

Lecture 1: Nuclear processes and radioactive sources

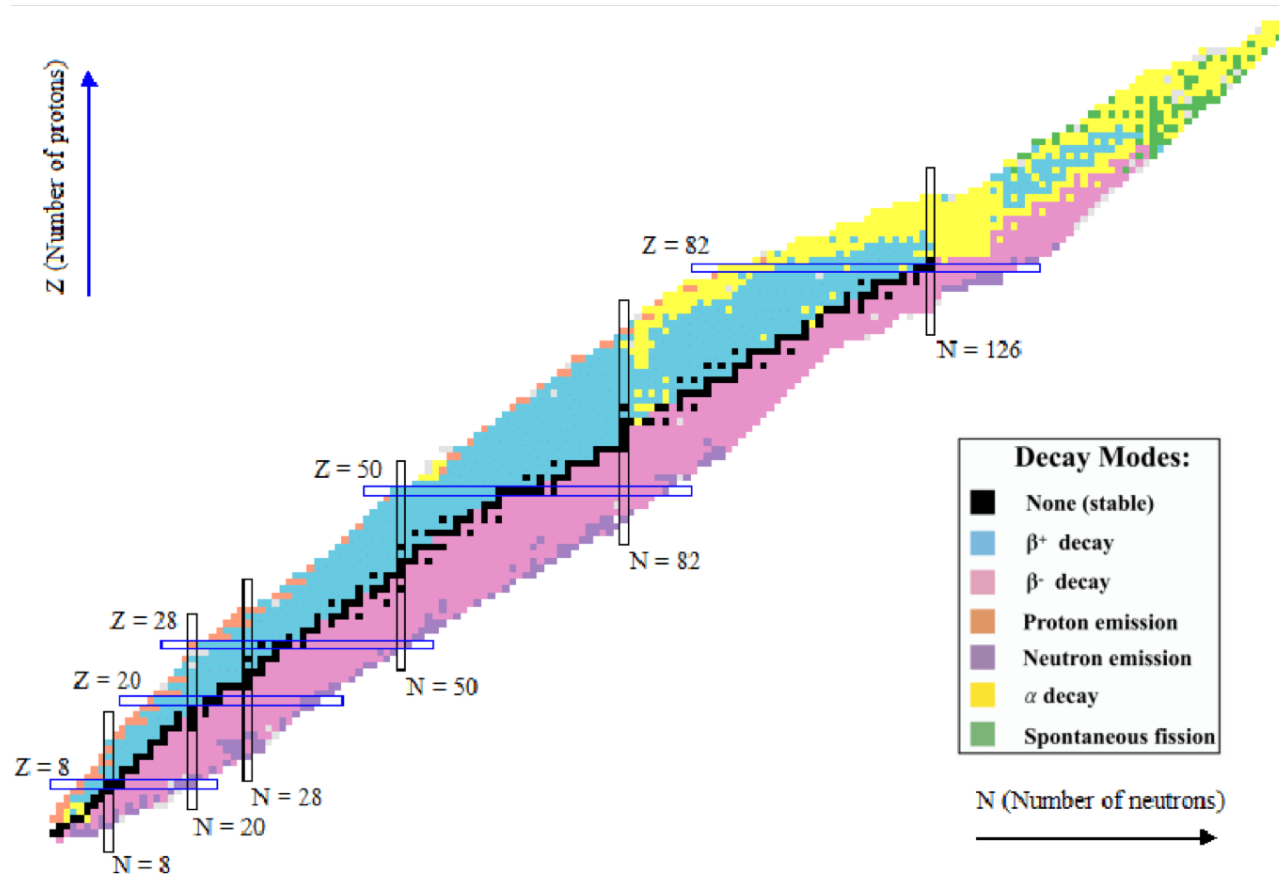
Chapter 1 except 1.11.2, 1.11.3

Radiation is the emission or transmission of energy in the form of waves or particles through space or a material medium (detector).

Radiation

Particles (corpuscular)

Electromagnetic waves



Particles are created via either **radioactive decay** or nuclear reactions

The same applies to gamma rays

Emitted radiation tells us about:

Nuclear processes, i.e. decay modes

Some nuclei with special decay mode are used for calibration purposes

Table 1.1. Characteristics of nuclear radiations

Type	Origin	Process	Charge	Mass [MeV]	Spectrum (energy)
α -particles	Nucleus	Nuclear decay or reaction	+ 2	3727.33	Discrete [MeV]
β^- -rays	Nucleus	Nuclear decay	- 1	0.511	Continuous [keV – MeV]
β^+ -rays (positrons)	Nuclear	Nuclear decay	+ 1	0.511	Continuous [keV – MeV]
γ -rays	Nucleus	Nuclear deexcitation	0	0	Discrete [keV – MeV]
x-rays	Electron cloud	Atomic deexcitation	0	0	Discrete [eV – keV]
Internal conversion electrons	Electron cloud	Nuclear deexcitation	- 1	0.511	Discrete [high keV]
Auger electrons	Electron cloud	Atomic deexcitation	- 1	0.511	Discrete [eV – keV]
Neutrons	Nucleus	Nuclear reaction	0	939.57	Continuous or discrete [keV – MeV]
Fission fragments	Nucleus	Fission	≈ 20	80 – 160	Continuous 30 – 150 MeV

In this lecture we will go through nuclear decay processes and corresponding radiation sources for the purpose of calibration.



"You'd better get your scales fixed, or I'm calling Weights and Measures!"

Calibration:



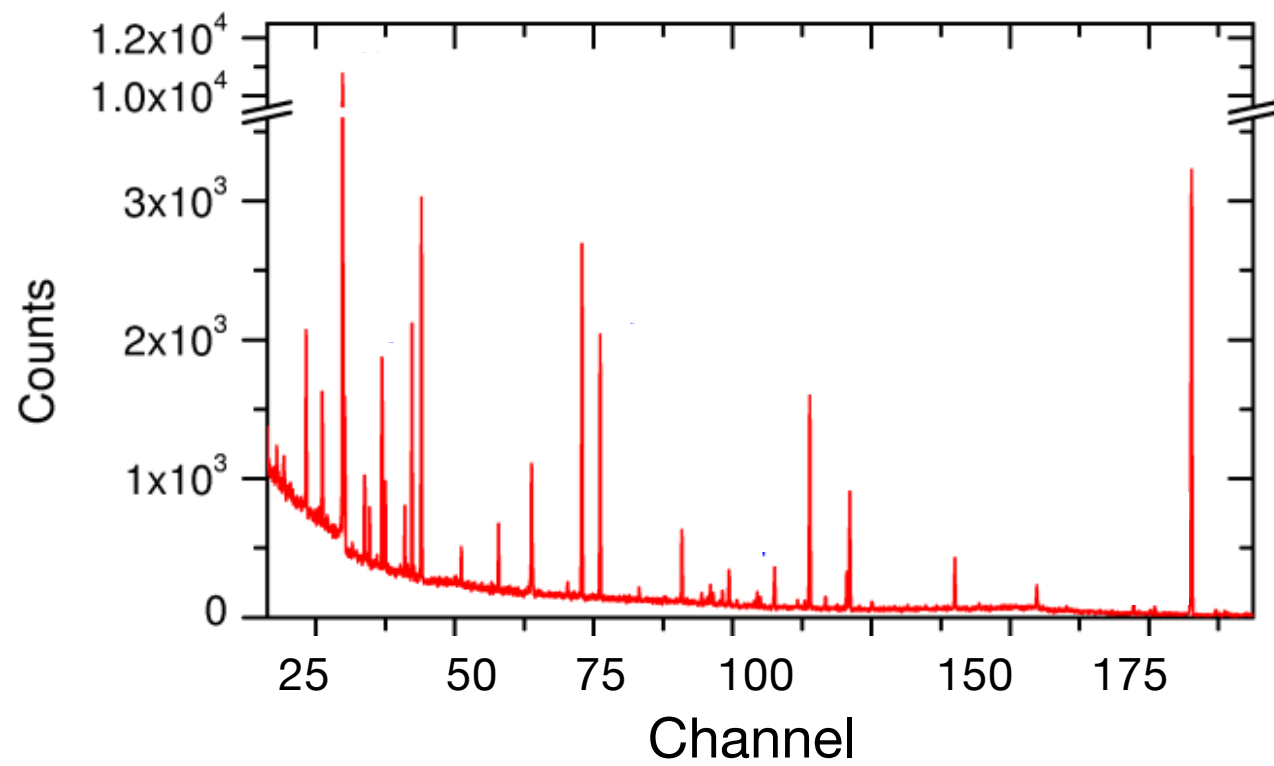
We need to calibrate our detectors.

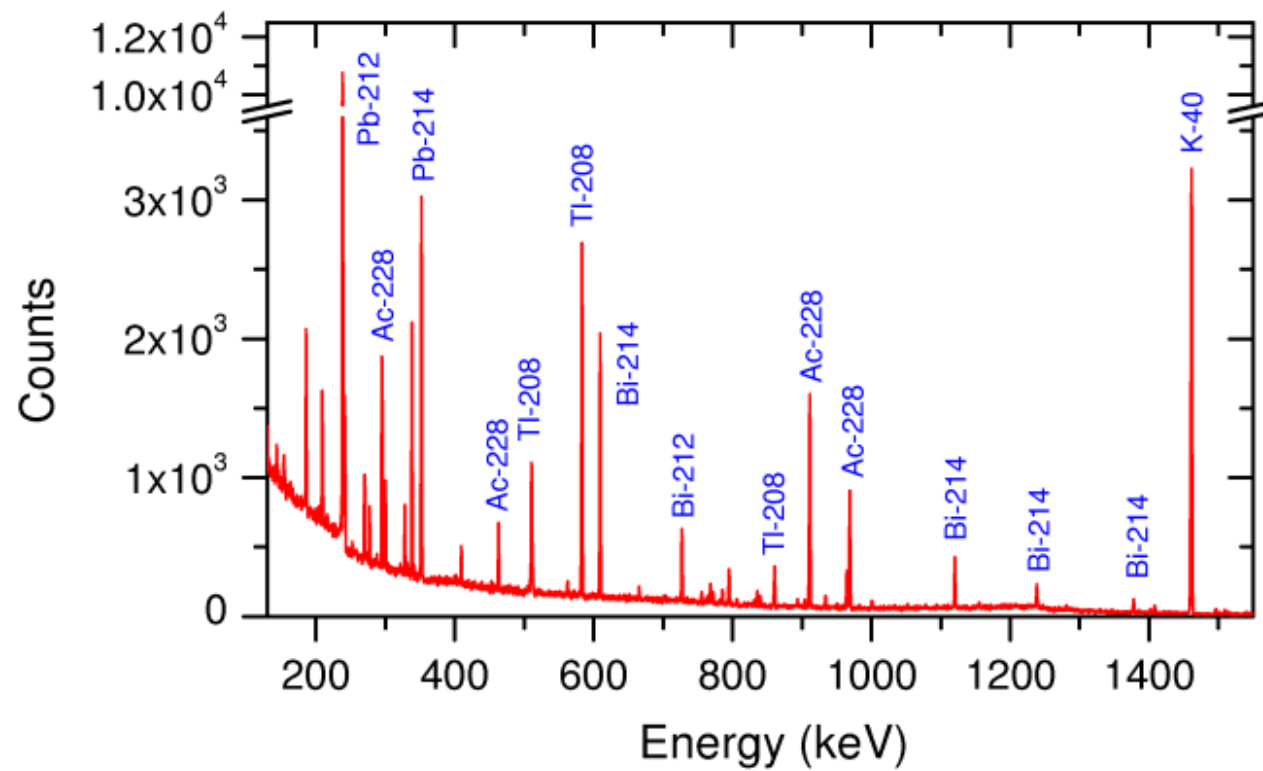
Charged particle detectors —> alpha (emitting) sources

Gamma-ray detectors —> Gamma (emitting) sources

Neutron detectors —> Neutron (emitting) sources

(Internal conversion) Electron detectors —> Internal
conversion (electron) (emitting) sources





Calibration sources should provide discrete energy, no continuous.

