

**NE585**  
**NUCLEAR FUEL CYCLES**  
**Nuclear engineering basics**  
**1**

**R. A. Borrelli**

**University of Idaho**



**Idaho Falls Center for Higher Education**

# Learning objectives

Demonstrating fundamental concepts in nuclear physics

Analyzing decay data to identify radionuclides

Summarizing different decay mechanisms

Book – Chapter 2

# Learning nodes

**Relativity**

**Atomic structure**

**Binding energy**

**Q-value**

**Radioactivity**

**Chart of the nuclides**

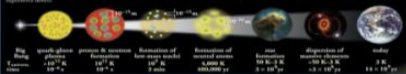
**Decay chains**

**Half life**

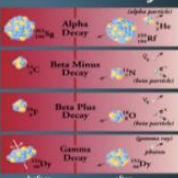
# Nuclear Science

## Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about  $10^9$  seconds, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. As time the temperature of the Universe cooled to about  $10^8$  K, this soup of quarks and gluons formed protons, neutrons, and electrons. As time passed, the temperature of the Universe cooled to about  $10^4$  K, and the electrons and protons combined to form neutral atoms. This is the point at which the universe became transparent to light. The matter in the universe was made of four normal matter. Due to gravity, clumps of matter condensed into stars, which burned and before long formed the first heavy chemical elements. Exploding stars (supernovae) form the most reactive elements and disperse them into space. Our earth was formed from supernovae debris.



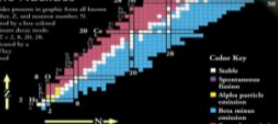
## Radioactivity



**Relaxation during transformations** is achieved by including different relaxation times for  $\alpha$  and  $\beta$  phases. The relaxation behavior of the  $\beta$  phase is taken to be identical to that of the  $\alpha$  phase parallel to the  $\beta$  axis, and the relaxation behavior of the  $\alpha$  phase is taken to be identical to that of the  $\beta$  phase perpendicular to the  $\beta$  axis. The same relaxation times are used for the  $\alpha$  and  $\beta$  phases. According to the assumption of uniform deformation, the relaxation times of the  $\alpha$  and  $\beta$  phases are assumed to be identical. The relaxation times of the  $\alpha$  and  $\beta$  phases are assumed to be identical.

## Chart of the Nuclides

The Chart of the Nuclides presents in graphic form all known nuclei with atomic number,  $Z$ , and mass number,  $N$ . Each nuclide is represented by a box outlined according to its predominant decay mode. **Major numbers** ( $N$  or  $Z = 2, 8, 20, 28, 50, 82$  and 126) are indicated by a triangle on the chart. They correspond to major shell gaps and these regions of greater nuclear binding energy.



**Color Key**

- Stable
- Spontaneous fission
- Alpha particle emission
- Beta minus emission
- Beta plus emission or electron capture

[www.CPEPweb.org](http://www.CPEPweb.org)

**Nuclear Science** is the study of the structure, properties, and interactions of the atomic nucleus. Nuclear scientists calculate and measure the masses, shapes, sizes, and decays of nuclei at rest and in motion. They ask questions, such as: Why do nucleons stay in the nucleus? What configurations of protons and neutrons are good? What happens when nuclei are compressed or rapidly rotated? What is the origin of the nuclei found on Earth?

**Legend**

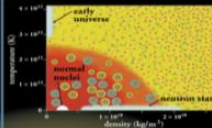
electron (e <sup>-</sup> )	quark	$A_{\text{electron}} = 18$
positron (e <sup>+</sup> )	gluon field	$Z_{\text{quark}} = 6$
neutrino	gluon	$N_{\text{gluon}} = 8$
antilepton (le <sup>+</sup> )	photon (γ)	$N_{\text{photon}} = 1$

### Unstable Nuclei

Stable nucleides form a narrow white band on the Chart of the Nuclides. Numerous products of unstable nucleides lie from this band and study their decay, thereby learning about the structure of nuclear excitations. In its present form, this chart contains about 2500 different nucleides. Nuclear theory predicts that there are at least 4000 more to be discovered with  $Z \leq 118$ .



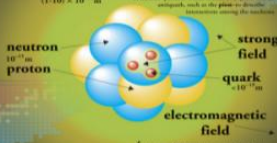
## Phases of Nuclear Matter



**N**uclear matter can exist in several phases. When collisions create nuclei, individual protons and neutrons may evaporate from the nucleus itself. At sufficiently high temperatures or densities, a gas of nucleons (and background) forms. At even more extreme conditions, individual nucleons may cease to have meaningful identities, merging into the quark-gluon plasma (yellow background). Current data provide hints that physicists have glimpsed the quark-gluon plasma.

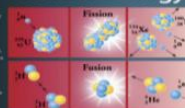
# The Nucleus

As the center of this story is a nucleus formed from nucleons—protons and neutrons. Each nucleon is made from three quarks held together by their strong interactions, which are mediated by gluons. In turn, the nucleon is held together by the strong interaction between the gluons and quarks comprising nucleons. Nuclear physicists often use the term *hadrons* to describe particles which consist of a pair of quarks, such as the *pions*—



In its turn, electrons range around the nucleus at distances typically up to 10,000 times the nuclear diameter. If the electron cloud were drawn to scale, this cloud would

## Nuclear Energy



*In the early stages of stellar evolution of gas giants and other stars, hydrogen flows to form bulges, releasing energy in the form of photons (light) and neutrinos. During the later stages of stellar evolution, more reactions melted up to and beyond uranium are accelerated by fusion. By increasing the number of reactions that occur from the base, scientists recently have demonstrated that reactions must have a mass greater than zero.*

## Applications



### Radioactive Dating



**Space Exploration**  
 Truncated and alpha particles, already observed elsewhere, are in Martian rocks. The Earth's structures are used to study ones from a distant hemisphere.



