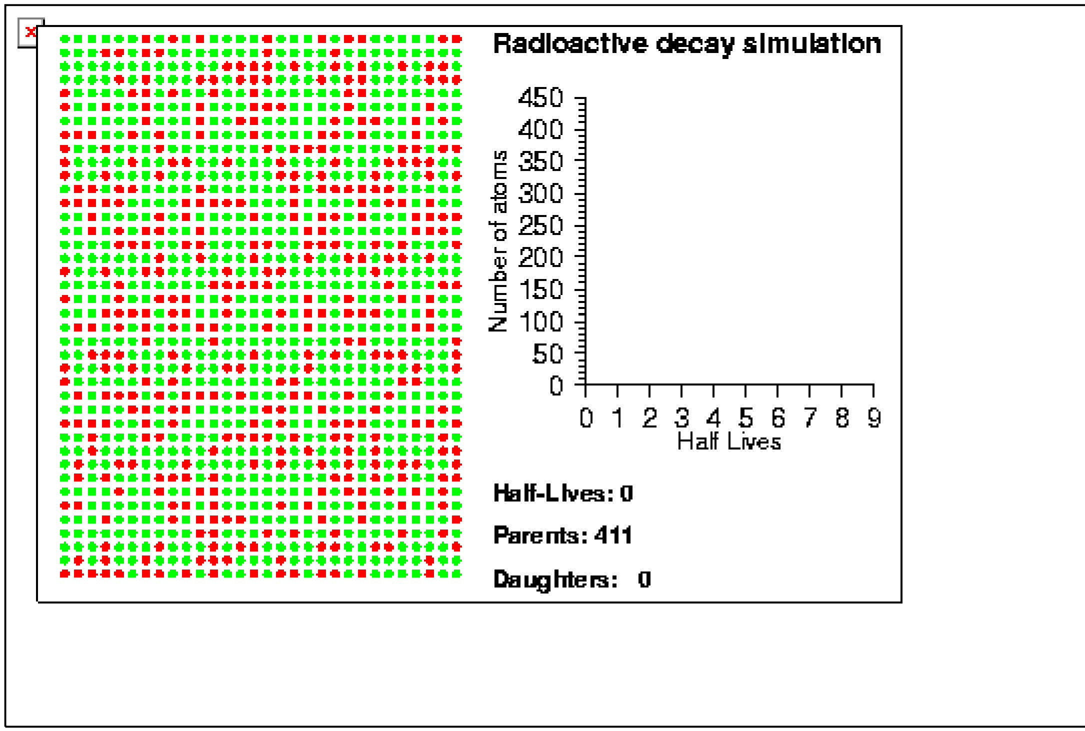


Nobel Prize 1908

Ernest Rutherford's

picture of transmutation. A radium atom emits an alpha particle, turning into "Emanation" (in fact the gas radon). This atom in turn emits a particle to become "Radium A" (now known to be a form of polonium). The chain eventually ends with stable lead. *Philosophical Transactions of the Royal Society of London,* 1905.

The radioactive decay law



exponential decay with time!

$$A_{mother}(t) = A_0 \cdot e^{-\lambda \cdot t}$$

$$A_{daughter}(t) = A_0 \cdot \left(1 - e^{-\lambda \cdot t}\right)$$

$\lambda \equiv$ decay constant;
a natural constant
for each radioactive
element.
Half life: $t_{1/2} = \ln 2/\lambda$