^{60}Co source (gamma source)



Today:

- Electrons

 - Beta electrons

 - Internal conversion electrons

 - Auger electrons

- Photons

 - X-rays

 - gamma rays

 - Annihilation radiation

- Alpha particles

- Neutrons

 - Spontaneous fission

 - (α ,n) sources

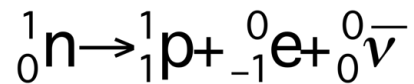
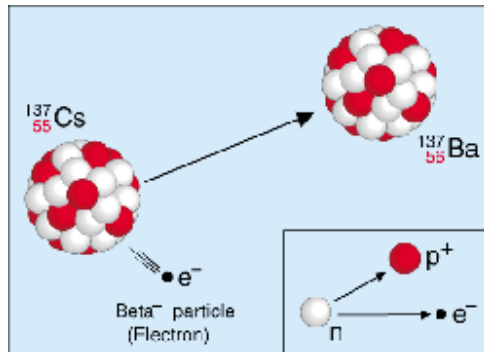
 - (α ,n) via accelerators

 - (γ ,n) Photoneutron sources

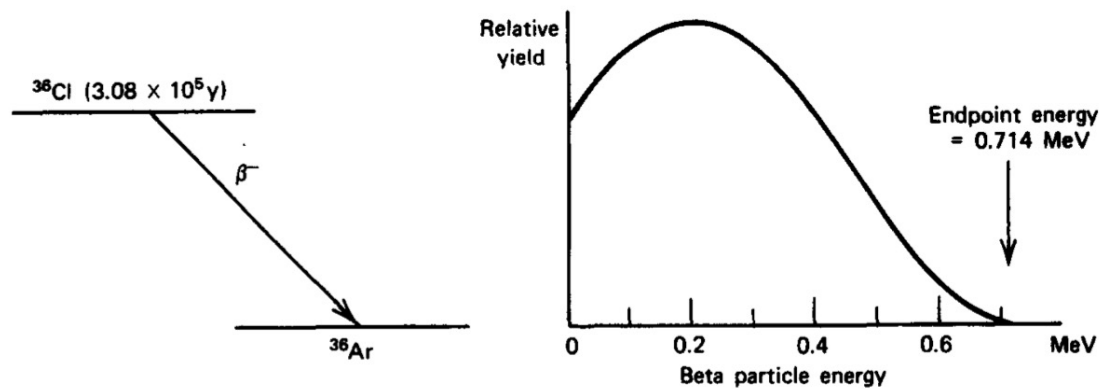
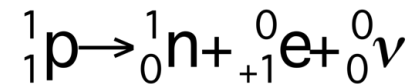
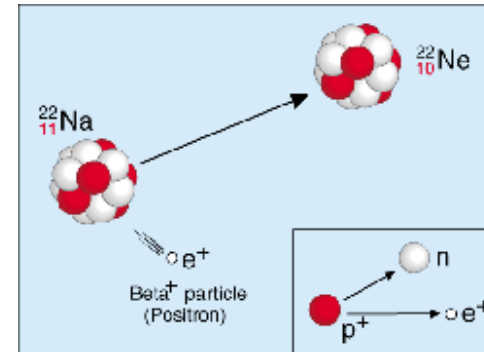
 - Radioactive decay

1. Beta (β) electrons:

(a) β^- decay, e^- (electron)

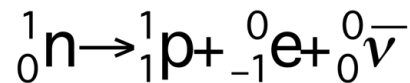
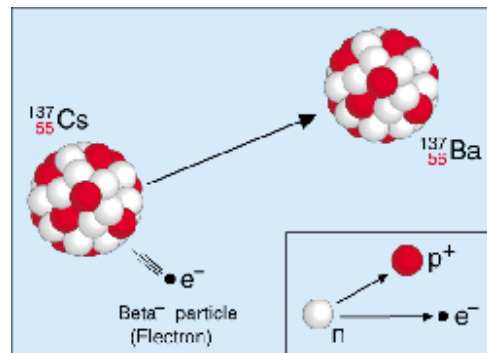


(b) β^+ decay, e^+ (positron)

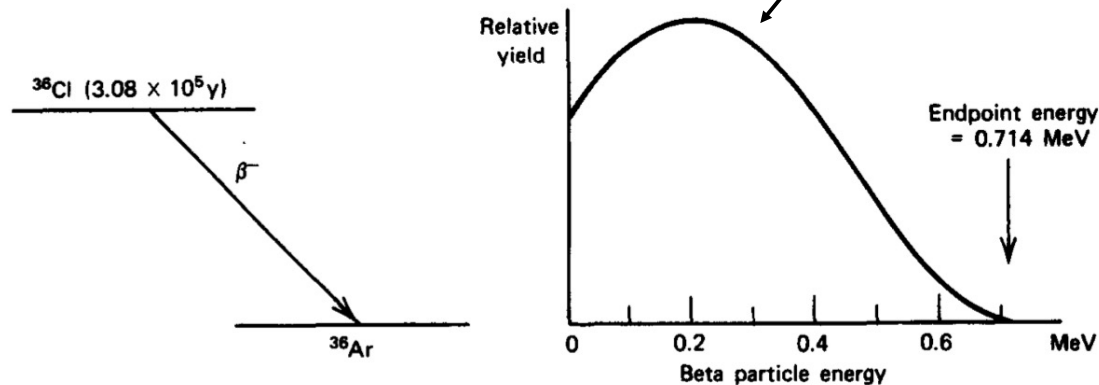


1. Beta (β) electrons:

(a) β^- decay, e^- (electron)



Electrons from beta decay are not mono energetic but continuous. They are , therefore, not used for calibration. BUT...



(b) β^+ decay, e^+ (positron)

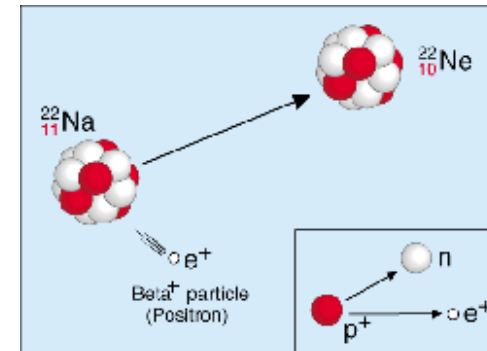
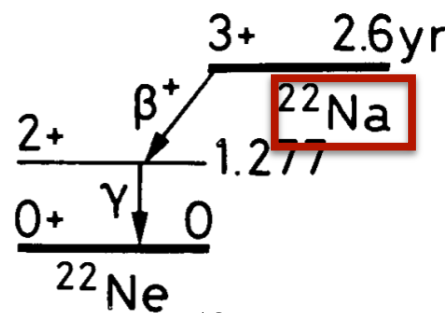
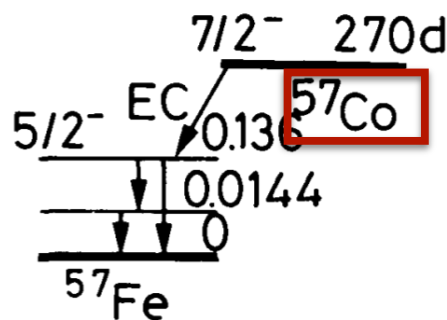
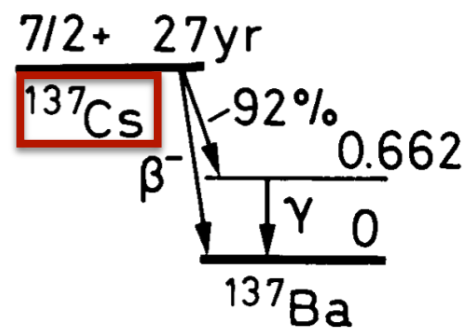
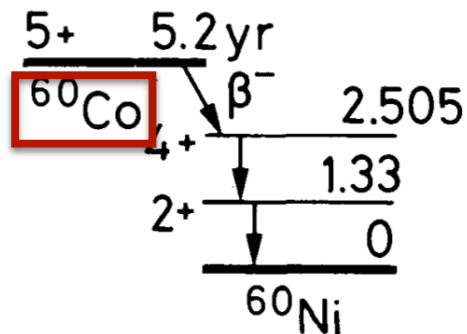


Table 1.1 Some "Pure" Beta-Minus Sources

Nuclide	Half-Life	Endpoint Energy (MeV)
^3H	12.26 y	0.0186
^{14}C	5730 y	0.156
^{32}P	14.28 d	1.710
^{33}P	24.4 d	0.248
^{35}S	87.9 d	0.167
^{36}Cl	$3.08 \times 10^5 \text{ y}$	0.714
^{45}Ca	165 d	0.252
^{63}Ni	92 y	0.067
$^{90}\text{Sr}/^{90}\text{Y}$	27.7 y/64 h	0.546/2.27
^{99}Tc	$2.12 \times 10^5 \text{ y}$	0.292
^{147}Pm	2.62 y	0.224
^{204}Tl	3.81 y	0.766

Data from Lederer and Shirley.¹

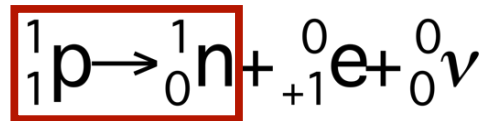
- When the beta decay does not occur to the ground state of the daughter nucleus but to an excited state of it, the daughter nucleus then emits gamma rays (i.e. gamma decays) to go back to its ground state.
- These gamma rays are used to calibrate gamma-ray detectors and the mother nucleus which beta decays into the daughter nucleus now is called “**gamma source**” even if it decays via beta-decay process.
- Sealing can be done thick enough to stop electrons to allow emission of gamma photons only.



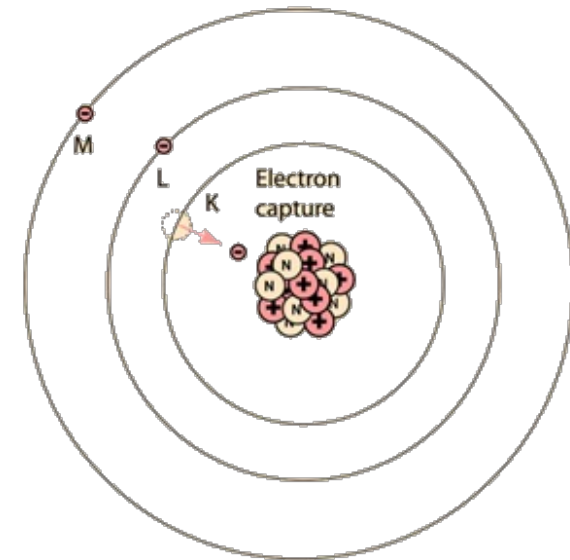
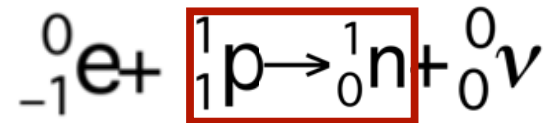
Electron Capture (EC)

- It is an equivalent process to β^+ decay but in EC an electron is captured from the atomic orbitals.
- Again, proton is transformed into a neutron as in β^+ decay

β^+ decay



EC



Only emitted particle EC is neutrino. The neutrino from EC is extremely difficult to detect directly. Therefore, electron capture is usually identified indirectly through the emitted X-rays or Auger electrons.

2. Internal conversion electrons

IC happens when γ decay is hindered: γ -decay takes long time (isomer) or energy is small or is not allowed at all. (γ -decay is forbidden for $0^+ \rightarrow 0^+$)
Nucleus gives its energy to an inner shell electron instead of a gamma ray.