### Nuclear Reactors

Nuclear reactors use the fission of  $^{235}\text{U}$  or  $^{239}\text{Pu}$  nuclei to produce electric power. Reactors used most often today are pressurized water reactors (PWRs). In a PWR, the nuclear fission reaction heats water, which circulates through a secondary loop, heating it. The heated water then turns a turbine, which generates electricity. The PWR design is used in most nuclear power plants in the United States.



### Smoke Detectors

Many smoke detectors use a small amount of the alpha emitter  $^{241}\text{Am}$  to ionize the air. Smoke entering the detector reduces the current and sets off the alarm.



**Nuclear Medicine**  
Diagnostic images, such as  $^{99m}\text{Tc}$ ,  $^{18}\text{F}$ ,  $^{131}\text{I}$ , are commonly used in the diagnosis of diseases of bones. Positron emitters, such as  $^{18}\text{F}$ , are used in Positron Emission Tomography (PET) to generate images of the activities.



### Magnetic Resonance Imaging

Magnetic Resonance Imaging (MRI) makes use of magnetic resonances involving the spin state of a nucleus in order to build chemical structures. This technique accurately maps the density of hydrogen to produce three-dimensional images of the human body.

© Copyright 2007 Consortium for Physics Education Project (CPEP) MS 5800008 1050, Berkeley, CA 94720 USA. Support from U.S. Department of Energy, Ernest Orlando Lawrence Berkeley National Laboratory - Nuclear Science Division, American Physical Society - Division of Nuclear Physics, J.M. Waisbick Fund, U.S. National Science Foundation.

# Relativity

# We apply energy from nuclear reactions and radiation interactions with matter

$$E_{REST} = m_0 c^2 \quad (1)$$

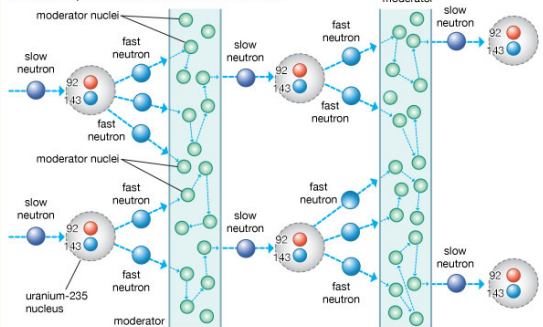
$$E = mc^2 \quad (2)$$

Rest mass energy for an electron – 0.511 *MeV*

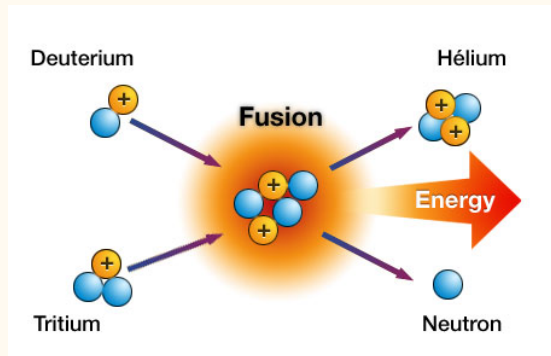
Save that for later

# Energy released or energy injected

Moderated, controlled fission of uranium-235



© 2012 Encyclopædia Britannica, Inc.



## Determine the energy of a fusion neutron that is not at rest

$$m = \frac{m_0}{\sqrt{1 - \left(\frac{v^2}{c^2}\right)}} \rightarrow E = mc^2 \quad (3)$$

With  $v = 5.2 \times 10^7 \text{ m/s}$ , that is about  $0.17c$ ; not negligible

So we have to compute the not rest mass

$$m_0(n) = 1.674927211 \times 10^{-27} \text{ kg}$$

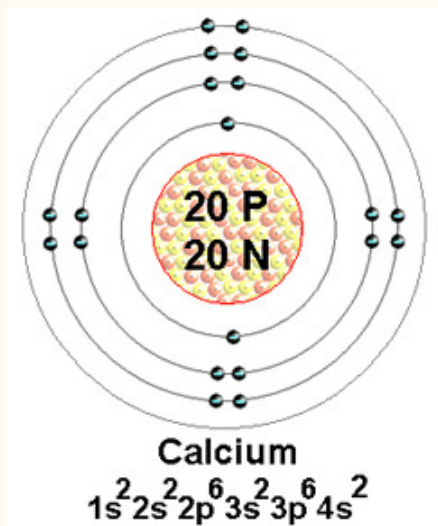
Fusion neutron at that speed has  $E = 14.5 \text{ MeV}$

For relativistic calculations use MeV



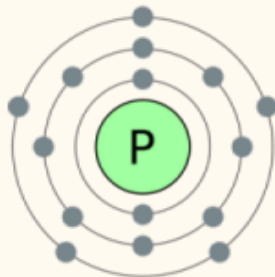
## **Atomic structure**

# The shell model describes how subatomic particles are arranged



15: Phosphorus

2,8,5



# Notation

$${}^A_Z Q_{A-Z} = {}^{235}_{92} U_{143}$$

# Periodic Table of the Elements



*Chem 3 Seaborg*

1 H Hydrogen 1.01																	2 He Helium 4.003	
3 Li Lithium 6.94	4 Be Beryllium 9.01																	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31																	18 Ar Argon 39.96
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.996	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.70	29 Cu Copper 63.55	30 Zn Zinc 65.37	31 Ga Gallium 69.72	32 Ge Germanium 72.59	33 As Arsenic 74.92	34 Se Selenium 78.96	35 Br Bromine 79.90	36 Kr Krypton 83.80	
37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.40	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.60	53 I Iodine 126.90	54 Xe Xenon 131.30	
55 Cs Cesium 132.91	56 Ba Barium 137.33	57 La Lanthanum 138.91	58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.93	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.97		
87 Fr Francium (223)	88 Ra Radium 226.03	89 Ac Actinium 227.03	90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium 237.05	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium 252	100 Fm Fermium 257	101 Md Mendelevium 261	102 No Nobelium 259	103 Lr Lawrencium 262		

