NEUTRON ACTIVATION ANALYSIS FUNDAMENTAL CONCEPTS

- **Nucleus – Nuclear Radiations**
- **Neutrons Classification**
- **Nuclear Reactions**
- **Neutron Reactions**
- **Neutron Sources**
- **Nuclear Reactor Schematic**
- **Neutron Flux**
- **Neutron Capture Cross-Sections**
- **Neutron Activation Radioactivity**

Nucleus

Material

↘

Compounds

↘

Elements

↘

Atoms

↓

(Neutrons + Protons) + Electrons
{Nucleus}

Element X can be depicted by

$${}^{A}_{Z}X_{N}$$

A = Mass Number
N = Neutron Number
Z = Atomic Number (Proton Number)

$$A = Z + N$$

Nucleus … …

	Mass	Charge
Neutron	- 1.008665 u	– No electrical charge
Proton	- 1.007277 u	– Positive charge
Electron	- 0.000548 u	– Negative charge

Ref: Nuclide Idotopes Chart of the Nuclides 16th Edition Lockheed Martin 2002

Nuclides

Isomer – Same N, Z, A but exists in an excited state for a period of time.

${}^{60}_{27}Co_{33}(T_{½}=5.26\,y)$ and ${}^{60m}_{27}Co_{33}(T_{½}=10.48\,m)$

Isotope – Same Z number, but different N

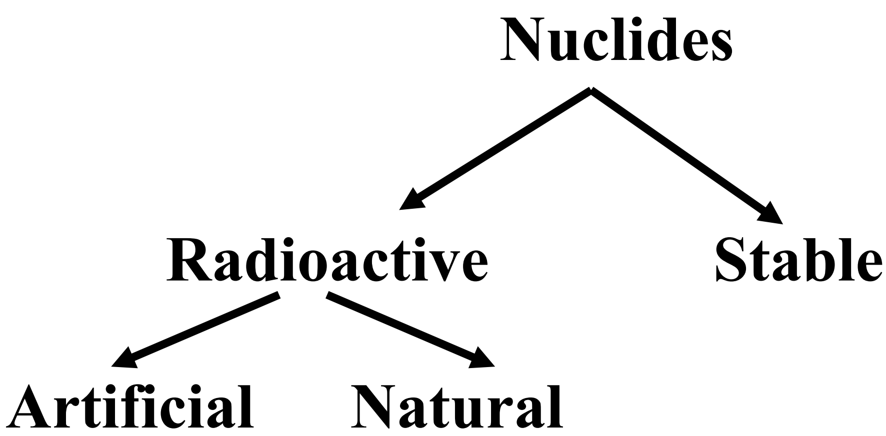
${}^{59}_{27}Co_{32}$, ${}^{60}_{27}Co_{33}$

Isobar – Same A number, but different Z

${}^{60}_{27}Co_{33}$, ${}^{60}_{28}Ni_{32}$

Isotone – Same N number

${}^{59}_{26}Fe_{33}$, ${}^{60}_{27}Co_{33}$, ${}^{61}_{28}Ni_{33}$



28	Ni 58.6934 Nickel	Ni48	Ni49 12 ms β^+ (p)	Ni50	Ni51 β^+ (p)	Ni52 ~0.04 s β^+ (p)	Ni53 0.05 s β^+ (p) 1.9	Ni54 0.10 s β^+ γ 937.1	Ni55 202 ms β^+ 7.66
27	Co 58.933200 Cobalt				Co50 44 ms β^+ (p) 2.73, 1.99	Co51 β^+ (p)	Co52 0.12 s β^+ γ 849.4, 1535.3, 1329.0, 1941.7 (p)	Co53 0.25 s 0.24 s β^+ β^+ p 1.55 γ 1328.2 ε ω ε ω	Co54 1.46 m 193.2 ms β^+4.5 β^+ 7.220 γ 1407, 1130, 411 ε ω ε ω

Cont....