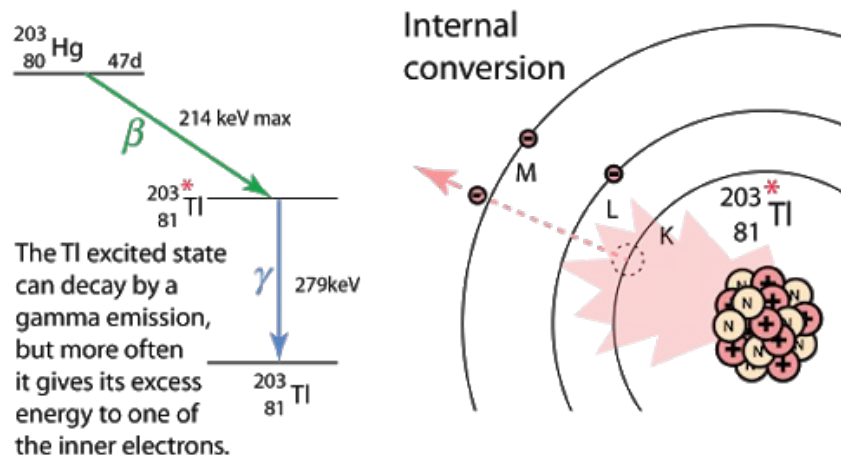


Figure: <http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/radact2.html>

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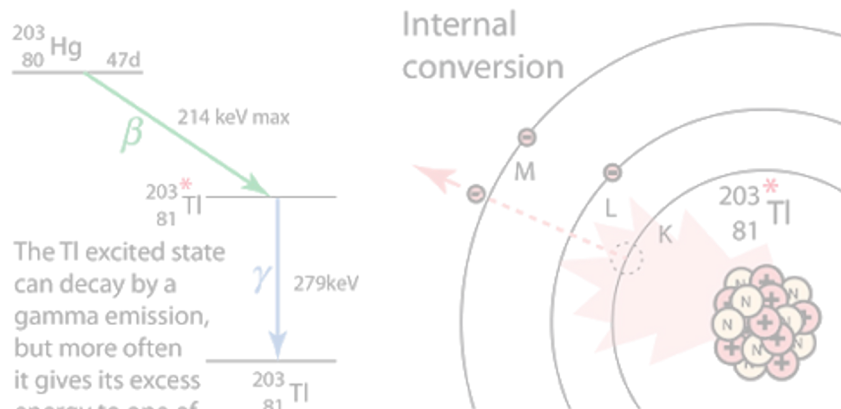
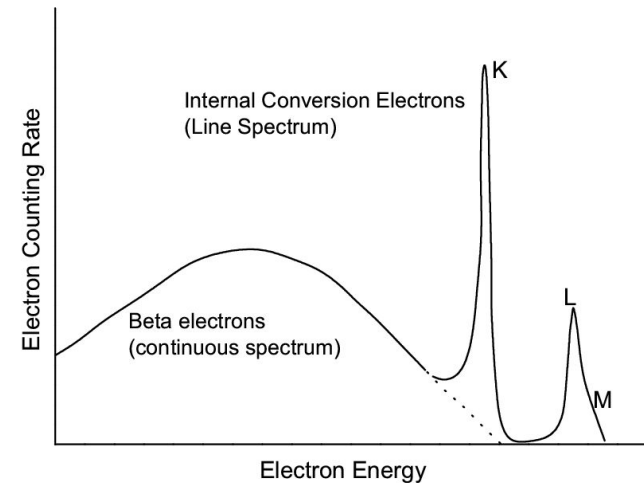


Table 1.4. Some internal conversion sources

Source	Energies [keV]
²⁰⁷ Bi	480, 967, 1047
¹³⁷ Cs	624
¹¹³ Sn	365
¹³³ Ba	266, 319

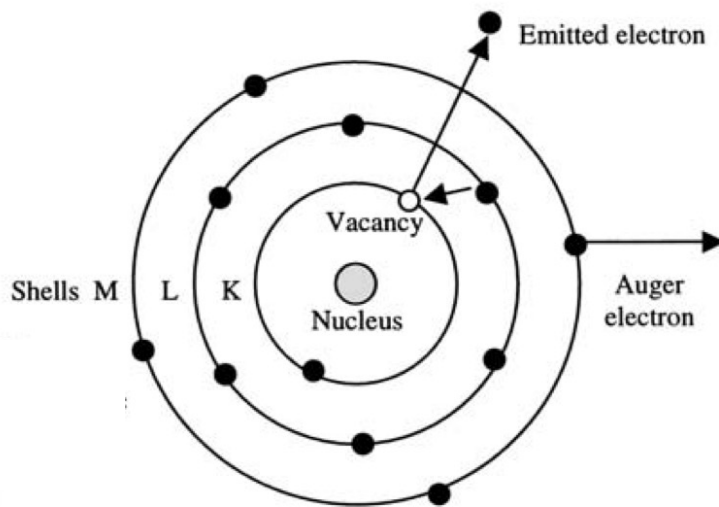


Electrons from internal conversion are mono energetic.

Good sources for calibration of electron detectors.

3. Auger electrons

- Auger electrons are emitted when the excitation energy in the “electronic shells” is transferred to the electrons instead of characteristics X-rays.
- The filling of this vacancy produces a cascade of inner-shell electron transitions with the emission of numerous Auger electrons from the single atom.
- Auger electron can happen after Electron Capture (EC)



Auger electrons are monoenergetic too like internal conversion electrons but the energy range is limited by a few keV.

Today:

- Electrons

 - Beta electrons

 - Internal conversion electrons

 - Auger electrons

- Photons

 - X-rays

 - gamma rays

 - Annihilation radiation

- Alpha particles

- Neutrons

 - Spontaneous fission

 - (α ,n) sources

 - (α ,n) via accelerators

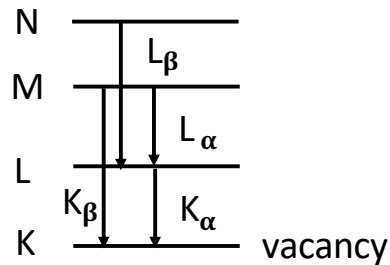
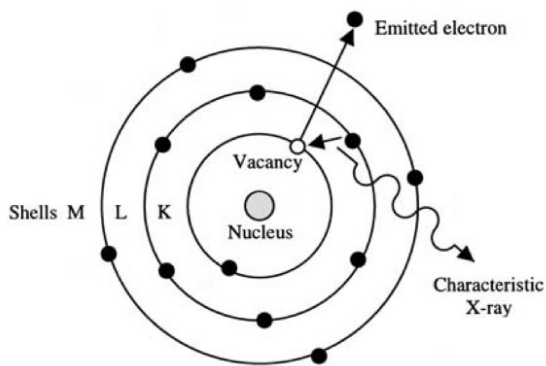
 - (γ ,n) Photoneutron sources

 - Radioactive decay

1. X rays :Low-energy photons

Characteristic X-rays are produced when an inner-shell vacancy is filled by an outer-shell electron. The photon energy equals the difference in the binding energies of the two shells.

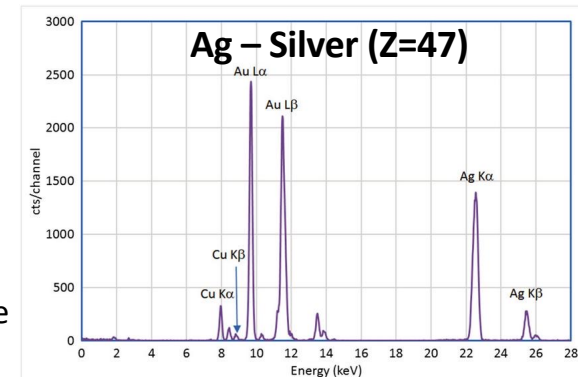
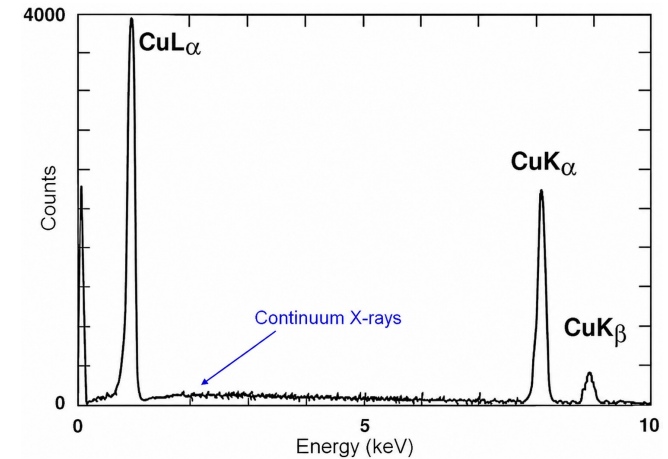
Each element has its own characteristic sets of X-rays



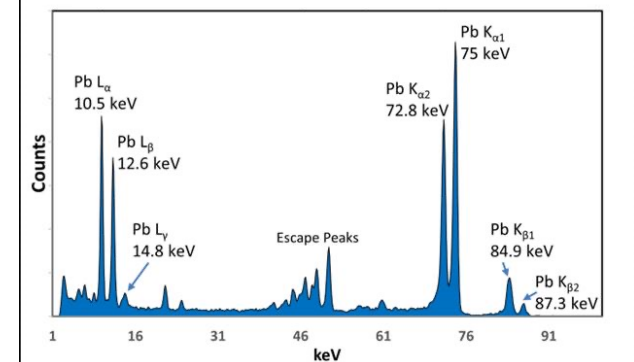
Photon energy = binding-energy difference

Shell	Subshells
K ($n = 1$)	1s
L ($n = 2$)	2s, 2p
M ($n = 3$)	3s, 3p, 3d
N ($n = 4$)	4s, 4p, 4d, 4f

Cu- Copper (Z=29)



Pb, led (Z=82)

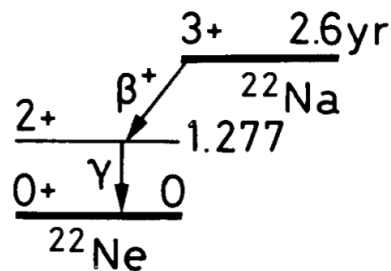
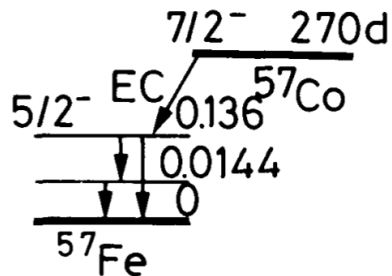
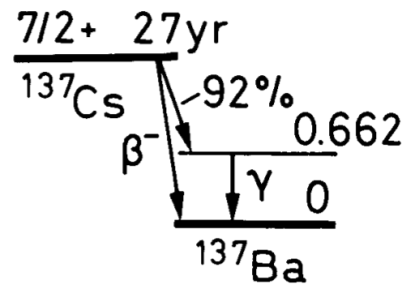
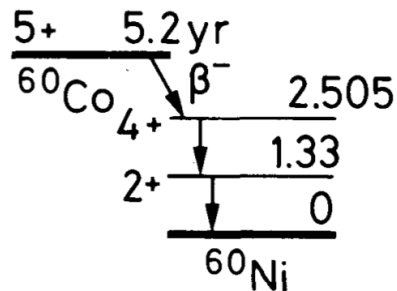


Higher Z → larger electron binding energies → higher-energy X-rays

2. γ rays :High-energy photons

Gamma rays are high-energy photons emitted by an excited atomic nucleus as it decays to a lower energy state. Nucleus can be left an excited state after a decay, such as beta, EC, alpha (or after a nuclear reaction)

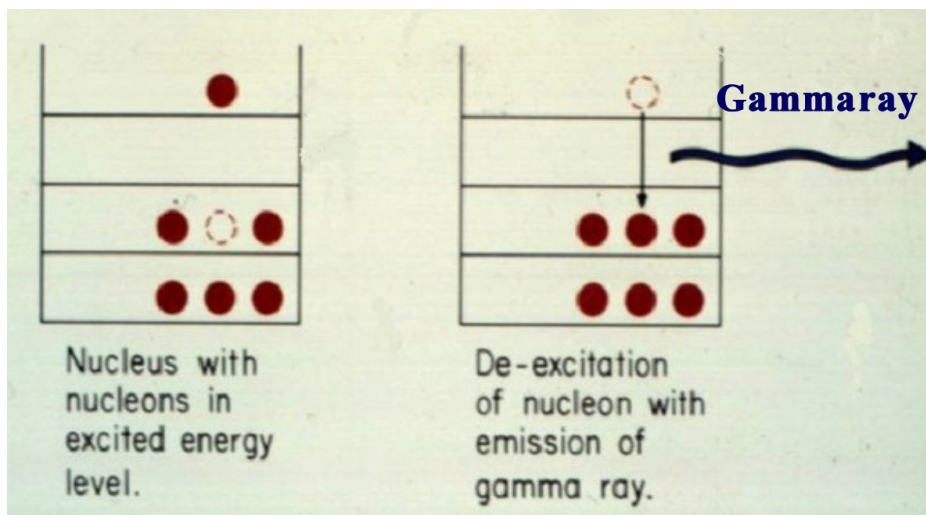
gamma-ray calibration sources for gamma-ray detectors:



Remember that γ rays in nuclear physics typically range from a few tens of keV to several MeV.