1st example: ^{22}Na

^{22}Na has a half-life of 2.6 years, what is the decay constant?
Mass number A=22; (don't confuse with activity *A(t)!*)

$$\lambda = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{2.6\,y} = 0.27\,y^{-1} :$$

$$1\,y = 3.14 \cdot 10^{7}\,s \approx \pi \cdot 10^{7}\,s$$

$$\lambda = \frac{\ln 2}{2.6 \cdot 3.14 \cdot 10^{7}\,s} = 8.5 \cdot 10^{-9}\,s^{-1}$$

radioactive decay laws

Activity of radioactive substance *A(t)* is at any time t proportional to number of radioactive particles *N(t)* :

$$A(t) = \lambda \cdot N(t)$$

A ^{22}Na source has an activity of 1 μCi = 10^{-6} Ci,
how many ^{22}Na isotopes are contained in the source?
(1 Ci = $3.7 \cdot 10^{10}$ decays/s)

$$N = \frac{A}{\lambda} = \frac{10^{-6}\,Ci}{8.5 \cdot 10^{-9}\,s^{-1}} = \frac{10^{-6} \cdot 3.7 \cdot 10^{10}\,s^{-1}}{8.5 \cdot 10^{-9}\,s^{-1}} = 4.36 \cdot 10^{12}$$

How many grams of ^{22}Na are in the source?

A gram of isotope with mass number A contains N_A isotopes

$$N_A \equiv \text{Avogadro's Number} = 6.023 \cdot 10^{23}$$

⇨ 22g of ^{22}Na contains $6.023 \cdot 10^{23}$ isotopes

$$N = 4.36 \cdot 10^{12} \ particles$$

$$1g = \frac{6.023 \cdot 10^{23}}{22} particles$$

$$N = \frac{22 \cdot 4.36 \cdot 10^{12}}{6.023 \cdot 10^{23}} g = 1.59 \cdot 10^{-10} g$$

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

How many particles are in the source after 1 y, 2 y, 20 y?

$$N(t) = 4.36 \cdot 10^{12} \cdot e^{-0.27\,y^{-1} \cdot t} \qquad A(t) = \lambda \cdot N(t) = 8.5 \cdot 10^{-9}\,s^{-1} \cdot N(t)$$

$$N(1y) = 4.36 \cdot 10^{12} \cdot e^{-0.27\,y^{-1} \cdot 1y} = 3.33 \cdot 10^{12} \qquad A(1y) = 28305\,s^{-1} = 0.765\,\mu Ci$$

$$N(2y) = 4.36 \cdot 10^{12} \cdot e^{-0.27\,y^{-1} \cdot 2y} = 2.54 \cdot 10^{12} \qquad A(2y) = 21590\,s^{-1} = 0.58\,\mu Ci$$

$$N(10y) = 4.36 \cdot 10^{12} \cdot e^{-0.27\,y^{-1} \cdot 10y} = 2.93 \cdot 10^{11} \qquad A(10y) = 2490.5\,s^{-1} = 0.067\,\mu Ci$$

Decay in particle number and corresponding activity!

2^{nd} example: Radioactive Decay

Plutonium ^{239}Pu, has a half life of 24,360 years.

1. What is the decay constant?
2. How much of 1kg ^{239}Pu is left after 100 years?

$$\lambda = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{24360y} = 2.85 \cdot 10^{-5} y^{-1}$$

$$N_{^{239}Pu}(t) = N_0 \cdot e^{-\lambda \cdot t} \Rightarrow N_{^{239}Pu}(100y) = 1kg \cdot e^{-2.85 \cdot 10^{-5} y^{-1} \cdot 100y}$$

$$N_{^{239}Pu}(100y) = 0.9972kg$$

$$N_{^{239}Pu}(1{,}000y) = 0.9719kg$$

$$N_{^{239}Pu}(10{,}000y) = 0.7520kg$$

$$N_{^{239}Pu}(24{,}360y) = 0.5kg$$

$$N_{^{239}Pu}(100{,}000y) = 0.0578kg$$

The first step: $E=m\cdot c^2$

"It followed from the special theory of relativity that mass and energy are both but different manifestations of the same thing - a somewhat unfamiliar conception for the average mind. Furthermore, the equation E is equal to m c-squared, in which energy is put equal to mass, multiplied by the square of the velocity of light, showed that very small amounts of mass may be converted into a very large amount of energy and vice versa. The mass and energy were in fact equivalent, according to the formula mentioned before. This was demonstrated by Cockcroft and Walton in 1932, experimentally."