atomic number

atomic weight

symbol

name

black

solid

blue

liquid

red

gas

white

synthetically prepared

most stable isotope

alkali metals

alkaline earth metals

transitional metals

other metals

nonmetals

noble gases

5  
B  
Boron  
10.81

6  
C  
Carbon  
12.01

7  
N  
Nitrogen  
14.01

8  
O  
Oxygen  
15.999

9  
F  
Fluorine  
18.998

10  
Ne  
Neon  
20.18

11  
Al  
Aluminum  
26.98

12  
Si  
Silicon  
28.08

13  
P  
Phosphorus  
30.97

14  
S  
Sulfur  
32.06

15  
Cl  
Chlorine  
35.45

16  
Ar  
Argon  
39.96

17  
K  
Potassium  
39.10

18  
Ca  
Calcium  
40.08

19  
Sc  
Scandium  
44.96

20  
Ti  
Titanium  
47.88

21  
V  
Vanadium  
50.94

22  
Cr  
Chromium  
51.996

23  
Mn  
Manganese  
54.94

24  
Fe  
Iron  
55.85

25  
Co  
Cobalt  
58.93

26  
Ni  
Nickel  
58.70

27  
Cu  
Copper  
63.55

28  
Zn  
Zinc  
65.37

29  
Ga  
Gallium  
69.72

30  
Ge  
Germanium  
72.59

31  
As  
Arsenic  
74.92

32  
Se  
Selenium  
78.96

33  
Br  
Bromine  
79.90

34  
Kr  
Krypton  
83.80

35  
Rb  
Rubidium  
85.47

36  
Sr  
Strontium  
87.62

37  
Y  
Yttrium  
88.91

38  
Zr  
Zirconium  
91.22

39  
Nb  
Niobium  
92.91

40  
Mo  
Molybdenum  
95.94

41  
Tc  
Technetium  
(98)

42  
Ru  
Ruthenium  
101.07

43  
Rh  
Rhodium  
102.91

44  
Pd  
Palladium  
106.40

45  
Ag  
Silver  
107.87

46  
Cd  
Cadmium  
112.41

47  
In  
Indium  
114.82

48  
Sn  
Tin  
118.71

49  
Sb  
Antimony  
121.76

50  
Te  
Tellurium  
127.60

51  
I  
Iodine  
126.90

52  
Xe  
Xenon  
131.30

53  
Cs  
Cesium  
132.91

54  
Ba  
Barium  
137.33

55  
La  
Lanthanum  
138.91

56  
Ce  
Cerium  
140.12

57  
Pr  
Praseodymium  
140.91

58  
Nd  
Neodymium  
144.24

59  
Pm  
Promethium  
(145)

60  
Sm  
Samarium  
150.36

61  
Eu  
Europium  
151.96

62  
Gd  
Gadolinium  
157.25

63  
Tb  
Terbium  
158.93

64  
Dy  
Dysprosium  
162.50

65  
Ho  
Holmium  
164.93

66  
Er  
Erbium  
167.26

67  
Tm  
Thulium  
168.93

68  
Yb  
Ytterbium  
173.04

69  
Lu  
Lutetium  
174.97

70  
Hf  
Hafnium  
178.49

71  
Ta  
Tantalum  
180.95

72  
W  
Tungsten  
183.85

73  
Re  
Rhenium  
186.21

74  
Os  
Osmium  
190.23

75  
Ir  
Iridium  
192.22

76  
Pt  
Platinum  
195.08

77  
Au  
Gold  
196.97

78  
Hg  
Mercury  
200.59

79  
Tl  
Thallium  
204.38

80  
Pb  
Lead  
207.19

81  
Bi  
Bismuth  
208.98

82  
Po  
Polonium  
(209)

83  
At  
Astatine  
(210)

84  
Rn  
Radon  
(222)

85  
Fr  
Francium  
(223)

86  
Ra  
Radium  
226.03

87  
Ac  
Actinium  
227.03

88  
Th  
Thorium  
232.04

89  
Pa  
Protactinium  
231.04

90  
U  
Uranium  
238.03

91  
Np  
Neptunium  
237.05

92  
Pu  
Plutonium  
244

93  
Am  
Americium  
243

94  
Cm  
Curium  
247

95  
Bk  
Berkelium  
247

96  
Cf  
Californium  
251

97  
Es  
Einsteinium  
252

98  
Fm  
Fermium  
257

99  
Md  
Mendelevium  
261

100  
No  
Nobelium  
259

101  
Lr  
Lawrencium  
262

© 1999 Lawrence Berkeley National Laboratory

**Binding energy**

# There are four fundamental forces of interaction

Gravity – Obvious

*Strong nuclear – Holds the nucleus together*

Electromagnetic – Basically electrons & magnetism

Weak nuclear – Changes the flavor of quarks

## To blow out a nucleus, a lot of energy is needed

Would it be constant or variable per nucleus?

Why would you want to blow out the nucleus?