Much higher in HEP!!

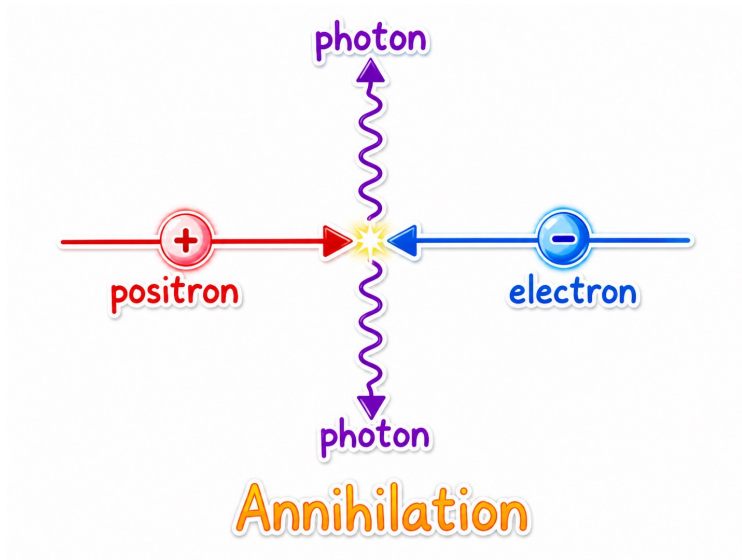
Neutrons and protons sit on orbits like electrons in atom: **Shell Model**



Unlike characteristic X-rays, whose energies are determined by electron-shell transitions, gamma-ray energies are determined by nuclear energy levels.

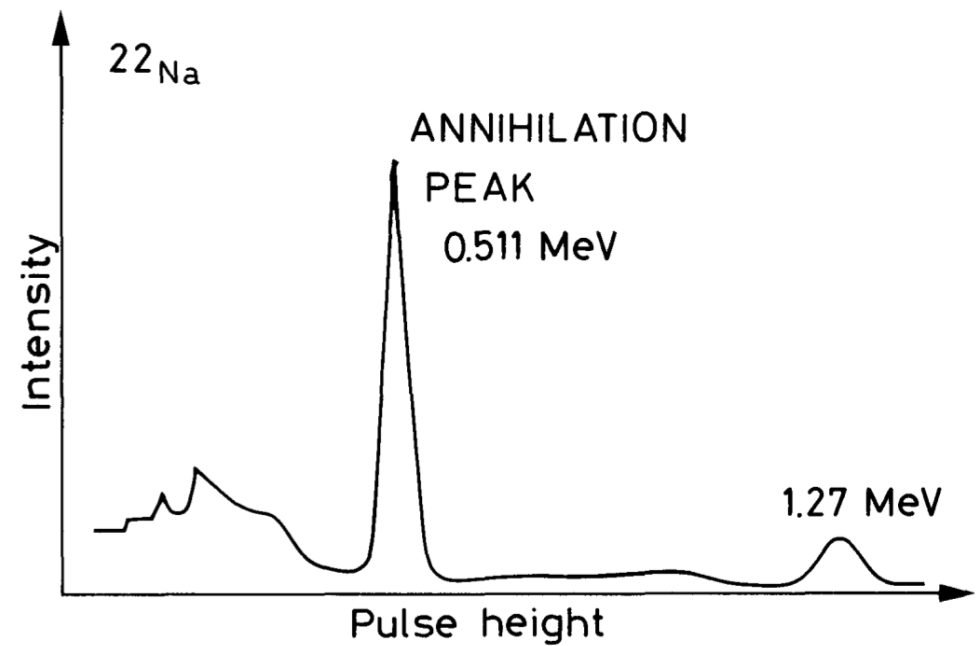
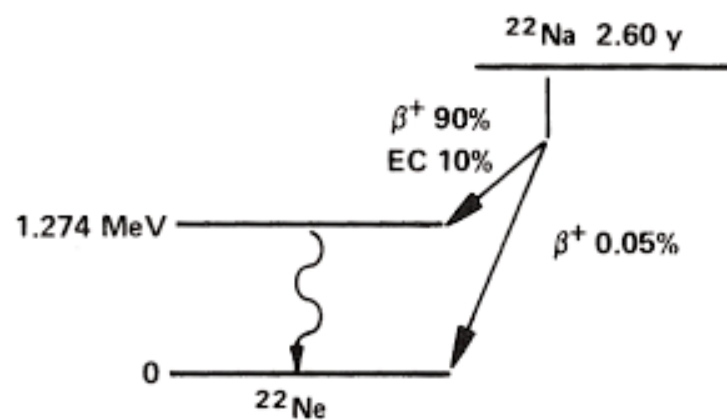
3. Annihilation radiation

- It is a gamma radiation.
- Occurs when a positron collides to electron and both particles cancel out, disappear, and two gamma rays at an energy of 0.511 MeV (=511 keV) are emitted.
- Momentum conservation requires the two photons to be emitted in opposite direction.



Source of annihilation is related to “positron’s existence in medium”:

β^+ decay where a proton is converted into neutron and *a positron is created*. ^{22}Na is a good annihilation source and of course it is, at the same time, a gamma source.

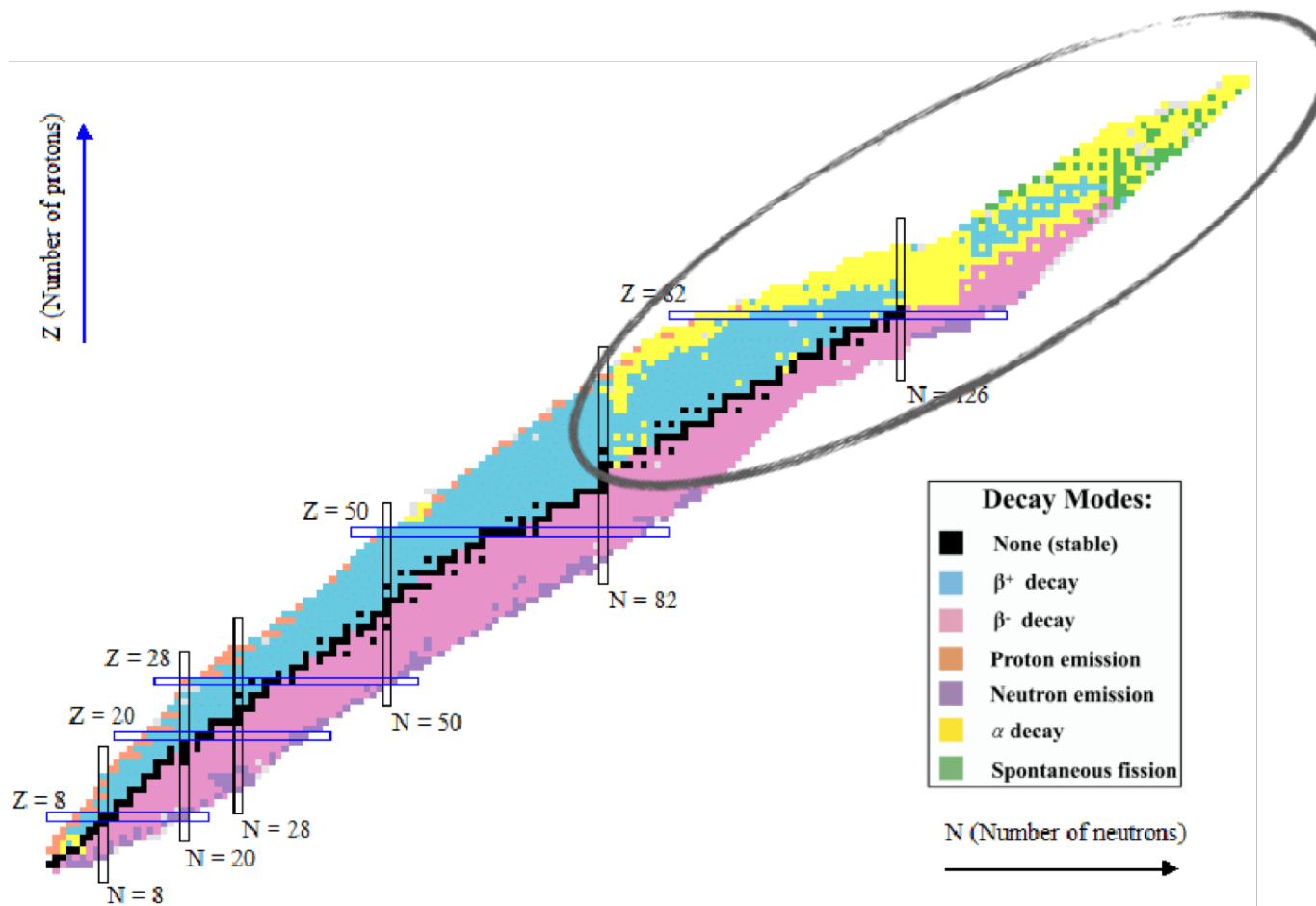


Today:

- Electrons
 - Beta electrons
 - Internal conversion electrons
 - Auger electrons
- Photons
 - X-rays
 - gamma rays
 - Annihilation radiation
- Alpha particles
- Neutrons
 - Spontaneous fission
 - (α, n) sources
 - (α, n) via accelerators
 - (γ, n) Photoneutron sources
- Radioactive decay

α particles: ${}^4\text{He}$ ($Z=2, N=2$)

- α particles are bound systems (nucleus) consisting of 2 protons and 2 neutrons.
- they are emitted by very heavy nuclei which are unstable against α decay.



