Experimental techniques for radiation dosimetry

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Physics contribution

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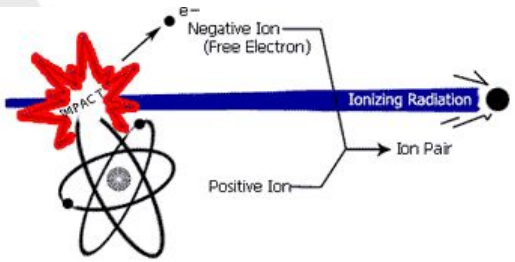
Workshop
Terapia por Captura Neutrónica en Boro (BNCT): aspectos interdisciplinarios para la realización de una radioterapia selectiva.
JORNADAS DEL CUIA EN ARGENTINA 10ª Edición

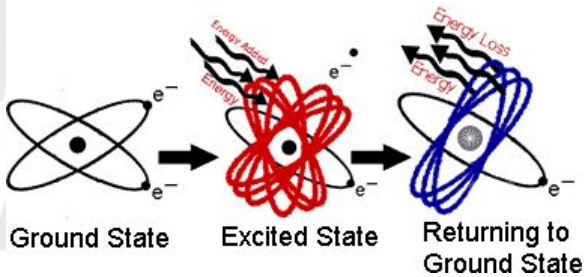
Introduction

The passage of ionizing radiations through matter induces processes of ionizations and excitations of the medium atoms and molecules.

These microscopic processes are the origin of macroscopic directly or indirectly measurable effects.

Any effect which causes the variation of a physical and/or chemical and/or biological parameters as a function of the energy absorbed per unit mass of a medium could be exploited to carry out a measurement of the absorbed dose.





Introduction

The various dosimetric methods can be distinguished in

- absolute methods which allows to obtain the dose value directly from the measure of physical or chemical parameters, such as
  - calorimetry,
  - chemical dosimetry,
  - ionometric method,

- relative methods which need an inter-calibration with some absolute methods, such as
  - film dosimetry,
  - thermoluminescence dosimetry,
  - optically stimulated luminescence dosimetry
  - electron spin resonance dosimetry

Introduction

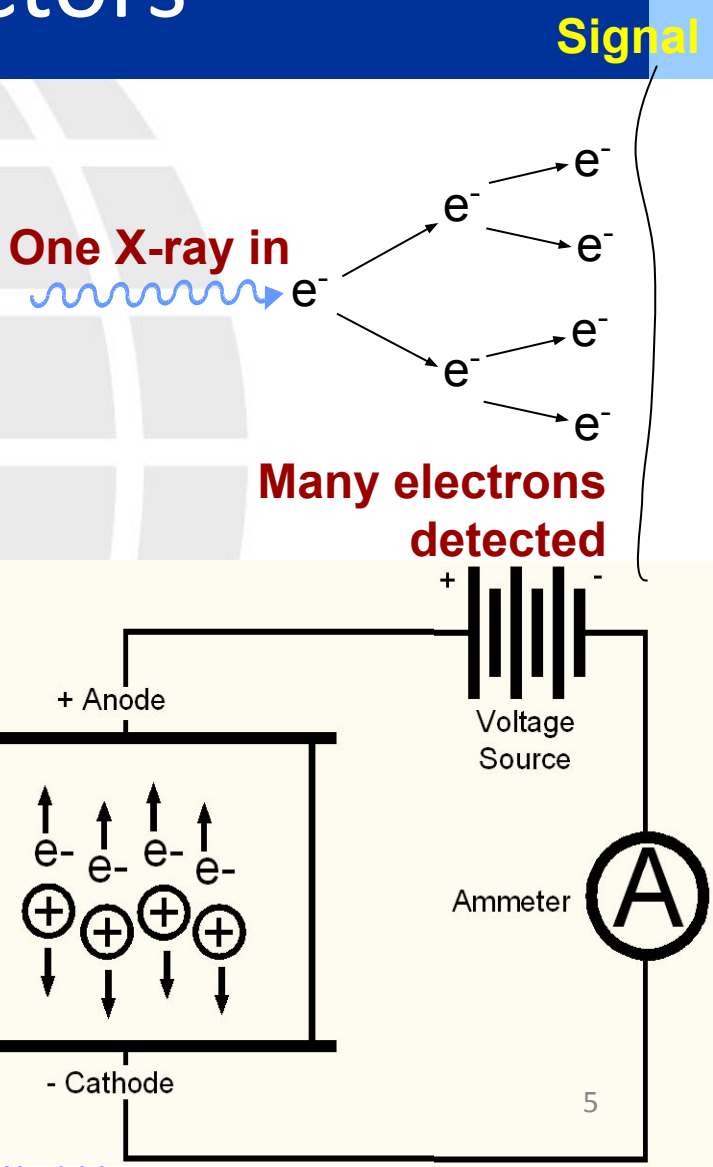
In this presentation the attention will be focused on