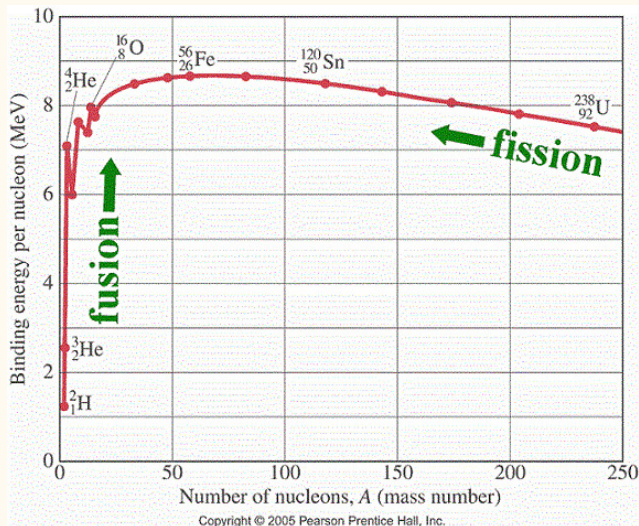
$$\Delta m = (A - Z)m_n - Zm_p - M \quad (4)$$

$$\Delta m({}_{94}^{239}\text{Pu}) = 1759 \text{ MeV} = 7.40 \frac{\text{MeV}}{\text{nucleon}} \quad (5)$$

This energy corresponds to a velocity of 0.88c

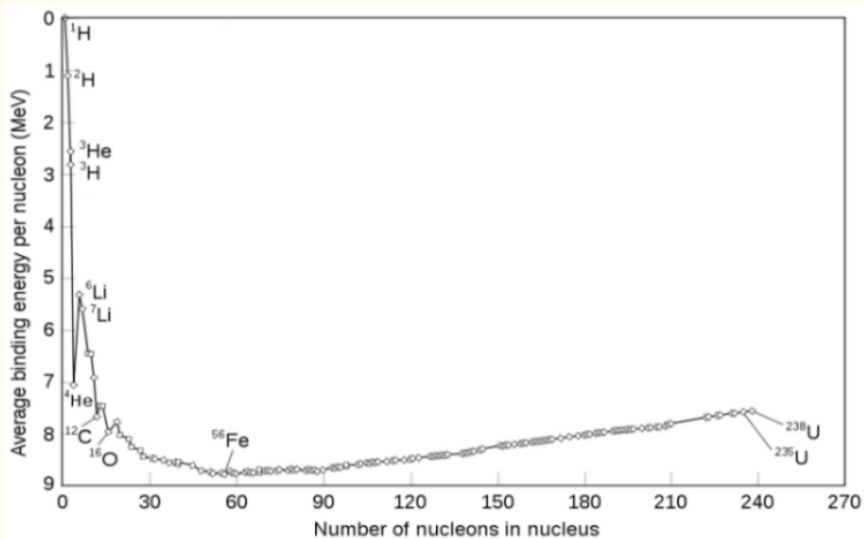
$$931.5 \frac{\text{MeV}}{\text{amu}}$$

# Binding energy is used to compare atomic stability, reaction energy, probability of fission/fusion



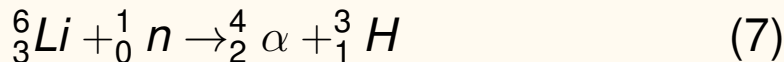
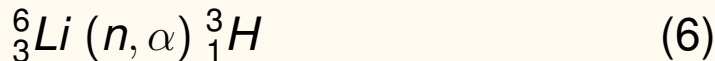


# Light nuclei get more stable by fusion; heavy nuclei get more stable by fission



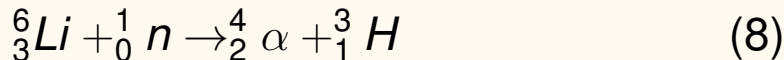
**Q-value**

# The Q-value for a reaction indicates energy requirements



- (1) Conservation of nucleons
- (2) Conservation of charge
- (3) Conservation of momentum
- (4) Conservation of energy

## Compute the Q value for this reaction



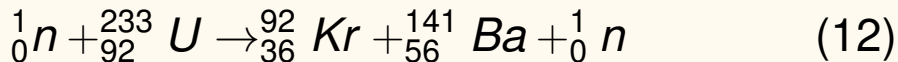
$$Q = [(M_{\text{Li}} + M_n) - (M_{\alpha} + M_H)]c^2 \quad (9)$$

$$Q = 4.78 \text{ MeV} \quad (10)$$

$$Q > 0 \rightarrow ?$$

$$Q < 0 \rightarrow ?$$

# What is the energy of fission from thorium and uranium fuel cycles?



For comparison, burning a carbon atom releases 4 eV

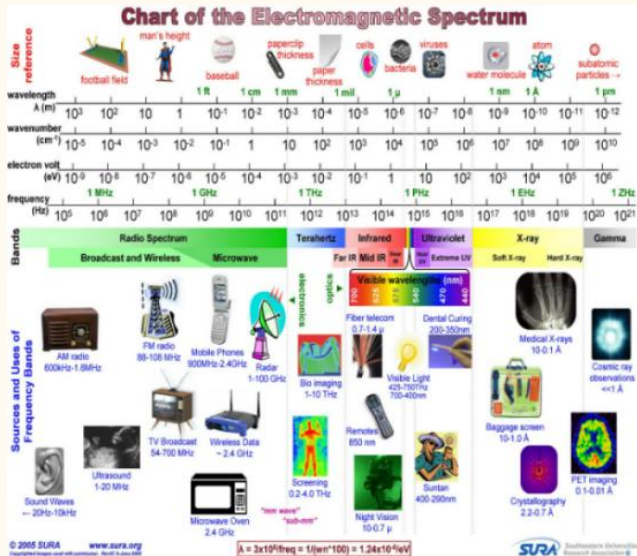
# Radioactivity

# Scientists in late 1800s made discoveries which would change the course of science, medicine, and history in the 20th Century