Albert Einstein

Nobel Prize 1921

Example: Mass-Energy

$$E = mc^2 \qquad 1\,J = 1\,kg\left(\frac{m}{s}\right)^2 \qquad c = 3\cdot 10^8\ \frac{m}{s}$$

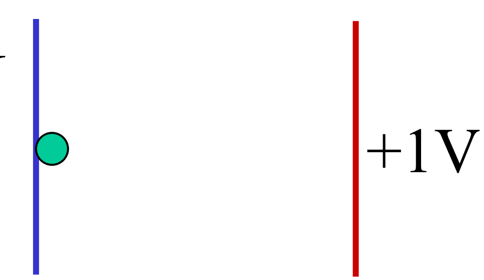
1kg of matter corresponds to an energy of:

$$E = 1kg\cdot\left(3\cdot 10^8\ m/s\right)^2 = 9\cdot 10^{16}\,kg\left(\frac{m}{s}\right)^2 = 9\cdot 10^{16}\,J$$

Definition: 1 ton of TNT = 4.184 x 10^9 joule (J).

1 kg (2.2 lb) of matter converted completely into energy would be equivalent to the energy released by exploding 22 megatons of TNT.

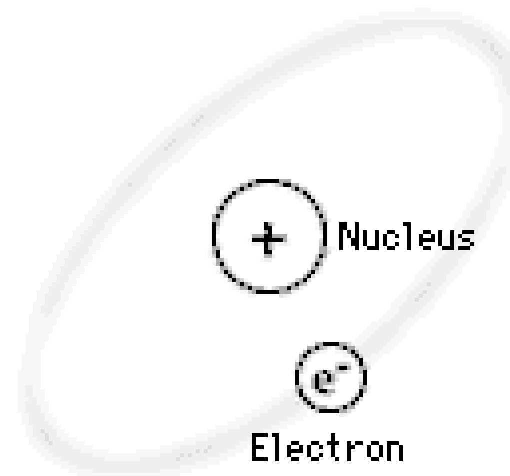
Nuclear physics units: $1\,eV = 1.6\cdot 10^{-19}\,J$



1 electron-volt is the energy one electron picks up if accelerated in an electrical potential of one Volt.

The discovery of the neutron

By 1932 nucleus was thought to consist of protons and electrons which were emitted in β-decay. New Chadwick's experiment revealed a third particle, the neutron



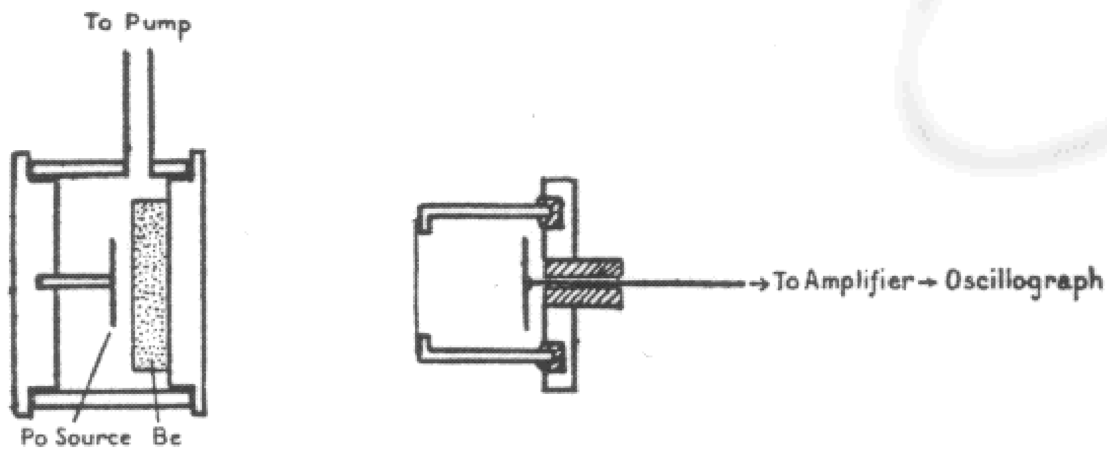
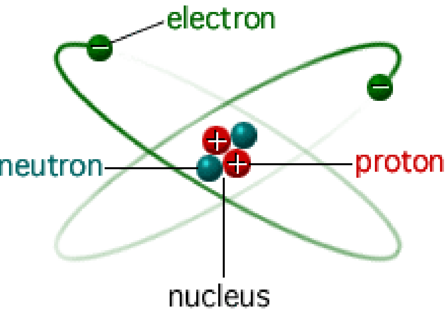