- gas-filled detectors
- thermoluminescence dosimetry
- electron spin resonance dosimetry
- neutron flux measurements though neutron activation method

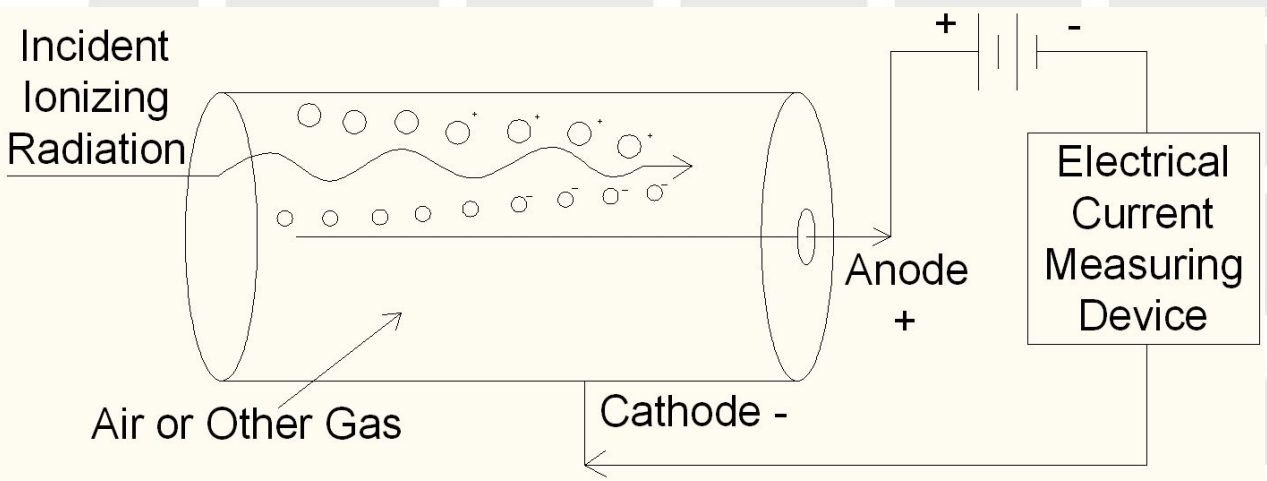
Gas-Filled Detectors

- Detect incident radiation by measurement of two ionization processes
  - Primary process: ions produced directly by radiation effects
  - Secondary process: additional ions produced from or by effects of primary ions
    - Townsend Avalanche

- Primary and secondary ions produced within the gas are separated by Coulombic effects and collected by charged electrodes in the detector
  - Anode (positively charged electrode)
    - Collects the negative ions
  - Cathode (negatively charged electrode)
    - Collects the positive ions