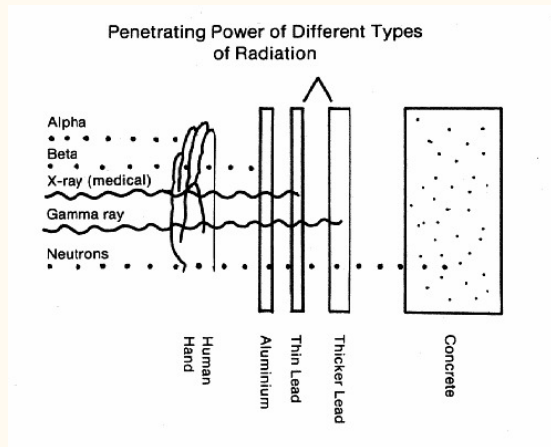
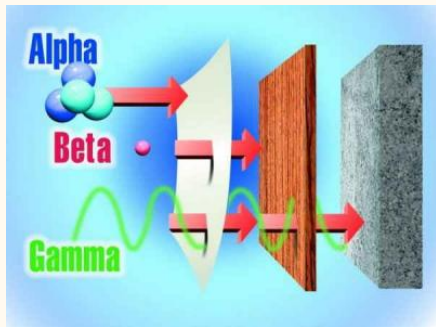
The Nobel Prize in Physics 1903 was divided, one half awarded to Antoine Henri Becquerel *"in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity"* the other half jointly to Pierre Curie and Marie Curie, née Sklodowska *"in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel"*.

# Radiation is energy as particles or electromagnetic waves, like sunshine





# Radiation is energy as particles or electromagnetic waves



# Radiation is energy as particles or electromagnetic waves

Charged particles are –

- protons (+)
- alpha (++)
- beta (+/-)
- heavy ions (varying)
- U,Pu (3+,4+,5+,6+)

Neutrons have no charge, but are also ionizing

Ionizing rays are x-rays, g-rays, cosmic rays

# Ernest Rutherford discovered the three main kinds of radioactive decay (Chemistry Nobel 08)

## Radioactivity

**Alpha Decay**

$^{263}_{106}\text{Sg} \rightarrow ^{259}_{104}\text{Rf} + ^4_2\text{He}$  (alpha particle)

**Beta Minus Decay**

$^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + e^- + \bar{\nu}_e$  (beta particle)

**Beta Plus Decay**

$^{18}_9\text{F} \rightarrow ^{18}_8\text{O} + e^+ + \nu_e$  (beta particle)

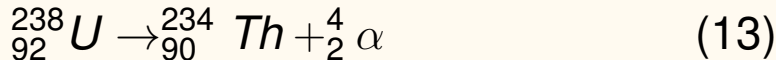
**Gamma Decay**

$^{152}_{66}\text{Dy} \rightarrow ^{152}_{66}\text{Dy} + \gamma$  (gamma ray)

before after

*Radioactive decay transforms a nucleus by emitting different particles. In **alpha** decay, the nucleus releases a  $^4_2\text{He}$  nucleus—an alpha particle. In **beta** decay, the nucleus either emits an electron and antineutrino (or a positron and neutrino) or captures an atomic electron and emits a neutrino. A positron is the name for the antiparticle of the electron. Antimatter is composed of antiparticles. Both alpha and beta decays change the original nucleus into a nucleus of a different chemical element. In **gamma** decay, the nucleus lowers its internal energy by emitting a photon—a gamma ray. This decay does not modify the chemical properties of the atom.*

## Alpha particle decay is the ejection of a helium atom from a heavy nucleus

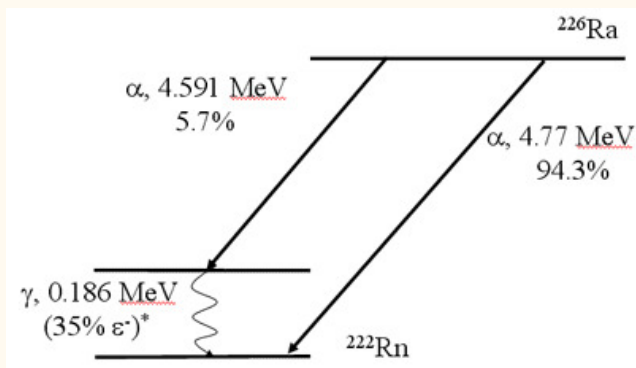


$$Q = 4.268 \text{ MeV} \quad (14)$$

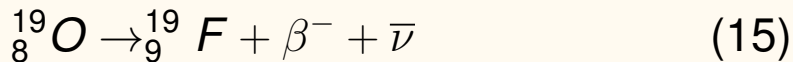
Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)