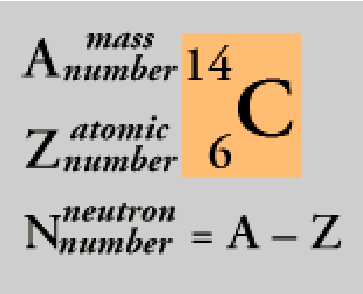
FIG. 1.

Nobel Prize 1935

Strong Polonium source emitted α particles which bombarded Be; radiation was emitted which – based on energy and momentum transfer arguments - could only be neutral particles with similar mass as protons $\Rightarrow$ neutrons: BEGIN OF NUCLEAR PHYSICS!



The model of the nucleus



Nucleus with Z protons (p) and N neutrons (n) with a total mass number A=Z+N

Hydrogen: 1 p, 0,1 n $\,^{1}_{1}H_{0}$ $\,^{2}_{1}D_{1}$

Helium: 2 p, 1,2 n $\,^{3}_{2}He_{1}$ $\,^{4}_{2}He_{2}$

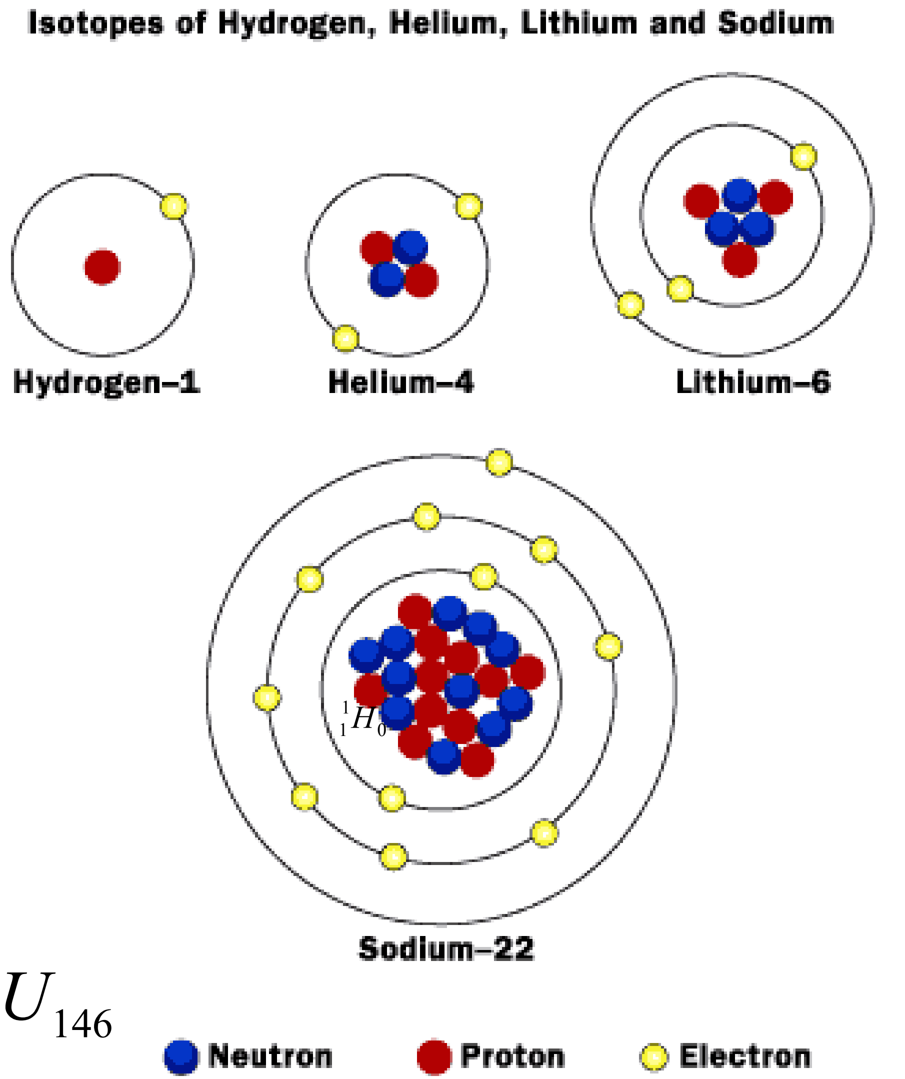
Lithium: 3 p, 3,4 n $\,^{6}_{3}Li_{3}$ $\,^{7}_{3}Li_{4}$