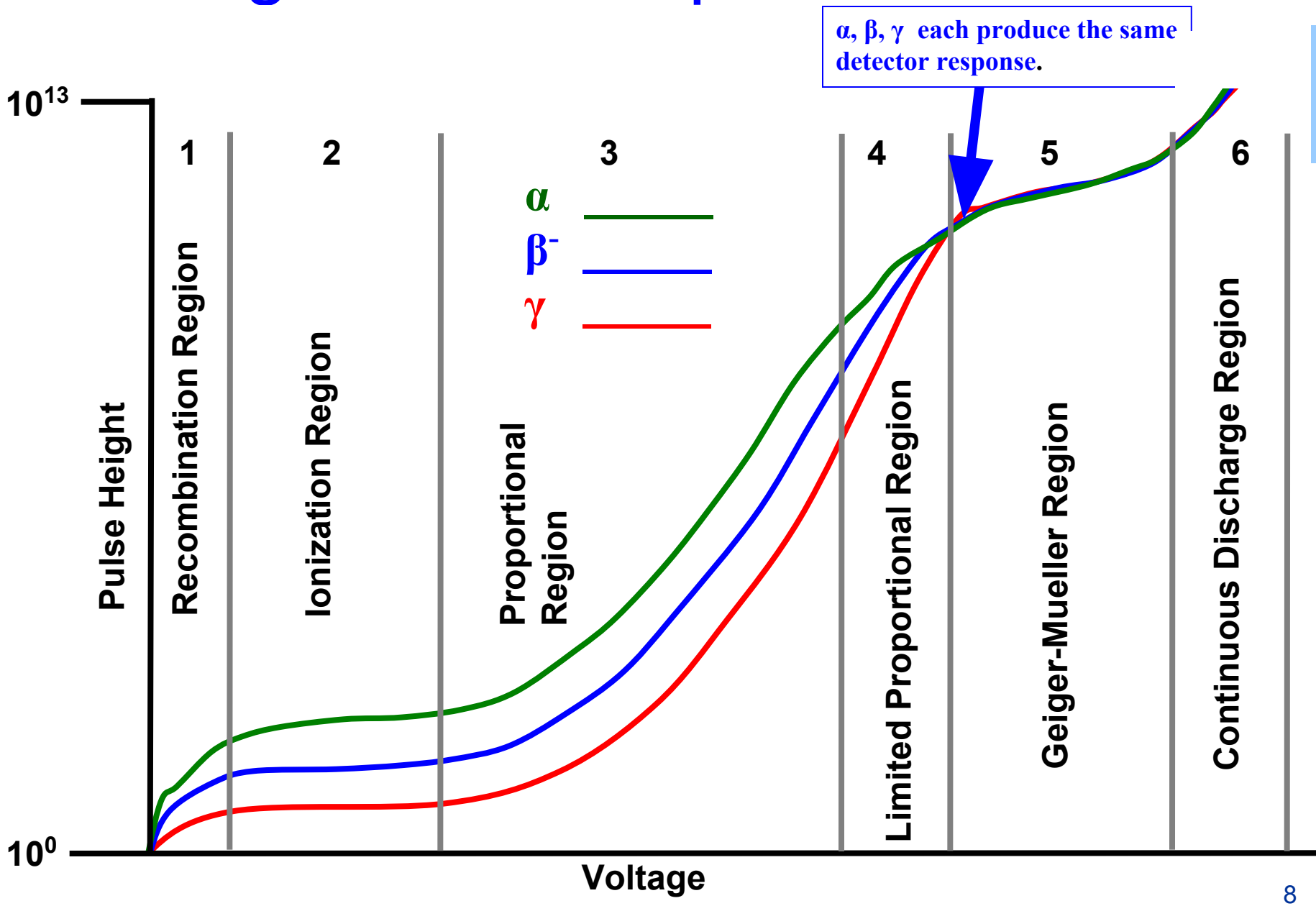
Gas-Filled Detectors



Gas-Filled Detectors

- Voltage too low
  - Ions may recombine and neutralize each other prior to reaching electrodes
- Proper operating voltage
  - All primary ion pairs are collected
- Voltage too high
  - Chamber becomes flooded with ions due to secondary ionizations caused by high-energy primary ions
  - Output current is no longer proportional to number of primary ionizations
  - Radiation events no longer measured
    - Ionization “avalanche” propagated by input voltage itself