Discrete energy spectrum

Some % decay at certain energy

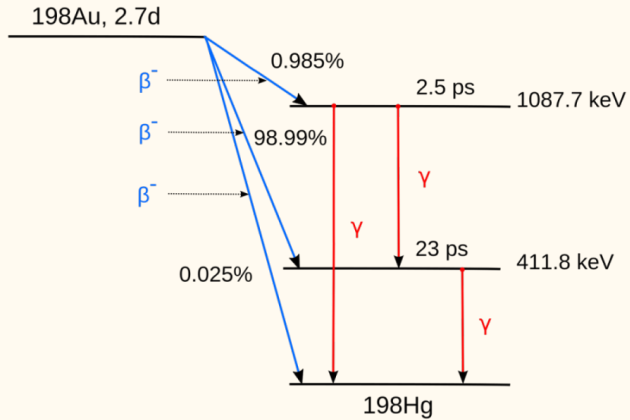


## $\beta^-$ particle decay occurs for unstable nuclei with excessive neutrons

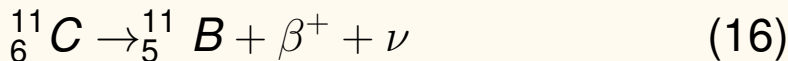


The neutron is converted to a proton and a beta negative (electron) and anti-neutrino (momentum) are ejected

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)



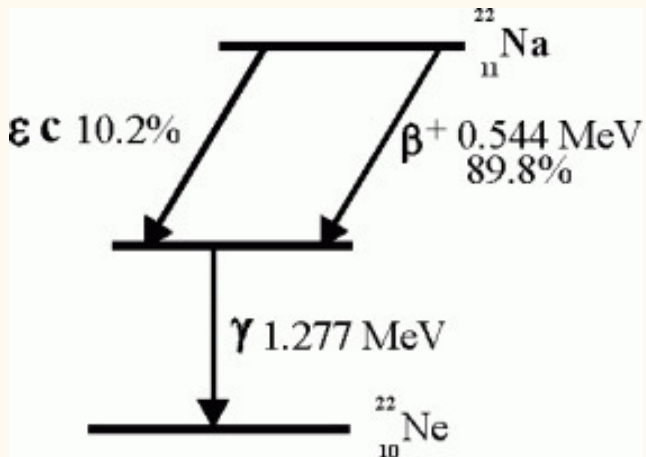
## $\beta^+$ particle decay occurs for unstable nuclei with deficient neutrons



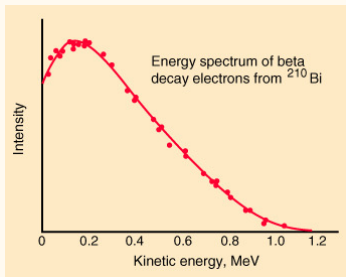
The proton is converted to a neutron and a beta positive (positron) and neutrino (momentum) are ejected

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)





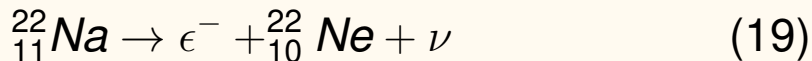
**In both forms of beta decay, the energies are exhibited by a continuous energy spectrum**



$$\overline{E}(\beta^-) = 0.3E_{MAX} \quad (17)$$

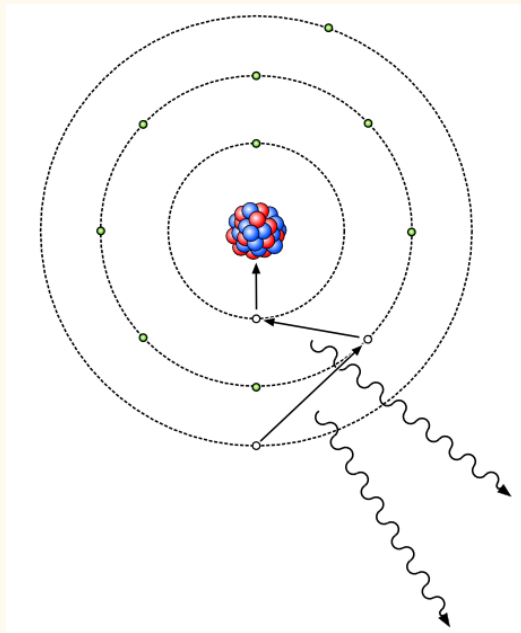
$$\overline{E}(\beta^+) = 0.4E_{MAX} \quad (18)$$

## Electron capture also occurs for unstable nuclei with deficient neutrons

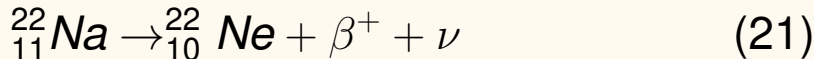
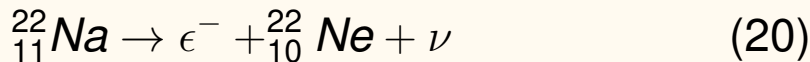


The K shell electron (not free) is absorbed by the nucleus to convert the proton to a neutron

Sometimes nucleus decays to excited state and then emits a gamma ray (for any kind of radiation)



## Electron capture and $\beta^+$ are competing processes



$$Q = 2.842 \text{ MeV} \quad (22)$$

$Q > 1.022 \text{ MeV}$  positron favored

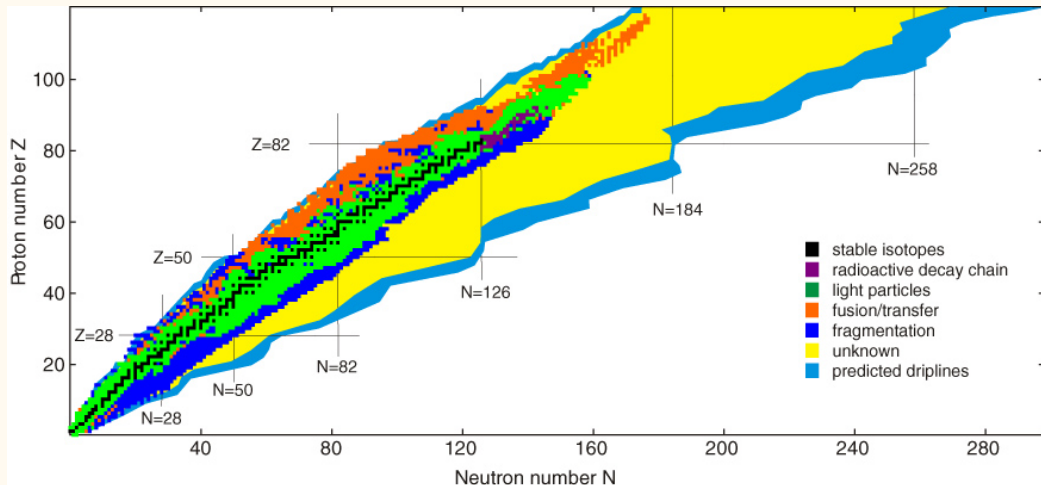
$Q < 1.022 \text{ MeV}$  electron capture favored