Carbon: 6 p, 6,7 n $\,^{12}_{6}C_{6}$ $\,^{13}_{6}C_{7}$

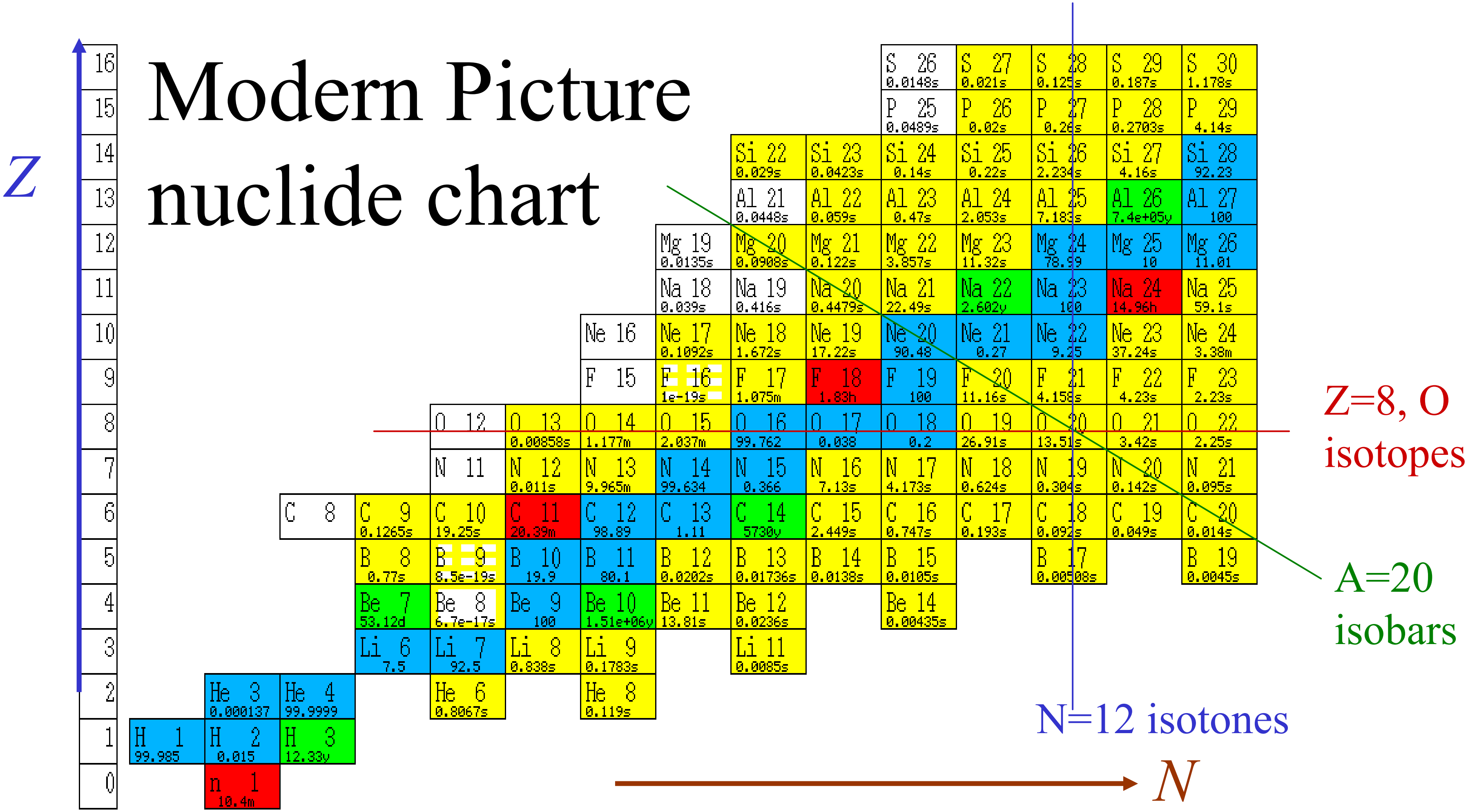
…

…

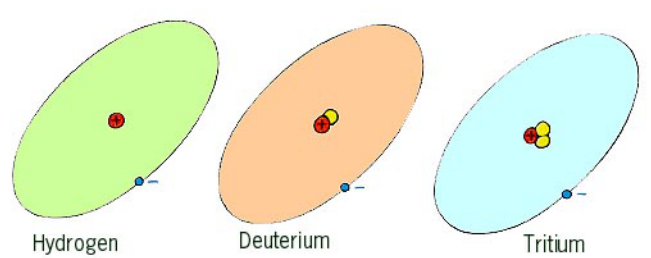
Uranium: 92 p, 143,146 n $\,^{235}_{92}U_{143}$ $\,^{238}_{92}U_{146}$



Modern Picture nuclide chart



hydrogen isotopes: Z=1



Isotopes: Z=constant, N varies!

Isotones: N=constant, Z varies!

Isobars: A=constant, Z,N varies!

Energy in Nuclei

According to Einstein's formula each nucleus with certain mass ***m*** stores energy $E=mc^2$