Ni56 5.9 d ε γ 158.4, 811.8, ...	Ni57 35.6 h ε, β^+.85, ... γ 1377.6, ...	Ni58 68.0769 σ_γ 4.6, 2.2 σ_α < .03 mb	Ni59 7.6E4 a ε β^+ ω, no γ σ_γ 78, 1.2E2 σ_α 14, 20 σ_p 2, 3	Ni60 26.2231 σ_γ 2.9, 1.5	Ni61 1.1399 σ_γ ~2.5, ~1.8 σ_α $\leq$ .03 mb	Ni62 3.6345 σ_γ 14.5, 6.6	Ni63 101. a β^+0.0669 no γ $\hat{\sigma}_\gamma$ 24	Ni64 0.9256 σ_γ 1.6, 1.2
Co55 17.53 h β^+1.50, 1.03, ... γ 931.2, 477.2, 1408.4, ... ε	Co56 77.3 d ε, β^+1.459, ... γ 846.8, 1238.3, ...	Co57 271.8 d ε γ 122.1, 136.5, 14.4, ...	Co58 9.1 h 70.88 d IT 24.9, e^- ε, β^+.474, ... σ_γ 1.4E5, 3E5 γ 810.8,.. σ_γ 1.9E3, 7E3	Co59 100 σ_γ (21+16), (39+35)	Co60 10.47 m 5.271 a IT 58.6, e^- β^-.318, ... β^- 1.6 ω, ... γ 1332.5, 1173.2, ... γ 1332.5 ω, ... σ_γ 6E1, 2.3E2 σ_γ 2.0, 4	Co61 1.650 h β^- 1.22, ... γ 67.4, ...	Co62 13.9 m 1.50 m β^- 2.9, ... β^- 4.1, 2.9, .. γ 1173.0, 1163.6, ... γ 1173.0, ...	Co63 27.5 s β^- 3.6, ... γ 87.3D, ...

URL for Table of Isotopes:

http://ie.lbl.gov/toi.htm

Nuclear Radiations

Radioactivity is produced when unstable nuclei decay. For example

1) The slow decay rate of primordial heavy elements such as U and Th

2) The radioactive daughter products which form during natural radioactive decay series of U and Th

3) Irradiation of stable isotopes with particles generate unstable isotopes, which decay to stable isotopes by emitting radiation. Neutron Activation is important in this regard.

4) Particle bombardment of fissionable element leads to unstable fission fragments

The disintegration of radionuclides releases excess energy in the form of nuclear radiations.

Radioactive decay takes place in several ways emitting radiation such as:

- **Alpha rays**
- **Beta (negative and positive) rays**
- **Gamma rays**
- **Neutrons**

- **Neutrinos**
- **Proton decay**
- **Internal conversion electrons**
- **Characteristic x-rays**
- **Fission fragments**

Gamma-rays and β^- play important role in neutron activation analysis.

Gamma rays are emitted when an excited nucleus de-excites, by the transition from an excited energy state to a lower energy state. Gamma-rays have well defined energies and their emission often is accompanied by nuclear reactions and nuclear decays.

Negative Beta particles (β^-) or negatrons are emitted when neutron is transformed into a proton during the nuclear transformation.
Negative beta particles are electrons formed during nuclear transformation, hence are of nuclear origin. The atomic number (Z) of the resultant nucleus is one unit greater, but the mass number is unchanged.

Neutrons Classification

Type	Energy
1. Thermal	0.025 eV
2. Epithermal	0.025 eV – 0.2 eV
3. Resonance	1 eV – 1000 eV
4. Intermediate	1 keV – 500 keV
5. Fast	> 0.5 MeV

Neutron classification according to kinetic energy

The pictorial representation of the above table is given in the reference:

Ref. Ch.2 General principles of neutron activation analysis, J. Dostal and C. Elson p 28 Figure 2.3, Mineralogical Association of Canada
Short Course in Neutron Activation Analysis in the Geosciences, Halifax May 1980,
Ed: G. K. Muecke

Nuclear Reaction

Nuclear reaction occurs when target nuclei are bombarded with nuclear particles, depicted pictorially

$$X + a \longrightarrow Y + b + Q$$

Or

X(a,b)Y

Target X is bombarded by particle “a”, Y is the product nuclei with resulting particle “b” .