Why?

# $\gamma$ -ray emission is not a decay mode, but superfast de-excitation of the nucleus

Interactions of gamma rays with matter is a very important branch of nuclear physics

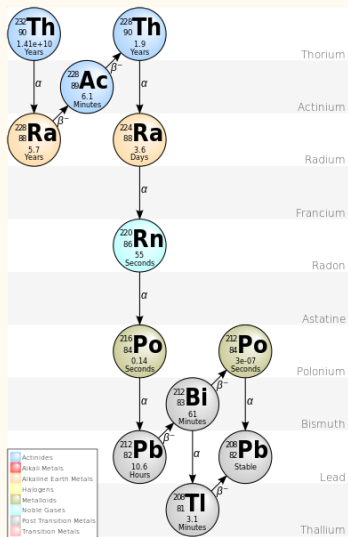
## **Chart of the nuclides**

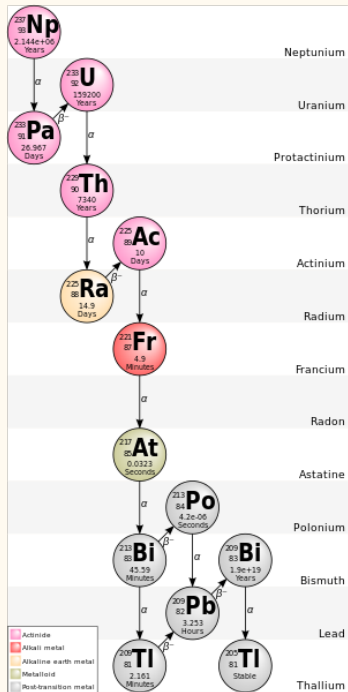


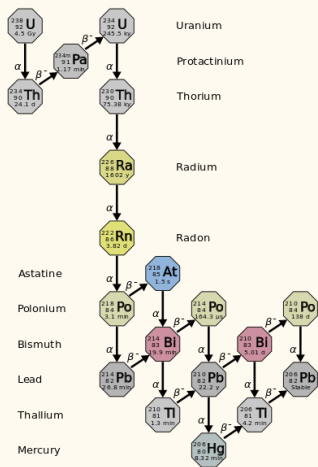


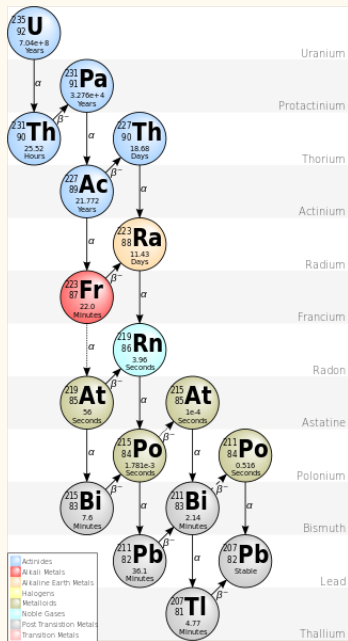
<p><b>Ra 224</b> 3.66 d</p> <p><math>\alpha</math> 5.6854 5.4486...</p> <p><math>\gamma</math> 241..., C14</p> <p><math>\sigma</math> 12.0</p>	<p><b>Ra 225</b> 14.8 d</p> <p><math>\beta^-</math> 0.3, 0.4</p> <p><math>\gamma</math> 40</p> <p><math>e^-</math></p>	<p><b>Ra 226</b> 1600 a</p> <p><math>\alpha</math> 4.7843, 4.601...</p> <p><math>\gamma</math> 186...</p> <p>C14</p> <p><math>\sigma</math> 12.8</p> <p><math>\sigma_f &lt; 5E-5</math></p>
<p><b>Fr 223</b> 21.8 m</p> <p><math>\beta^-</math> 1.1...</p> <p><math>\alpha</math> 5.34</p> <p><math>\gamma</math> 50, 80, 235...</p>	<p><b>Fr 224</b> 3.3 m</p> <p><math>\beta^-</math> 2.6, 2.8...</p> <p><math>\gamma</math> 216, 132, 837 1341...</p>	<p><b>Fr 225</b> 4.0 m</p> <p><math>\beta^-</math> 1.6...</p> <p><math>\gamma</math> 182, 32, 225 200...</p>
<p><b>Rn 222</b> 3.825 d</p> <p><math>\alpha</math> 5.48948...</p> <p><math>\gamma</math> (510)</p> <p><math>\sigma</math> 0.74</p>	<p><b>Rn 223</b> 23.2 m</p> <p><math>\beta^-</math></p> <p><math>\gamma</math> 593, 417, 636 655...</p>	<p><b>Rn 224</b> 1.78 h</p> <p><math>\beta^-</math></p> <p><math>\gamma</math> 261, 266...</p>

## Decay chains









**Half life**

# A radioactive isotope decays with a unique characteristic time

Decay is stochastic, characterized by Poisson distribution

So the decay of any one radionuclide cannot be predicted

The probability per time that a nucleus will decay is a constant



## Decay is described by a Poisson process

Occurrences are randomly distributed in time

What is the 'occurrence' here?