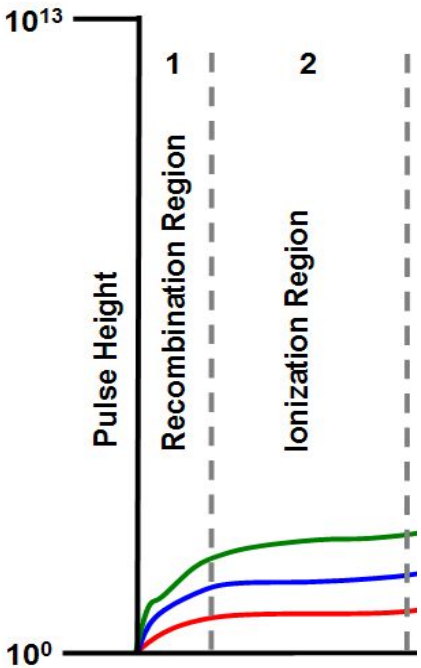
Six-Region Gas Amplification Curve



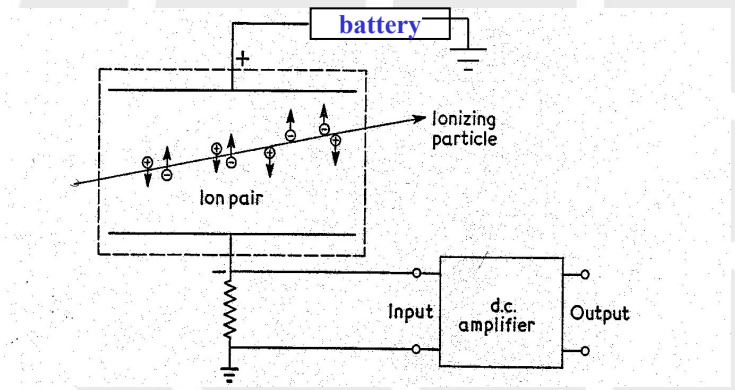
Six-Region Gas Amplification Curve

1. Recombination Region
   - Applied voltage too low
   - Recombination occurs
   - Low electric field strength

2. Ionization Chamber Region
   (aka Saturation Region)
   - Voltage high enough to prevent recombination
     - All primary ion pairs collected on electrodes
   - Voltage low enough to prevent secondary ionizations
   - Voltage in this range called saturation voltage
   - As voltage increases while incident radiation level remains constant, output current remains constant (saturation current)



Ionization chamber



- Low voltage (30 – 100 V)
- Air filled vented to atmosphere
- Radiation entering produces ion pair
- Ion pair drift to respective electrodes
- Produces very small current 10^{-14}A
- Tissue equivalent (Z=7.5)
- Flat response to gamma energies

$$D_{air} = \frac{Q}{m}\left(\frac{\overline{W}}{e}\right)_{air} = X\left(\frac{\overline{W}}{e}\right)_{air}$$