α -decay

α decay occurs via quantum tunneling, i.e. barrier mechanism (physics textbooks or FYS3500 course in spring)

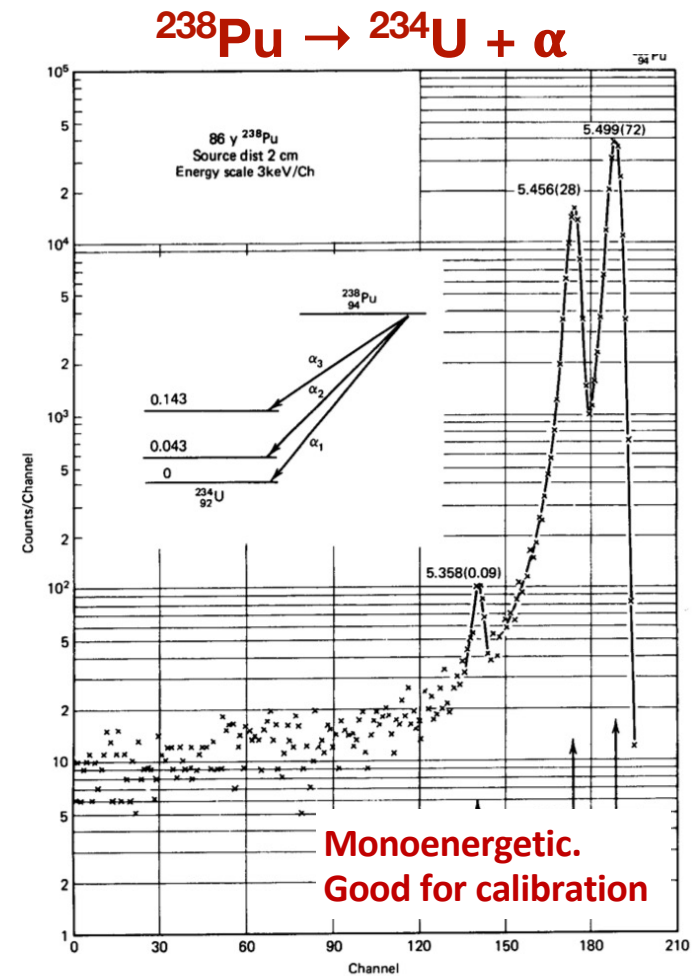
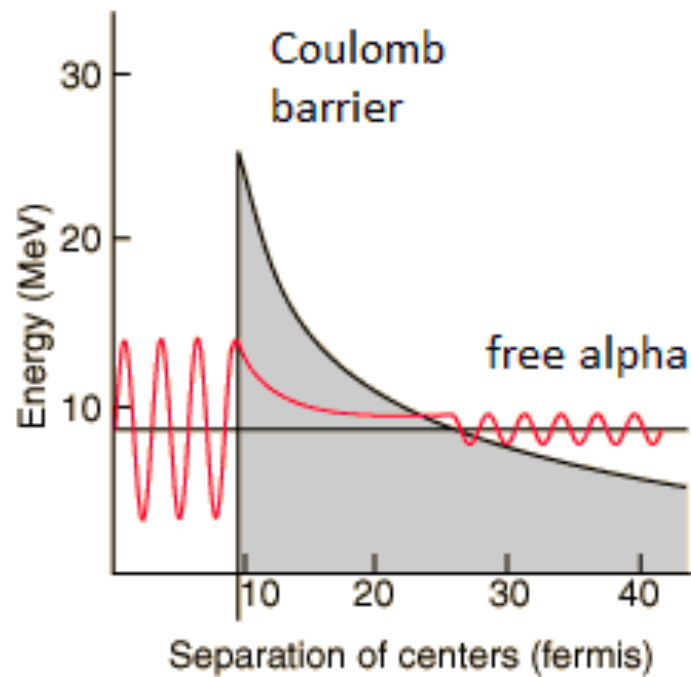


Figure 1.3 Alpha particle groups produced in the decay of ^{238}Pu . The pulse height spectrum shows the three groups as measured by a silicon surface barrier detector. Each peak is identified by its energy in MeV and percent abundance (in parentheses). The insert shows the decay scheme, with energy levels in the product nucleus labeled in MeV. (Spectrum from Chanda and Deal.²)

α -decay

- α -decay probability is proportional to decreasing decay time
- α -decay time is strongly correlated with α energy.

Table shows alpha sources to calibrate charged particle detectors.

Note that energy of alphas emitted from these sources are ~ 5 MeV

Table 1.3 Common Alpha-Emitting Radioisotope Sources

Source	Half-Life	Alpha Particle Kinetic Energy (with Uncertainty) in MeV		Percent Branching
^{148}Gd	93 y	3.182787	± 0.000024	100
^{232}Th	1.4×10^{10} y	4.012	± 0.005	77
		3.953	± 0.008	23
^{238}U	4.5×10^9 y	4.196	± 0.004	77
		4.149	± 0.005	23
^{235}U	7.1×10^8 y	4.598	± 0.002	4.6
		4.401	± 0.002	56
		4.374	± 0.002	6
		4.365	± 0.002	12
		4.219	± 0.002	6
^{236}U	2.4×10^7 y	4.494	± 0.003	74
		4.445	± 0.005	26
^{230}Th	7.7×10^4 y	4.6875	± 0.0015	76.3
		4.6210	± 0.0015	23.4
^{234}U	2.5×10^5 y	4.7739	± 0.0009	72
		4.7220	± 0.0009	28
^{231}Pa	3.2×10^4 y	5.0590	± 0.0008	11
		5.0297	± 0.0008	20
		5.0141	± 0.0008	25.4
		4.9517	± 0.0008	22.8
^{239}Pu	2.4×10^4 y	5.1554	± 0.0007	73.3
		5.1429	± 0.0008	15.1
		5.1046	± 0.0008	11.5
^{240}Pu	6.5×10^3 y	5.16830	± 0.00015	76
		5.12382	± 0.00023	24
^{243}Am	7.4×10^3 y	5.2754	± 0.0010	87.4
		5.2335	± 0.0010	11
^{210}Po	138 d	5.30451	± 0.00007	99+
^{241}Am	433 y	5.48574	± 0.00012	85.2
		5.44298	± 0.00013	12.8
^{238}Pu	88 y	5.49921	± 0.00020	71.1
		5.4565	± 0.0004	28.7
^{244}Cm	18 y	5.80496	± 0.00005	76.4
		5.762835	± 0.000030	23.6
^{243}Cm	30 y	6.067	± 0.003	1.5
		5.992	± 0.002	5.7
		5.7847	± 0.0009	73.2
		5.7415	± 0.0009	11.5
^{242}Cm	163 d	6.11292	± 0.00008	74
		6.06963	± 0.00012	26
$^{254\text{m}}\text{Es}$	276 d	6.4288	± 0.0015	93
^{253}Es	20.5 d	6.63273	± 0.00005	90
		6.5916	± 0.0002	6.6

Data from Rytz.³

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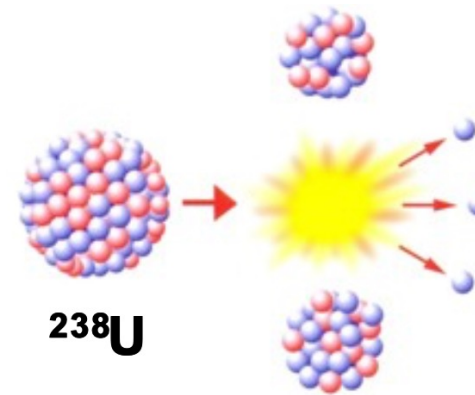
 - (α, n) via accelerators

 - (γ, n) Photoneutron sources

 - Radioactive decay

1-Spontaneous fission

- heavy nucleus splits
- several neutrons emitted
- caused by Coulomb vs nuclear-force competition



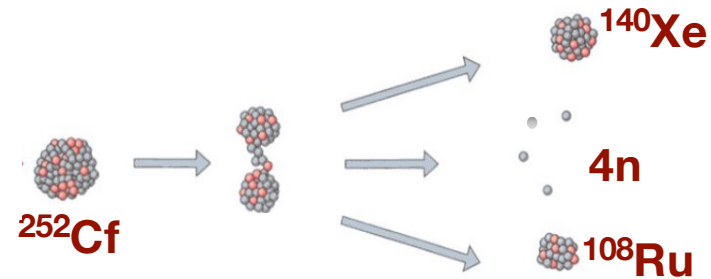
$$B = a_v A - a_s A^{2/3} - \frac{a_c Z(Z-1)}{A^{1/3}} - \frac{a_A (A - 2Z)^2}{A} + \Delta \propto A$$

$$\Delta E_{\text{Coul}} = \frac{3}{5} \frac{Z(Z-1)e^2}{4\pi\epsilon_0 R} \propto Z^2$$

Winner in
heavy
elements!!

A: Atomic mass number
Z: Atomic number

- heavy nucleus splits
- several neutrons emitted
- caused by Coulomb vs nuclear-force competition
- useful neutron source (Cf-252, Z=98)



1

IA

1A

2

IIA

2A

3

IIIB

3B

4

IVB

4B

5

VB

5B

6

VIB

6B

7

VIIB

7B

8

VIII

8

9

VIII

8

10

VIII

8

11

IB

1B

12

IIB

2B

13

IIIA

3A

14

IVA

4A

15

VA

5A

16

VIA

6A

17

VIIA

7A

18

VIIIA

8A

1

H

Hydrogen

1.008

2

He

Helium

4.003

3

Li

Lithium

6.941

4

Be

Beryllium

9.012

11

Na

Sodium

22.990

12

Mg

Magnesium

24.305

19

K

Potassium

39.098

20

Ca

Calcium

40.078

37

Rb

Rubidium

84.468

38

Sr

Strontium

87.62

55

Cs

Cesium

132.905

87

Fr

Francium

223.020

56

Ba

Barium

137.328

88

Ra

Radium

226.025

21

Sc

Scandium

44.956

22

Ti

Titanium

47.867

23

V

Vanadium

50.942

24

Cr

Chromium

51.996

25

Mn

Manganese

54.938

26

Fe

Iron

55.845

27

Co

Cobalt

58.933

28

Ni

Nickel

58.693

29

Cu

Copper

63.546

30

Zn

Zinc

65.38

31

Ga

Gallium

69.723

32

Ge

Germanium

72.631

33

As

Arsenic

74.922

34

Se

Selenium

78.971

35

Br

Bromine

79.904

36

Kr

Krypton

84.798

39

Y

Yttrium

88.906

40

Zr

Zirconium

91.224

41

Nb

Niobium

92.906

42

Mo

Molybdenum

95.95

43

Tc

Technetium

98.907

44

Ru

Ruthenium

101.07

45

Rh

Rhodium

102.906

46

Pd

Palladium

106.42

47

Ag

Silver

107.868

48

Cd

Cadmium

112.411

49

In

Indium

114.818

50

Sn

Tin

118.711

51

Sb

Antimony

121.760

52

Te

Tellurium

127.6

53

I

Iodine

126.904

54

Xe

Xenon

131.29

72

Hf

Hafnium

178.49

73

Ta

Tantalum

180.948

74

W

Tungsten

183.84

75

Re

Rhenium

186.207

76

Os

Osmium

190.23

77

Ir

Iridium

192.217

78

Pt

Platinum

195.085

79

Au

Gold

196.967

80

Hg

Mercury

200.592

81

Tl

Thallium

204.383

82

Pb

Lead

207.2

83

Bi

Bismuth

208.980

84

Po

Polonium

[209]

85

At

Astatine

209.987

86

Rn

Radon

222.01

104

Rf

Rutherfordium

[261]

105

Db

Dubnium

[262]

106

Sg

Seaborgium

[266]

107

Bh

Bohrium

[264]

108

Hs

Hassium

[269]

109

Mt

Meitnerium

[268]

110

Ds

Darmstadtium

[269]

111

Rg

Roentgenium

[272]

112

Cn

Copernicium

[277]

113

Nh

Nihonium

unknown

114

Fl

Flerovium

[289]

115

Uup

Ununpentium

unknown

116

Lv

Livermorium

[293]

117

Uus

Ununseptium

unknown

118

Uuo

Ununoctium

unknown

Lanthanide Series

57

La

Lanthanum

138.905

58

Ce

Cerium

140.116

59

Pr

Praseodymium

140.908

60

Nd

Neodymium

144.243

61

Pm

Promethium

144.913

62

Sm

Samarium

150.36

63

Eu

Europium

151.964

64

Gd

Gadolinium

157.25

65

Tb

Terbium

158.925

66

Dy

Dysprosium

162.500

67

Ho

Holmium

164.930

68

Er

Erbium

167.259

69

Tm

Thulium

168.934

70

Yb

Ytterbium

173.055

71

Lu

Lutetium

174.967

Actinide Series

89

Ac

Actinium

227.028

90

Th

Thorium

232.038

91

Pa

Protactinium

231.036

92

U

Uranium

238.029

93

Np

Neptunium

237.048

94

Pu

Plutonium

244.064

95

Am

Americium

243.061

96

Cm

Curium

247.070

97

Bk

Berkelium

247.070

98

Cf

Californium

251.080

99

Es

Einsteinium

[254]

100

Fm

Fermium

257.095

101

Md

Mendelevium

258.1

102

No

Nobelium

259.101

103

Lr

Lawrencium

[262]