Q is the energy of the nuclear reaction, which is the difference between the masses of the reactants and the products.

Ex:

$${}^{59}_{27}Co_{32} + {}^{1}_{0}n_{1} \rightarrow {}^{60}_{27}Co_{33} + \gamma$$

or

$${}^{59}_{27}Co_{32}(n, \gamma)\,{}^{60}_{27}Co_{33}$$

Neutron Reactions

When target nuclei are bombarded with neutrons, of the many possible nuclear reactions that can take place, the four major reactions are

1) **Neutron capture**
2) **Transmutation**
3) **Fission reaction**
4) **Inelastic Scattering**

1)Neutron capture:

The target nucleus absorbs (captures) a neutron resulting in a product isotope, the mass number of which is incremented by one. If the product nucleus is unstable, it usually de-excites by emission of gamma rays and/or β^- .

Ex:

$^{58}_{26}Fe_{32}$ (n,γ) $^{59}_{26}Fe_{33}$.

2)Transmutation
Target nucleus absorbs a neutron, emitting charged/non-charged particles like alpha, proton, 2 neutrons, deutron. The unstable product nucleus generally de-excites through β⁻ emission back to the target nucleus

$^{55}_{25}Mn_{30}$ (n,p) $^{55}_{24}Cr_{30}$.

$$^{55}_{24}Cr_{30} \xrightarrow{\beta^-} {}^{55}_{25}Mn_{30} \,.$$

Transmutation neutron reactions are caused by neutrons of high energies (fast or intermediate neutrons).

3) Fission Reaction:
Fissionable target nucleus (usually Z >90) absorbs a neutron, triggering the fission

process, splitting into two large segments and simultaneously releasing 2 to 3 neutrons.
The fission process can become a chain reaction producing large amount of neutrons which become source to a NUCLEAR REACTOR.

4)Inelastic Scattering:
Target nucleus does not absorb the incident neutron, but only part of the neutron energy is transferred to the target.

For detailed text reference:
Ch.2 General principles of neutron activation analysis, J. Dostal and C. Elson
p 21-42,
Mineralogical Association of Canada
Short Course in Neutron Activation Analysis in the Geosciences, Halifax May 1980,
Ed: G. K. Muecke

Neutron Sources

Major sources:

1) **Nuclear Reactors**
2) **Fast Neutron Generators**
3) **Cyclotrons**
4) **Isotopic Neutron Sources**

Nuclear Reactor
Brief Outline

U, Th and Pu are fissionable materials, with radio-isotopes ^{233}U, ^{235}U, ^{238}U , ^{232}Th, ^{239}Pu, ^{241}Pu. Fission is triggered when a fissionable target nucleus captures thermal or fast neutrons. This neutron reaction splits the target nucleus into two lighter nuclei and an average of 2 to 3 neutrons is emitted in case of ^{235}U by thermal neutron bombardment. The first fission process may trigger second fission reaction when one of the neutrons emitted is captured by another fissionable nucleus, and this process in turn may trigger a third and so on thus creating a chain reaction

^{235}U has 0.714% isotopic abundance.
(Abundance is the atom percentage of an isotope present in the mixture)

Table 2:
Reactor Components and materials

Component	Material	Function
Fuel	^{235}U	
Moderator	Light and Heavy Water, C, Be	To reduce energy of fast to thermal
Coolant	Light and Heavy Water, C, Be, Air, etc	To remove heat
Reflector	Same as moderator	To reduce leakage
Shielding	Concrete, Water, Pb, Steel, Polyethylene	To provide protection from radiation
Control Rods	Cd, B, Hf	To control neutron production rate
Structure	Al, Steel. Zr,	To provide support