Homogeneous, long term decay rate is constant

$$\mu \equiv \lambda \Delta t \quad (23)$$

$$P(n) = e^{-\mu} \cdot \frac{\mu^n}{n!} \quad (24)$$

What is the expected value and variance of the distribution?

## A radioactive isotope decays with a unique characteristic time

$n(t)$  atoms at  $t$  have decayed in  $dt$

$$\lambda n(t) dt \quad (25)$$

The number of atoms that decay on average in the interval  $t, (t + dt)$  can be expressed as –

$$-dn(t) = \lambda n(t) dt \quad (26)$$

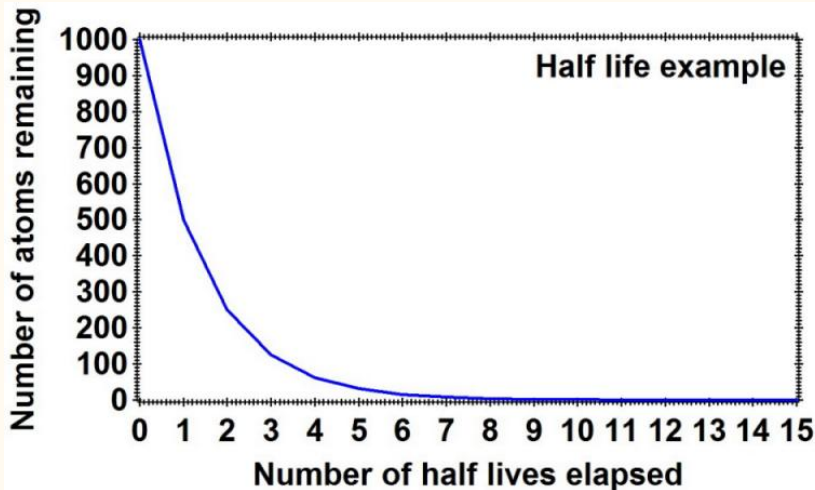
You should be able to solve this for  $n(0) = n_0$

# Radionuclides are characterized by half life

$$t_{\frac{1}{2}} = \frac{\ln 2}{\lambda} \quad (27)$$

Half life can be derived from the decay law

# A radionuclide is 'negligible' after 10 half-lives have elapsed



Why would this be important?

# How was half-life discovered?

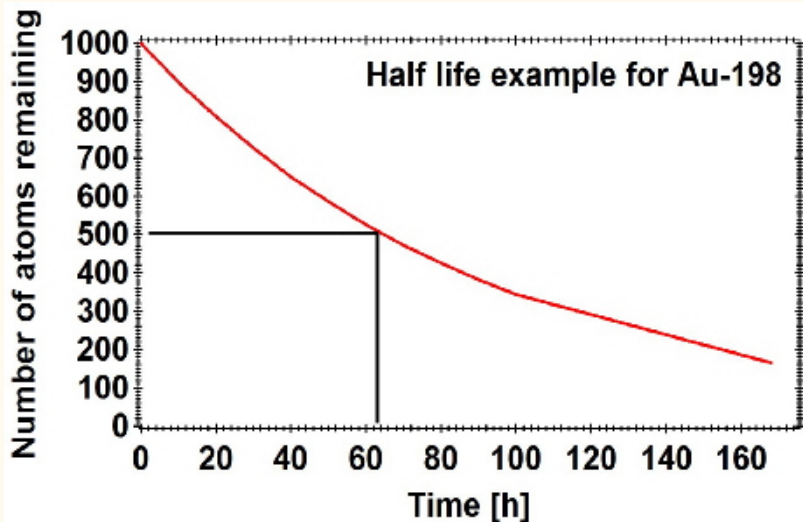
Rutherford discovered alpha and beta particle decay

In the course of, he noticed that there was a characteristic time

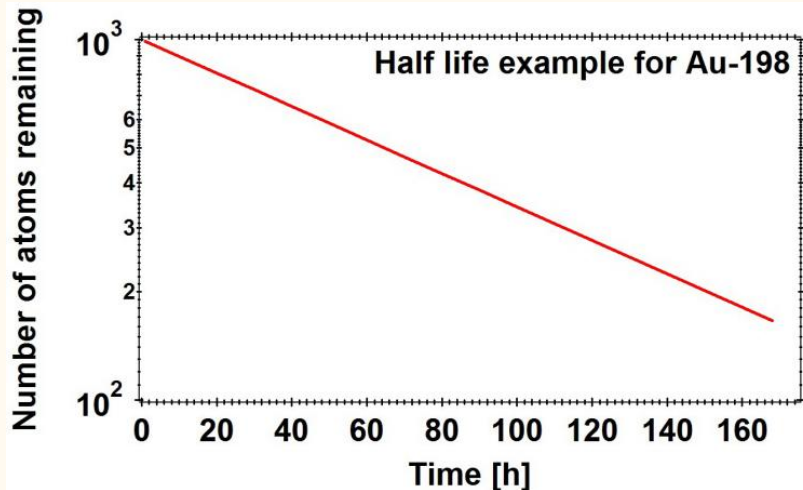
Basically observed decay time was the same for each atom

Experiments with thorium led to the discovery of radon

Then observing the radon gas led to the decay/half-life (65 s)



# Engineers like straight lines



Slope of the line is the decay constant