Ionization chamber

Ionization chamber

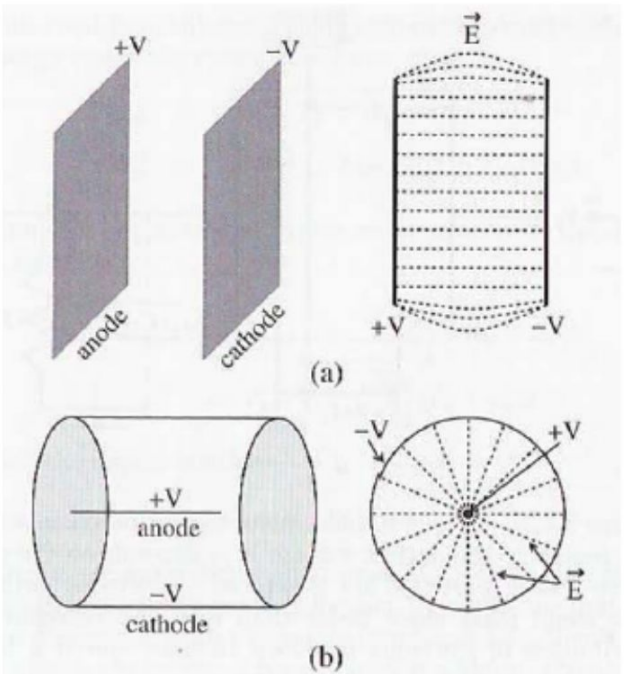
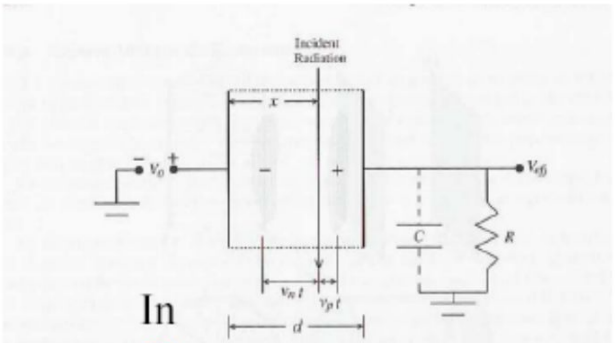


Figure 3.4.2: (a) Parallel plate ion chamber and a two dimensional view of electric field inside its active volume. The curved electric field at the sides may induce nonlinearity in the response. (b) Cylindrical ion chamber and a two dimensional view of radial electric field in its active volume. The increased flux of electric lines of force near the positively charged anode wire greatly enhances the electron collection efficiency.



In
Planar Geometry
Electrical field is constant

In
Cylindrical Geometry
Electrical field is NOT constant:

With E=-gradV
and V(r) from laplace equation we have

$$|\vec{E}(r)| = \frac{U_0}{r \ln r_a/r_i},$$

Ionization chamber

Advantages

- Used as a doserate monitor
- Can measure gamma > 12 keV and beta > 70 keV (with cf applied)
- Detects neutrons (~ 8% efficiency)

Disadvantages

- Low currents = expensive electronics
- Very slow response times
- Susceptible to high humidity or moisture
- Susceptible to air pressure changes
- Contamination by radioactive gases

GAS DETECTORS FOR NEUTRONS

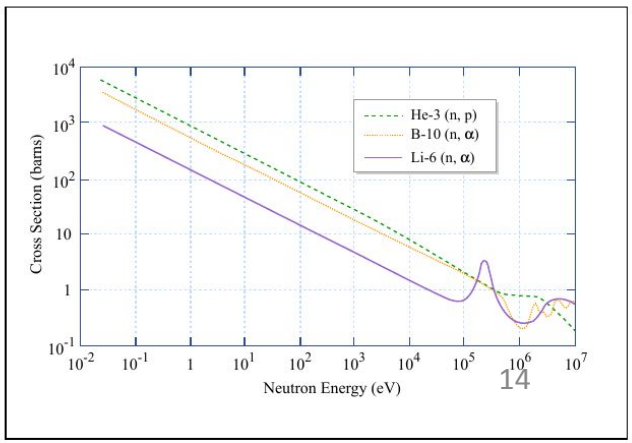
For thermal neutrons

- Two important aspects to consider
  - Find a material with large capture cross section for thermal neutrons
  - Find an arrangement that allows you to distinguish from gamma rays
- High Q-value of neutron capture will make it easier