Cladding	Al, Stainless steel, Zr alloy	To provide corrosion resistance to fuel, containment of fission products

Source:
Chapter 1: Introduction, page 7,
Arthur R. Foster and Robert L. Wright, Jr.
Basic Nuclear Engineering, Second Edition
Allyn and Bacon Inc., Boston

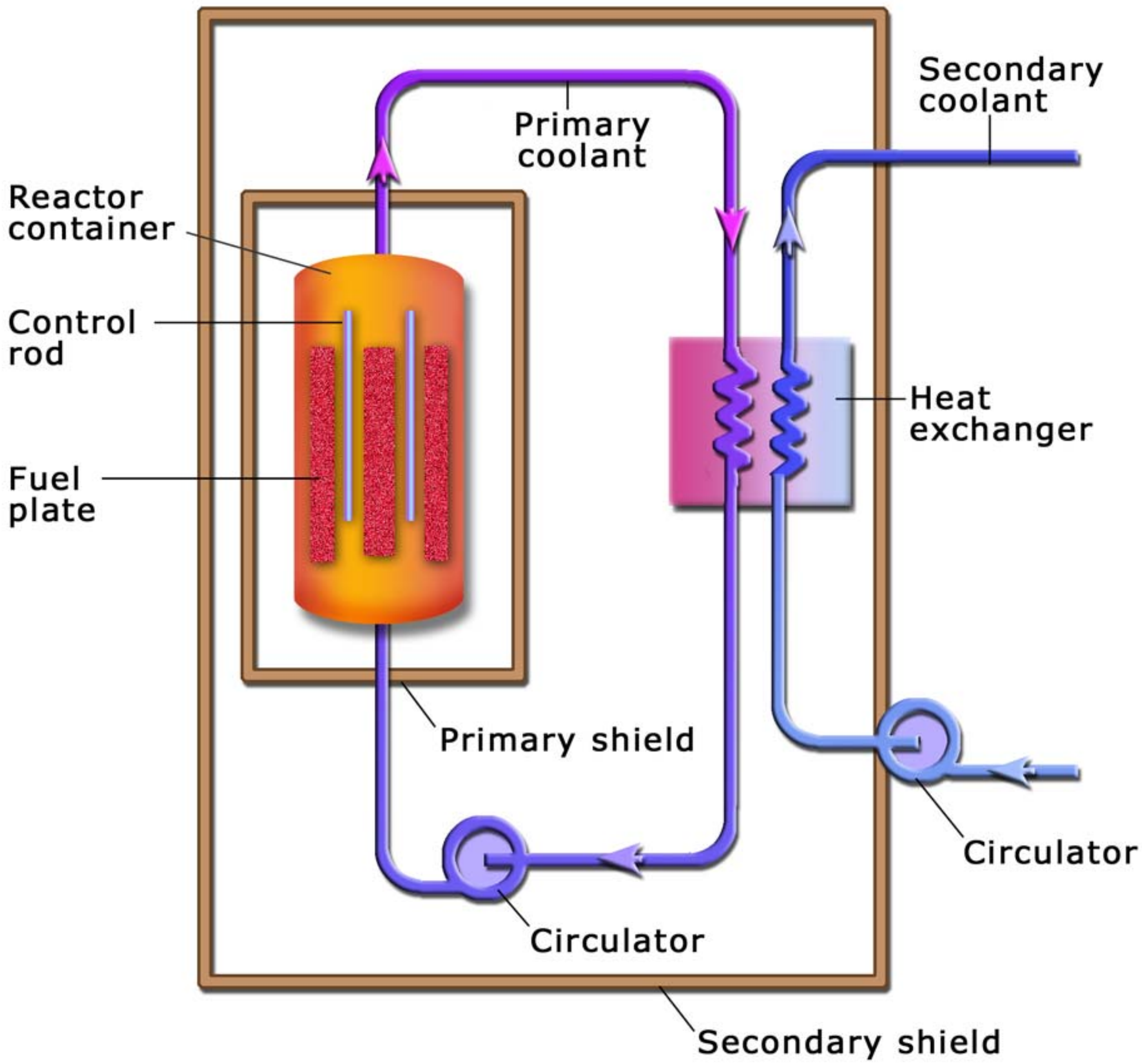


Figure 1: Schematic of a nuclear reactor

NEUTRON FLUX

Neutron flux is the amount of neutrons available for irradiation. The unit of neutron flux is the number of neutrons incident per square centimeter area per second, as shown below:

$$n.cm^{-2}.sec^{-1}$$

Thermal neutron activation analysis requires at least a minimum neutron flux of 10^9 and 10^{10} $n.cm^{-2}.sec^{-1}$

The neutron flux 10^{11} and 10^{13} $n.cm^{-2}.sec^{-1}$ can be generated by research reactors of total power 100-200 kW. The irradiation time for neutron activation analysis depends on applications.

Neutron energy spectrum is shown in figure 2 on Page 18.

NEUTRON CAPTURE CROSS-SECTIONS

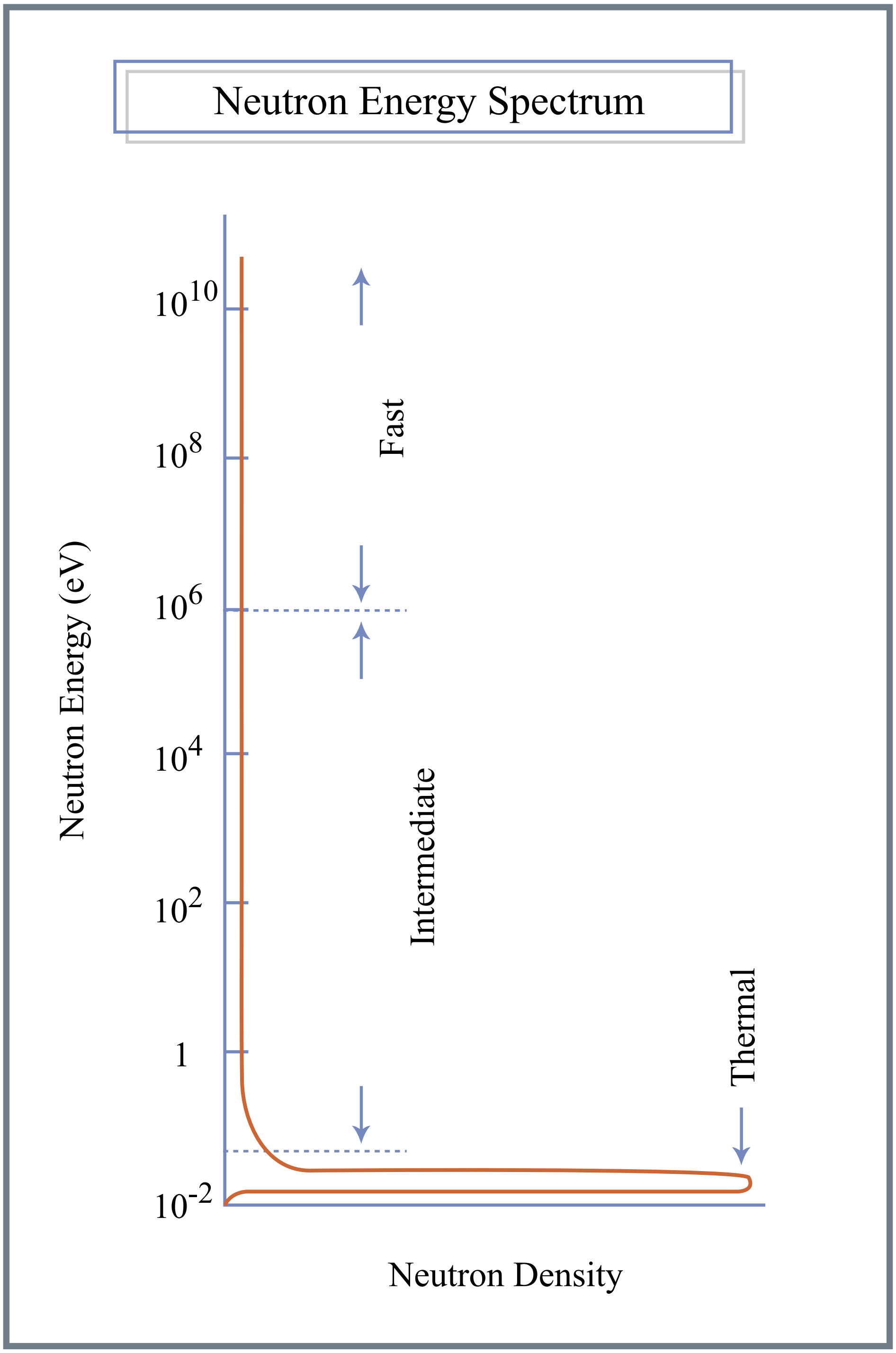
NEUTRON ACTIVATION occurs as a result of interaction between incident neutron and target nucleus of an atom. The radius of a typical atom is of the order of 10^{-10} m; that of a nucleus is of 10^{-14} m; and that of neutron is of 10^{-18} m.