Alkali Metal

Alkaline Earth

Transition Metal

Basic Metal

Semimetal

Nonmetal

Halogen

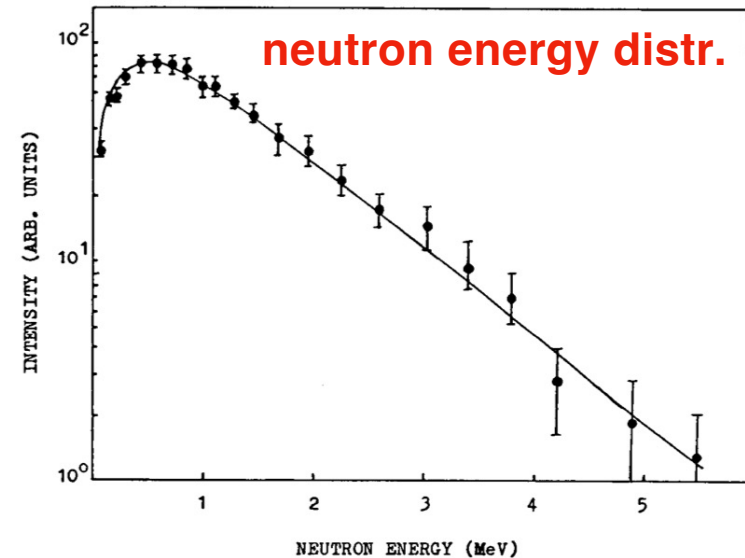
Noble Gas

Lanthanide

Actinide

Figure: from Knoll

- heavy nucleus splits
- several neutrons emitted
- caused by Coulomb vs nuclear-force competition
- useful neutron source (^{252}Cf , $Z=98$)
- Emitted neutrons are fast neutrons
- Continuous, not monoenergetic.
- Thickness of the container



$$\frac{dN}{dE} = E^{1/2} e^{-E/T}$$

T: constant = 1.3 MeV for ^{252}Cf
E: energy of neutron in MeV

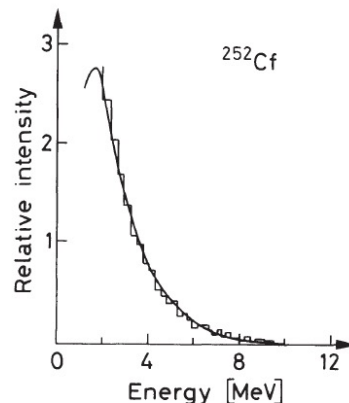
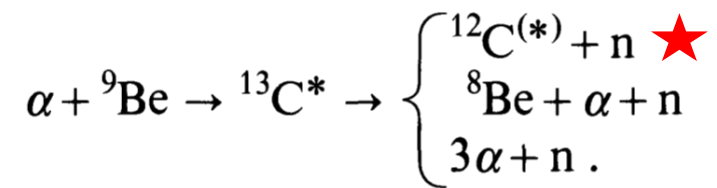


Fig. 1.5. Neutron energy spectrum from ^{252}Cf (from Lorch et al. [1.2]). The form of the spectrum can be described by a Maxwellian distribution

Figure: from Leo

2- neutrons from (α,n) sources via α emitters

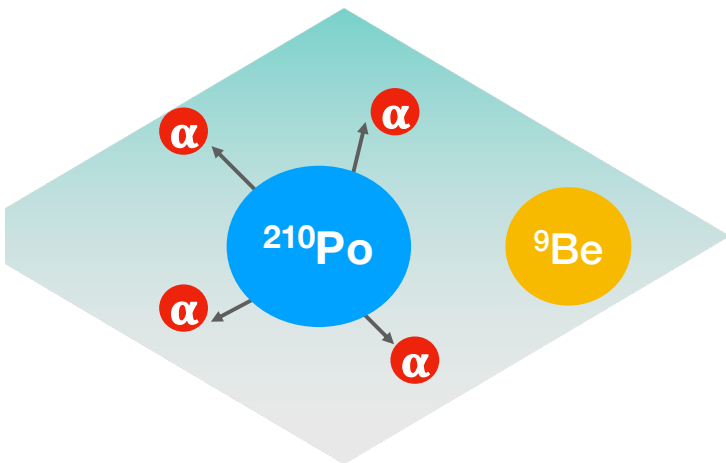
(α,n) sources are created via nuclear reactions.



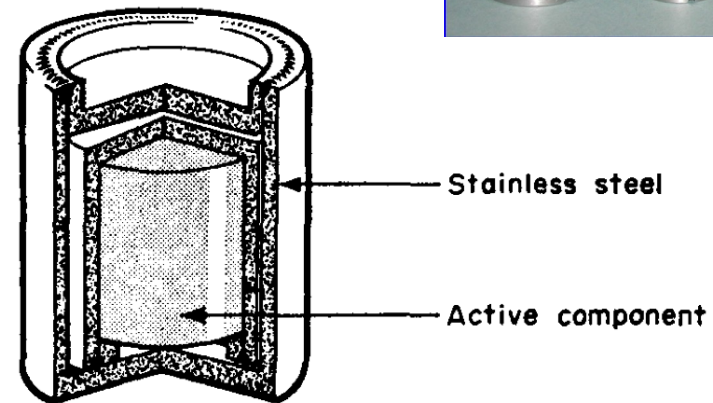
Be is the most common target material to create free neutrons

(α,n) sources are generally made by mixing the target material with a suitably strong α emitter.

intimate contact: Powdered ${}^9\text{Be}$ metal & an oxide of the alpha emitter



Am/Be Sources



A typical Be(α,n) source

Figure: from Knoll

Table 1.6 Characteristics of Be(α , n) Neutron Sources

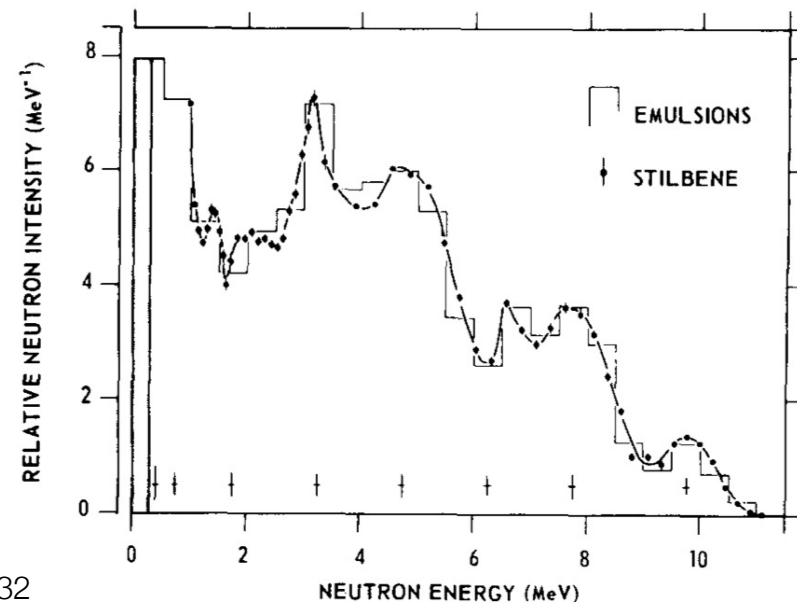
α -emitter/Be source	Half-Life	E_α (MeV)	Neutron Yield per 10^6 Primary Alpha Particles		Percent Yield with $E_n < 1.5$ MeV	
			Calculated	Experimental	Calculated	Experimental
$^{239}\text{Pu}/\text{Be}$	24000 y	5.14	65	57	11	9–33
$^{210}\text{Po}/\text{Be}$	138 d	5.30	73	69	13	12
$^{238}\text{Pu}/\text{Be}$	87.4 y	5.48	79 ^a	—	—	—
$^{241}\text{Am}/\text{Be}$	433 y	5.48	82	70	14	15–23
$^{244}\text{Cm}/\text{Be}$	18 y	5.79	100 ^b	—	18	29
$^{242}\text{Cm}/\text{Be}$	162 d	6.10	118	106	22	26
$^{226}\text{Ra}/\text{Be}$ + daughters	1602 y	Multiple	502	—	26	33–38
$^{227}\text{Ac}/\text{Be}$ + daughters	21.6 y	Multiple	702	—	28	38

Neutrons are not monoenergetic

smearing of the alpha particle spectrum due to energy loss

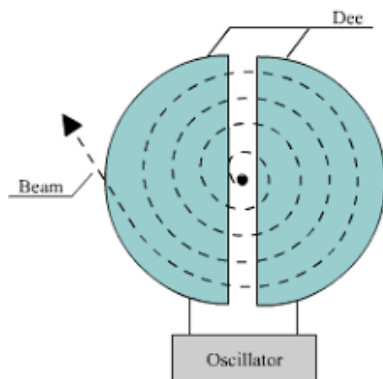
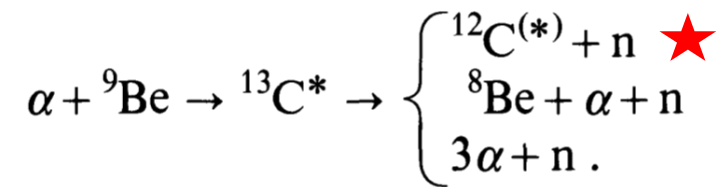
Figures:from Knoll

Pu/Be source

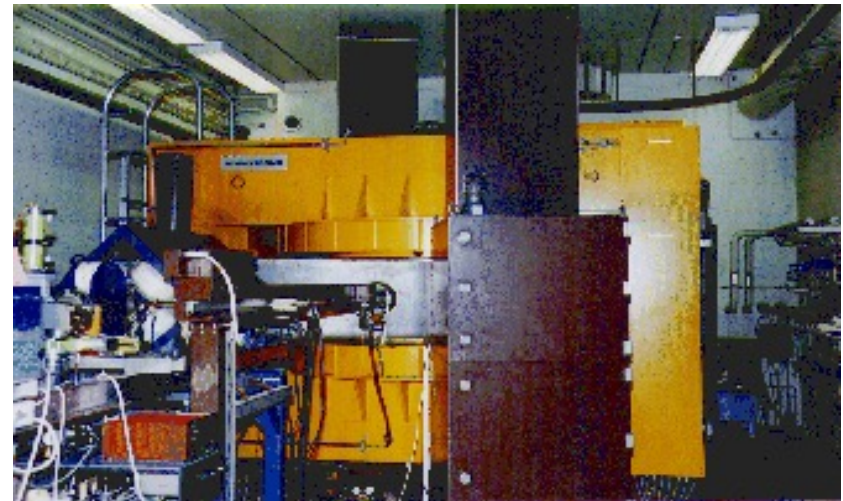
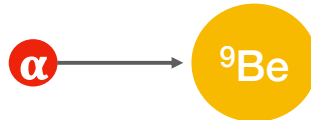


3- neutrons from (α ,n) sources via accelerators

Neutrons can be created directly from accelerating α particle on to a ^9Be target **via accelerators**.