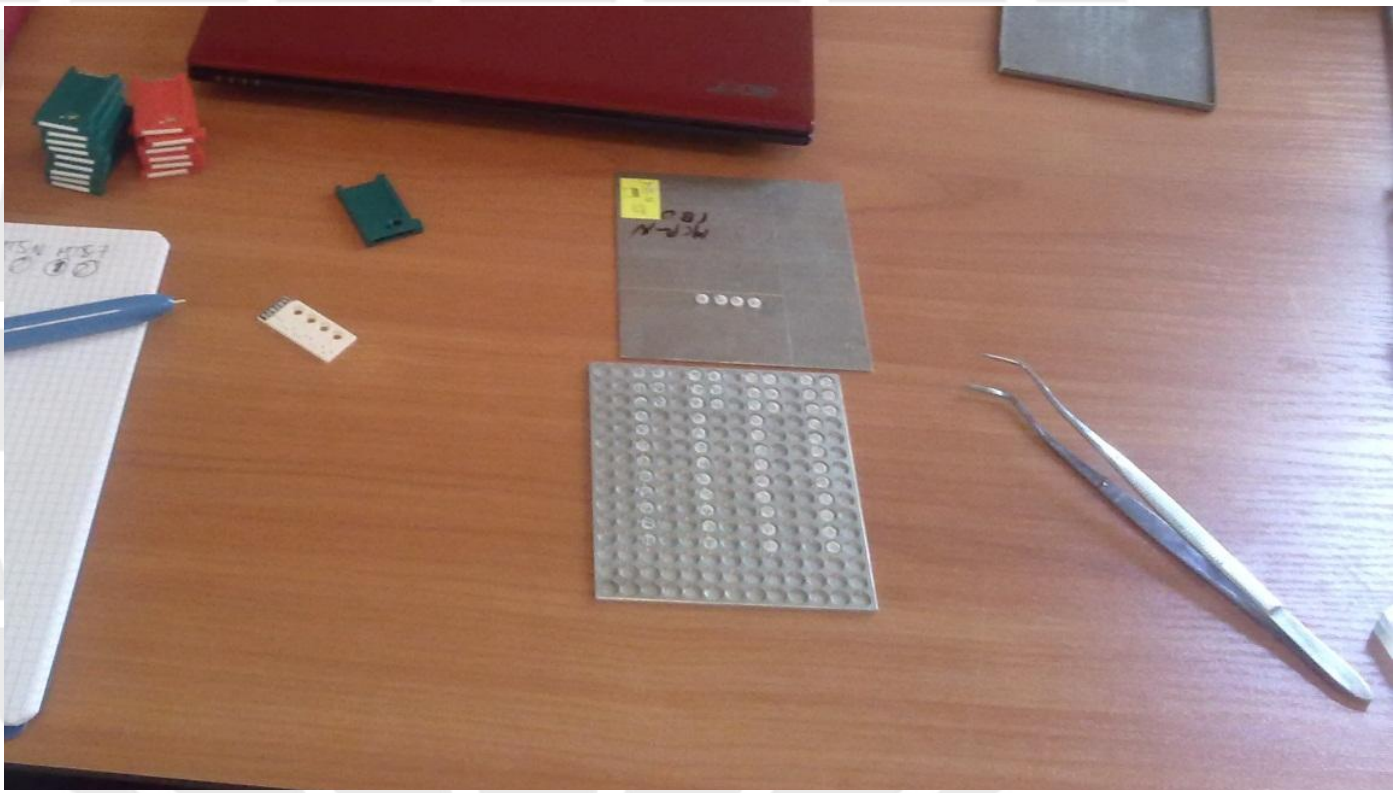
$$^{3}He + n \rightarrow {}^{3}H + {}^{1}H + 765\ keV$$