The probability that such an interaction to take place, for a nuclear transformation to occur, depends on the energy of the neutron and the nature of the target nucleus and is referred to as the

NEUTRON CAPTURE CROSS-SECTION

of the isotope leading to a specified nuclear reaction.

The neutron capture cross-sections are expressed in units of area, in 'barns', where
1 barn = 10^{-24} cm^2 .



Neutron Energy Spectrum
Neutron Energy (eV)
10^10
10^8
10^6
10^4
10^2
1
10^-2
Fast
Intermediate
Thermal
Neutron Density

Neutron Generators:

Neutron generators typically generate fast neutrons. The target nuclei of deuterium or tritium when bombarded with deuterium (^{2}H) ions, the neutron interaction generates fast neutron flux of energies 2.5 MeV and 14 MeV respectively.

Cyclotrons:

The involved neutron reaction is $^{9}Be\,(d,n)\,^{10}B$. The neutron flux of 10^{10} to 10^{12} n. $cm^{-2}.sec^{-1}$ gets generated.

Isotopic Neutron Sources:

^{252}Cf, ^{210}Po-Be, ^{226}Ra-Be

NEUTRON ACTIVATION ANALYSIS
RADIOACTIVITY

Activity Equation

A = number of decays per second (Activity) dps

N = number of atoms of the target isotope

$$= \frac{m}{w} \times \theta \times 6.023 \times 10^{23}$$

m = mass of the element in the irradiated sample g
θ = isotopic abundance
w = Atomic weight of the element

λ = decay constant $= 0.693/t_{1/2}$
$t_{1/2}$ = Half-life of the isotope

ϕ = neutron flux $n.cm^{-2}.sec^{-1}$
σ = activation cross-section $10^{-24}\ cm^2$
t_{irr} = irradiation time

$$A = N \sigma \phi [1 - \exp(-\lambda t_{irr})]$$

After a delay of time t_d

$$A = N \sigma \phi [1 - \exp(-\lambda t_{irr})]\exp(-\lambda t_d)$$

For a counting time of t_c

$$A = N \sigma \phi [1 - \exp(-\lambda t_{irr})]\exp(-\lambda t_d) [1 - \exp(-\lambda t_c)]$$

Neutron Activation Analysis by comparator method

$A_{Standard}$ = Activity of an isotope of an element in the known (Standard) is proportional to the amount present.

A_{Sample} = Activity of the isotope of the same element in the unknown (Sample)

$Amount_{Standard}$/ $Amount_{Sample}$

=

$A_{Standard}$ / A_{Sample}

Session 1 End