Proton	m_p	$= 1.007596 \cdot 1.66 \cdot 10^{-24}$ g	$= 1.672 \cdot 10^{-24}$ g
Neutron	m_n	$= 1.008486 \cdot 1.66 \cdot 10^{-24}$ g	$= 1.674 \cdot 10^{-24}$ g
Carbon	$m_{^{12}C}$	$= 12.00000 \cdot 1.66 \cdot 10^{-24}$ g	$= 1.992 \cdot 10^{-23}$ g
Uranium	$m_{^{238}U}$	$= 238.050783 \cdot 1.66 \cdot 10^{-24}$ g	$= 3.952 \cdot 10^{-22}$ g

Binding energy B of nucleus

$$B = (Z \cdot m_p + N \cdot m_n - M) \cdot c^2$$

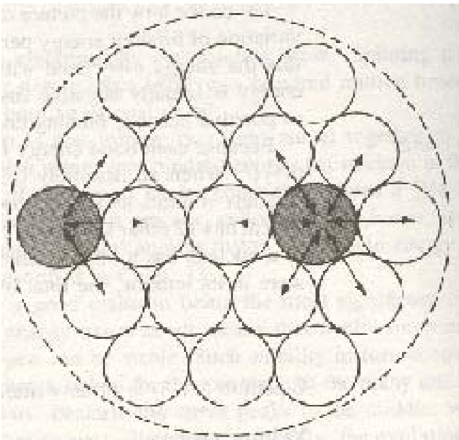
$B(^{12}C) = 1.47 \cdot 10^{-11}$ J; $B/A = 1.23 \cdot 10^{-12}$ J