$$^{10}B + n \rightarrow {}^{7}Li^{*} + {}^{4}He + 2310\ keV$$

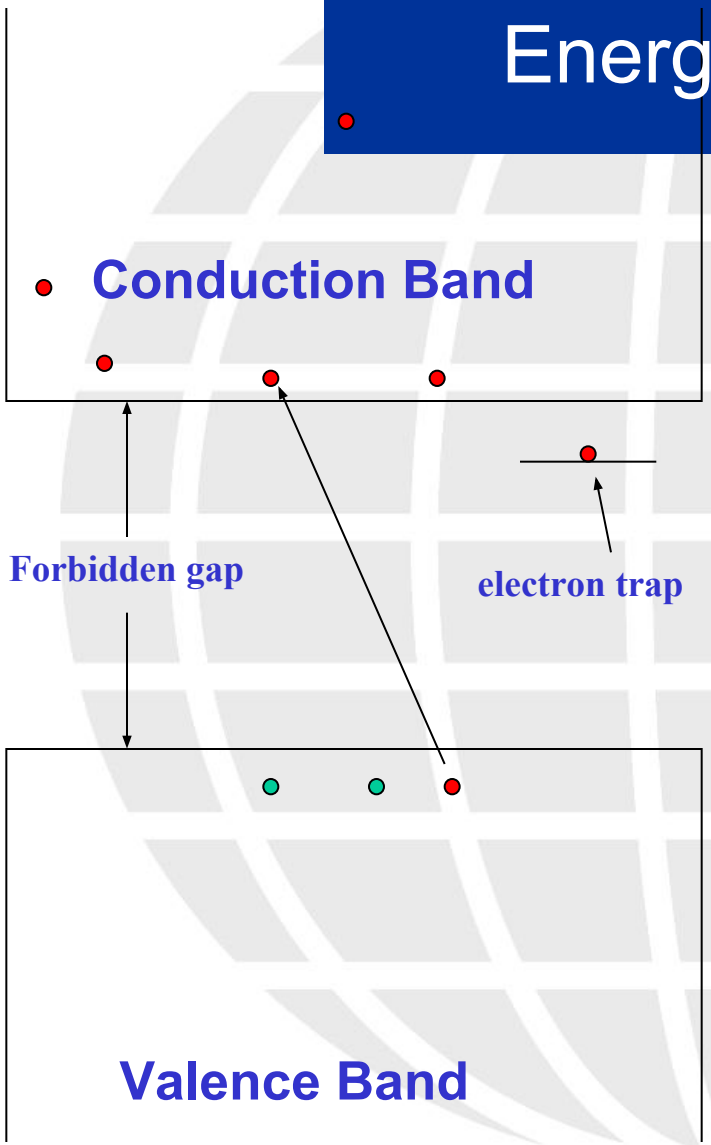
and $^{7}Li^{*} \rightarrow {}^{7}Li + 480\ keV$.



What is a TLD?



Energy level structure in solids



- Single atoms or molecules display energy levels
- When these come together to form a solid the discrete levels become energy *bands*
- Top 2 bands are the Valence and Conduction bands
- Valence band is nearly full, conduction nearly empty
- Forbidden region has no electrons in pure crystal
- Extension (in eV) of forbidden region depends on type of solid
- Impurities or dopants introduce electron 'traps'
- Excitation leaves the valence band with a 'hole'
- Conduction electron drops down to the valence band emitting a photon of light
- Introduction of dopants increases the efficiency

What is a TLD?

- A slide containing pellets of variously doped Lithium Fluoride phosphors
- Common variations used:
  - LiF:Mg,Ti [N or 7] MTS
  - LiF:Mg,Cu,P [N or 7] MCP
- The N and 7 stand for which lithium is used in the sample
  - N -> 'Natural', a combination of lithium 6 and 7.
  - 7 -> Only lithium 7 is used
- The material has thermoluminescent properties after exposure to radiation
- Each type has a different sensitivity (efficiency) to different types of radiation
  - For example, lithium 7 is not sensitive to thermal neutrons, but lithium 6 is [this difference can be used to work out the thermal neutron dose]
- TLDs can be calibrated in specific radiation fields and this information can then be used to determine the dose absorbed by the material [TLDs can be calibrated using gamma source Co60]
- Designed for personal dosimetry