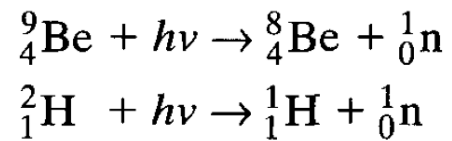
Cyclotron



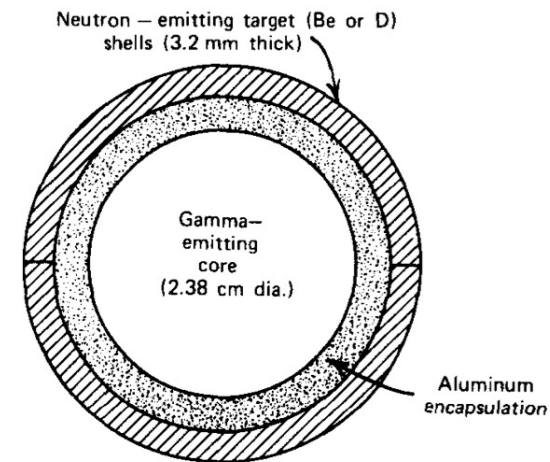
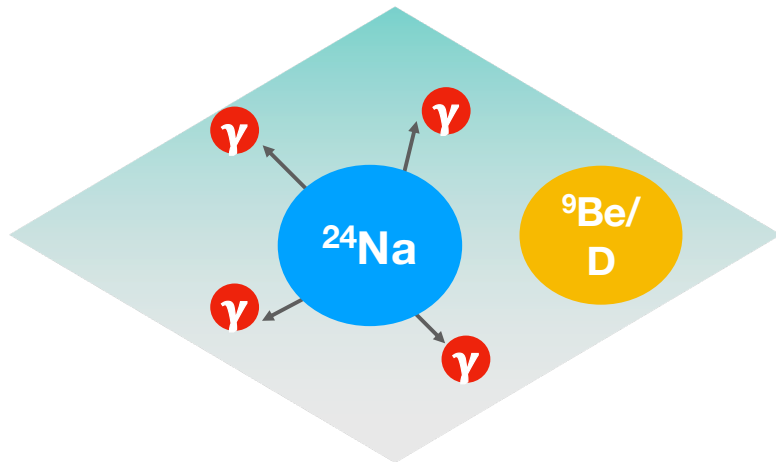
Our Cyclotron at OCL

4- neutrons from (γ,n) (photoneutron) sources:

Gamma-ray emitters can also be used to produce neutrons when combined with an appropriate target material.



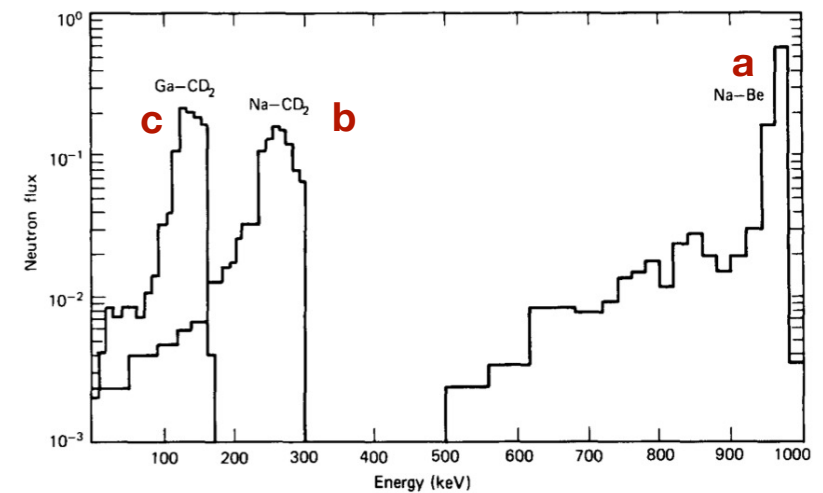
Neutrons created via gamma emitters are called **photoneutrons**.



Photoneutron source

Table 1.8 Photoneutron Source Characteristics

Gamma-Ray Emitter	Half-Life ^a	Gamma Energy ^a (MeV)	Target	Neutron Energy ^b (keV)	Neutron Yield (n/s) for 10 ¹⁰ Bq Activity ^c
²⁴ Na	15.0 h	2.7541	Be a	967	340,000
		2.7541	D b	263	330,000
²⁸ Al	2.24 min	1.7787	Be	101	32,600
³⁸ Cl	37.3 min	2.1676	Be	446	43,100
⁵⁶ Mn	2.58 h	1.8107	Be	129	91,500
		2.1131		398	
		2.9598		1,149	
		2.9598	D	365	162
⁷² Ga	14.1 h	1.8611	Be	174	64,900
		2.2016		476	
		2.5077		748	
		2.5077	D c	140	25,100
⁷⁶ As	26.3 h	1.7877	Be	109	3,050
		2.0963		383	
⁸⁸ Y	107 d	1.8361	Be	152	229,000
		2.7340		949	
		2.7340	D	253	160
^{116m} In	54.1 min	2.1121	Be	397	15,600
¹²⁴ Sb	60.2 d	1.6910	Be	23	210,000
¹⁴⁰ La	40.3 h	2.5217	Be	760	10,200
		2.5217	D	147	6,600
¹⁴⁴ Pr	17.3 min	2.1856	Be	462	690



Advantage:
Photoneutrons are monoenergetic.

Summary

Particle Name	Symbols	Charge (in units of e)	Nucleon Number
Electron	$e^{-}, \beta^{-}, {}^0_{-1}e$	-1	0
Positron	$e^{+}, \beta^{+}, {}^0_{+1}e$	+1	0
Proton	$p, {}^1_1p, {}^1_1H$	+1	1
Neutron	$n, {}^1_0n$	0	1
Alpha particle	$\alpha, {}^4_2\alpha, {}^4_2He$	+2	4
Photon	$\gamma, {}^0_0\gamma$	0	0
Neutrino	$\nu, {}^0_0\nu$	0	0
Antineutrino	$\bar{\nu}, {}^0_0\bar{\nu}$	0	0

Electrons:

Beta decay, electron capture,
internal conversion, auger
electrons

Electromagnetic radiation: Photons

Gamma rays : keV-MeV high-energy photons
X-rays: eV -keV low-energy photons
Annihilation radiation: 511 keV

Bremsstrahlung:

Heavy Charged particles:

Alpha : Alpha decay

Fission fragments: Spontaneous fission

Nuclei in general : Nuclear reactions

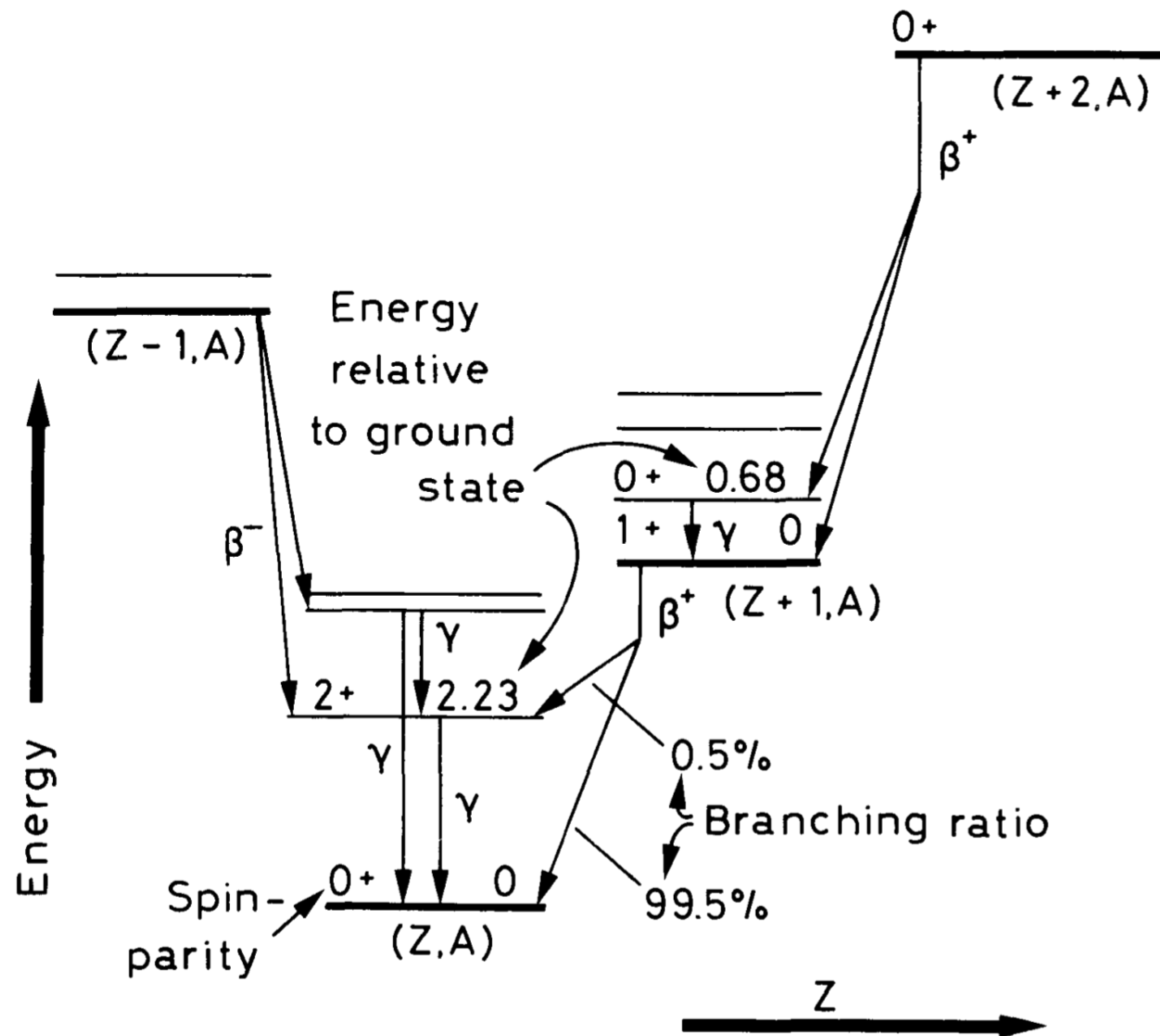
Neutrons:

Spontaneous fission

(α, n) reactions

(γ, n) reactions

n-induced fission (fission reactors)



Today:

- Electrons

 - Beta electrons

 - Internal conversion electrons

 - Auger electrons

- Photons

 - X-rays

 - gamma rays

 - Annihilation radiation

- Alpha particles

- Neutrons

 - Spontaneous fission

 - (α, n) sources

 - (α, n) via accelerators

 - (γ, n) Photoneutron sources

Radioactive decay

Radioactive decay

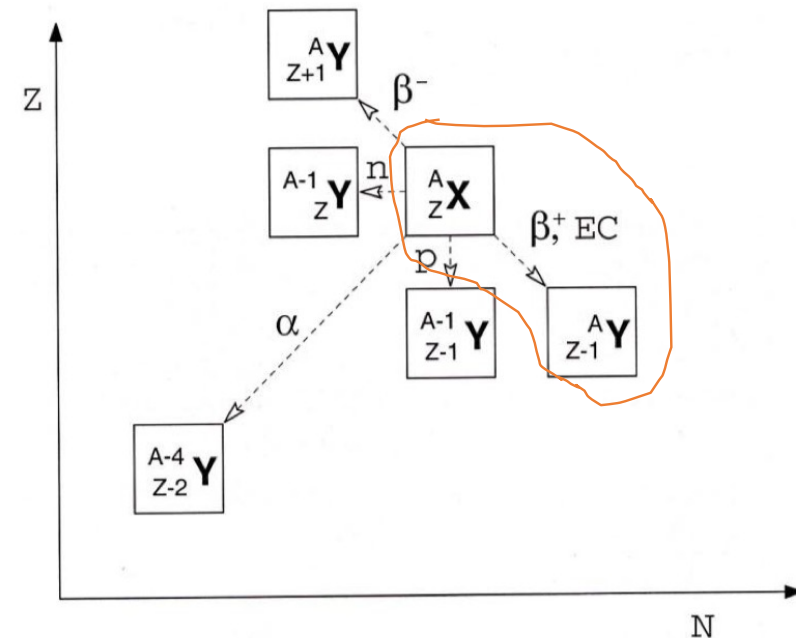
Naturally occurring radioactive nuclei undergo a combination of α , β , E capture, and γ decays. These are spontaneous decays.