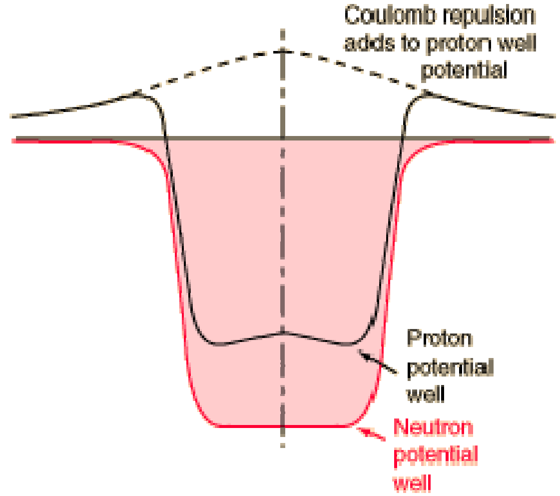
$B(^{238}U) = 2.64 \cdot 10^{-10}$ J; $B/A = 1.21 \cdot 10^{-12}$ J

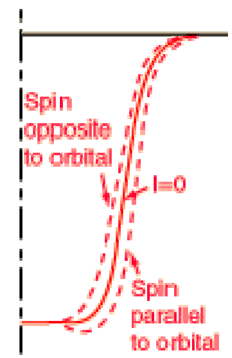
1 amu=1/12($M^{12}C$)=$1.66 \cdot 10^{-24}$ g

Breaking up nuclei into their constituents requires energy

Nuclear Potential







$$B = a_v \cdot A - a_s \cdot A^{2/3} - a_c \cdot Z \cdot (Z-1) \cdot A^{-1/3} - a_{sym} \cdot \frac{(A-2Z)^2}{A} + \delta$$

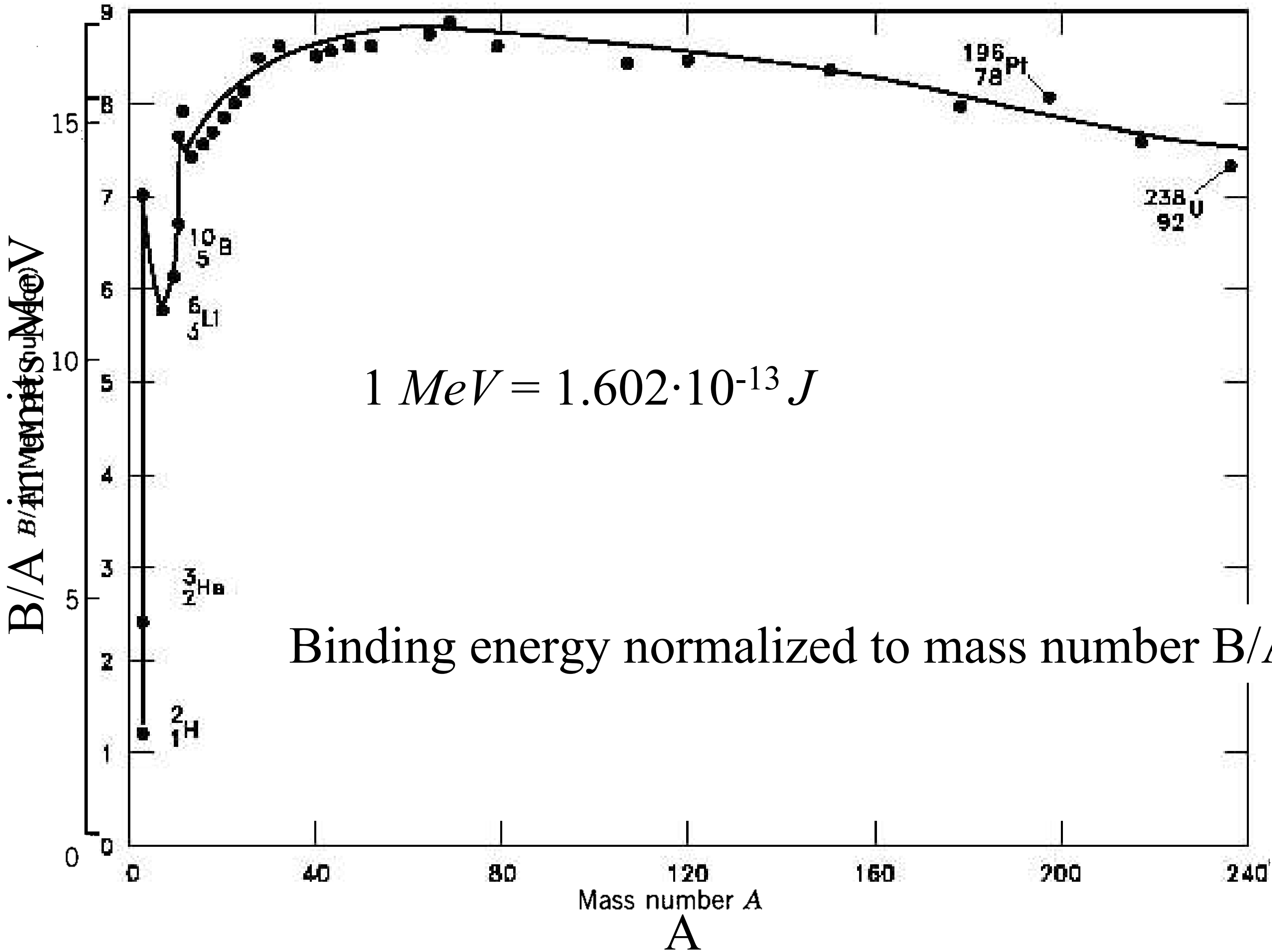
$$\delta = +a_p \cdot A^{-4/3}\ (Z, N\ even);\ \delta = -a_p \cdot A^{-4/3}\ (Z, N\ odd);\ \delta = 0\ (A = Z + N\ odd);$$

$$a_v = 15.5 MeV;\ a_s = 16.8 MeV;\ a_c = 0.72 MeV;\ a_{sym} = 23 MeV;\ a_p = 34 MeV$$

http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/liqdrop.html#c2

$$1\ MeV = 1.602 \cdot 10^{-13}\ J$$

Nuclear Binding Energy



$1\ MeV = 1.602 \cdot 10^{-13}\ J$

Binding energy normalized to mass number B/A

Example: Nuclear Binding Energy

Conversion of nuclei through fusion or fission leads to release of energy!

isotope	B (J)
^{2}H	$3.34131\cdot10^{-13}$
^{4}He	$4.53297\cdot10^{-12}$
^{12}C	$1.47643\cdot10^{-11}$
^{119}Pd	$1.59643\cdot10^{-10}$
^{238}U	$2.88631\cdot10^{-10}$

$$^{2}_{1}H_1 + ^{2}_{1}H_1 \Rightarrow ^{4}_{2}He_2 + Q$$

$$Q = B(^{4}He) - 2\cdot\left(B(^{2}H) + B(^{2}H)\right)$$

$$Q = 2\cdot 3.34131\cdot10^{-13}J - 4.53295\cdot10^{-12}J = 3.8647\cdot10^{-12}J$$

$$^{238}_{92}U_{146} \Rightarrow 2\ ^{119}_{46}Pd_{73} + Q$$

$$Q = B(^{119}_{46}Pd_{73}) + B(^{119}_{46}Pd_{73}) - B(^{238}_{92}U_{146})$$

$$Q = 2.88631\cdot10^{-10}J - 2\cdot1.59633\cdot10^{-10}J = 3.06542\cdot10^{-11}J$$

http://ie.lbl.gov/toimass.html
http://nucleardata.nuclear.lu.se/database/masses/
http://www.nndc.bnl.gov/masses/mass.mas03

Nuclear Energy possible through fission and fusion