Reminder: For a spontaneous decay to occur, Q-value should be larger than zero:

$$Q = (M_{\text{initial}} - M_{\text{final}})c^2 > 0$$

$$Q_{\beta^+} = \{M(^A X) - [M(^A Y) + m(p)]\} c^2 > 0$$

Q-value: total energy released in a given nuclear decay or a reaction



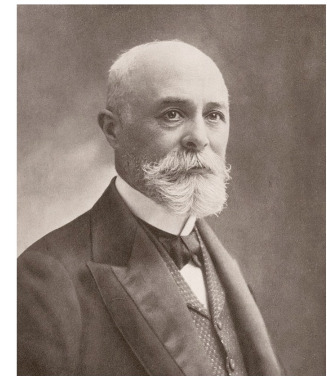
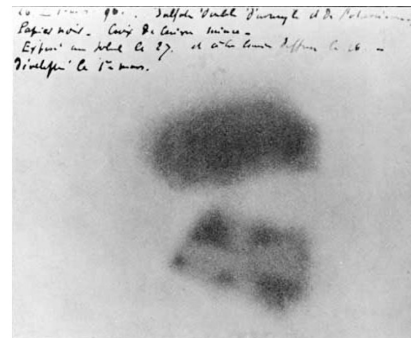
Radioactivity was discovered in 1896 by Henri Becquerel.

Decay rate of a pure radioactive substance decreases with time according to an **exponential decay**.

Decay is a statistical process

Henri Becquerel (1852-1908)

Discovery of radioactivity



[P. Nadar]

Radioactivity was discovered in 1896 by Henri Becquerel.

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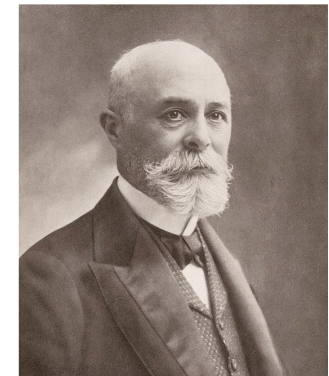
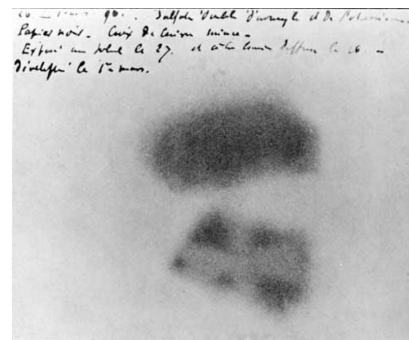
Decay is a statistical process



to know when a nucleus will decay into another nucleus is impossible, but is possible to predict the probability of nuclear decay in a unit of time and consequently the mean number of decayed nuclei per second

Henri Becquerel (1852-1908)

Discovery of radioactivity



[P. Nadar]

If N radioactive nuclei present at time t and no new nuclei are introduced in the sample, then the number of dN decaying in a time dt is proportional to N

λ is the proportionality constant.

Number of radioactive
nuclei which decay in a dt
time period (interval)

Number of radioactive
nuclei present in a
sample

$$\frac{dN}{dt} \propto N$$

$$\frac{dN}{dt} = -\lambda N$$

Decay constant (decay
probability)

Exponential decay law

$$dN = -\lambda N dt$$

$$\frac{dN}{N} = -\lambda dt$$

$$\int_{N_0}^N \frac{dN}{N} = \int_0^t -\lambda dt$$

$$N_0 = N(t=0)$$

$$\ln N - \ln N_0 = -\lambda t$$

$$\ln \frac{N}{N_0} = -\lambda t$$

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

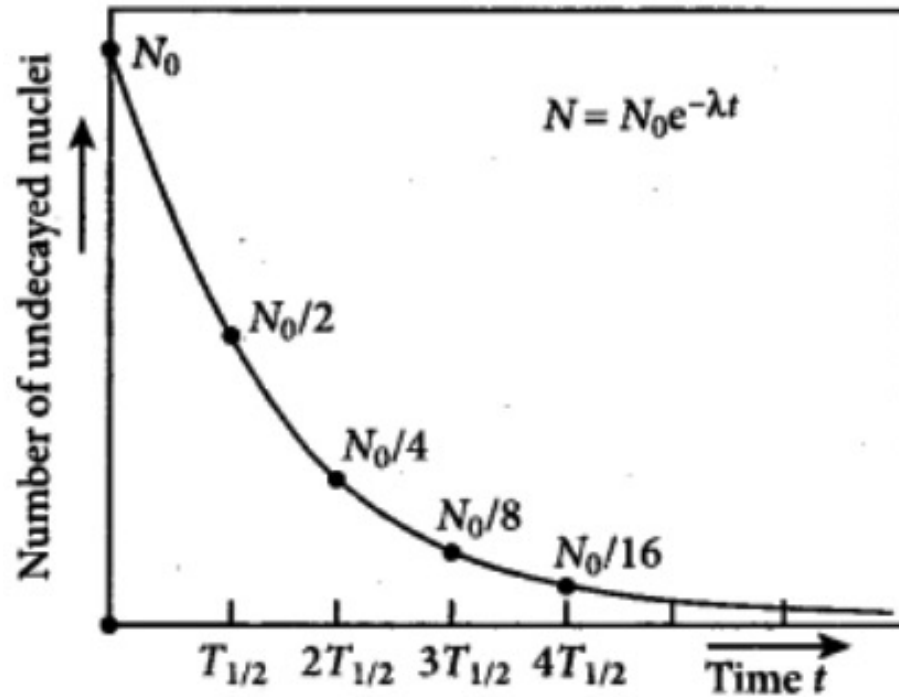
Where

N_0 : Number of unstable nuclei at $t=0$

$N(t)$: Number of unstable nuclei remaining at time t

λ : decay constant

t)



∴ Law of radioactive decay

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

$$t_{1/2} = \frac{0.693}{\lambda} \quad T_{1/2} = t_{1/2} : \text{decay half life}$$

Decay constant

$$\tau = \frac{1}{\lambda}$$

Mean lifetime

Decay constant

Mean lifetime is the average time the particle will exist without decaying or atomic nucleus in a sample will exist without transforming to another one. (Calculated statistically)

shorter lifetime ~ higher decay constant (probability)

Half-life

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

$$N(t_{1/2}) = N_0 / 2 = N_0 e^{-\lambda t_{1/2}}$$

$$1/2 = e^{-\lambda t_{1/2}}$$

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

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

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

$$t_{1/2} = \frac{0.693}{\lambda}$$

$$t_{1/2} = 0.693 \tau$$

The half-life is defined as the time elapsed when the intensity of the radiation is reduced to one half of its original value.

Activity

Number of decays per unit time is called Activity.

$$A = \frac{\Delta N}{\Delta t} \quad A = -\lambda N \quad A(t) = A_0 e^{-\lambda t}$$

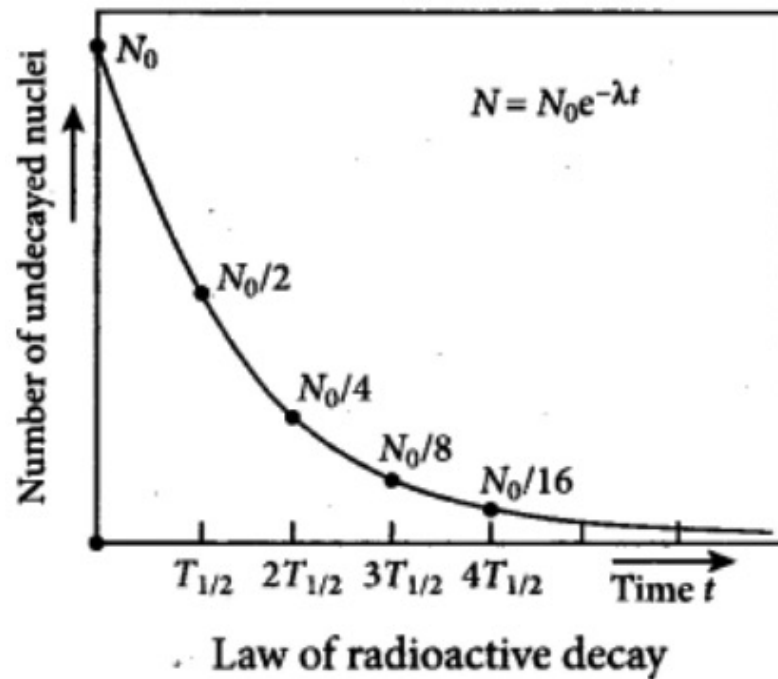
Units of Activity

1 Becquerel (Bq) = 1 disintegration/s

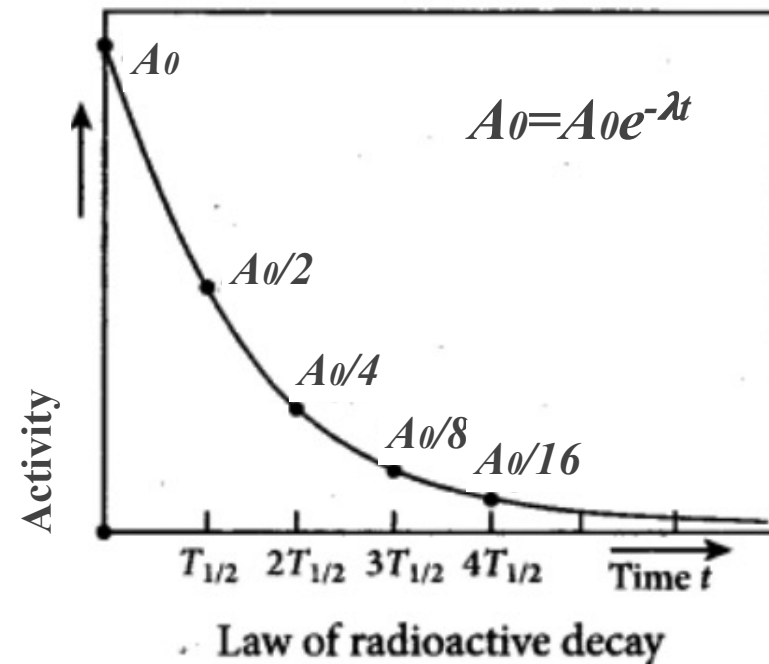
1 Curie (Ci) = 3.7×10^{10} disintegrations/s (dps) (activity of 1g ^{226}Ra)

What are we detecting from a sample in the lab?

Decay law in this form is rather limited for us since N is number of undecayed nuclei in a sample, thus very difficult quantity to measure.



It is easier to count the number of decays (by observing the emitted radiation) that occur between the times t_1 and t_2



We will do this counting experiment soon
(Exp 1: Geiger-Muller experiment)

Fluctuations in Radioactive Decay

Consider now the number of decays undergone by a radioactive source in a period of time Δt which is short

compared to the half-life of the source. The activity of the source may then be considered as constant.

If we repeat the measurement of the number of decays (n) in the interval Δt , fluctuations will be observed for these several sets of measurements.

Fluctuations are statistical nature of the decay process;

From the radioactive decay law, it can be shown that the probability of observing n counts in a period Δt is given by a Poisson distribution:

$$P(n, \Delta t) = \frac{m^n}{n!} \exp(-m)$$

m : average number of counts in a Δt time

$$\sigma = \sqrt{m} \quad \text{Standard deviation of the Poisson distribution}$$

Fluctuations in Radioactive Decay

Example: A source is observed for a period of 5 s during which 900 counts are accumulated by the detector. What is the count rate per second and error from this measurement?

Take the measurement as a single trial for the determination of the mean count rate in 5 s, i.e., $m = 900$ for $\Delta t = 5$ s. The standard deviation is then

$$\sigma = \sqrt{900} = 30.$$

The count rate per second is then

$$\text{rate/s} = (900 \pm 30)/5 = (180 \pm 6) \text{ cts/s}.$$

$$\sigma = \sqrt{m}$$

Questions after this lecture:

- When does internal conversion happen?
- Are beta electrons suitable for calibrating electron detectors? Why?
- Give an example of a process to create fast positrons and a good positron emitter source.
- Can you give examples of good gamma-ray calibration sources?
- What are sources of charged particles? Give examples.
- What is a half-life in a given radioactive decay? Why is it important?
- If we observe a radioactive source for a period of 10 seconds, during which 1000 counts are accumulated by the detector, what is the count rate per second and error from this measurement?