How TLDs work

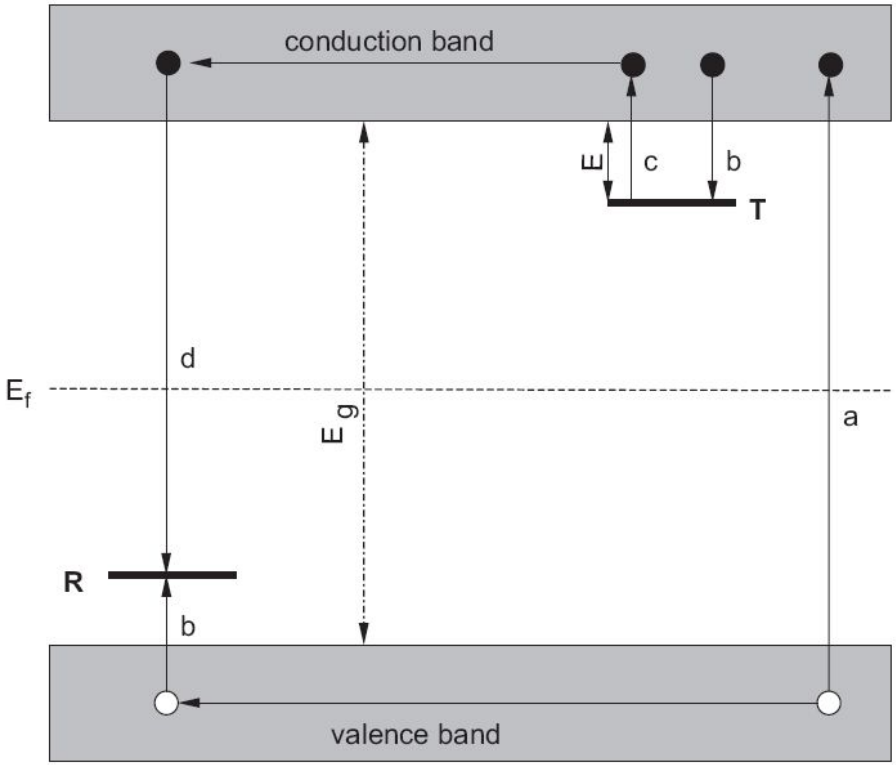
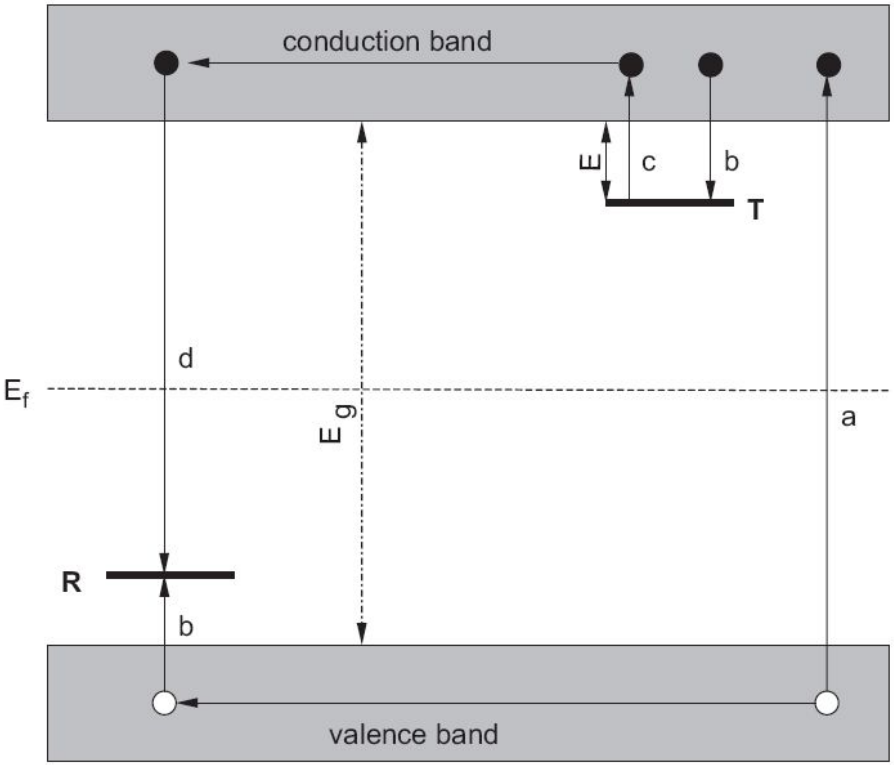


Fig. 1. Energy band model showing the electronic transitions in a TL material according to a simple two-level model: (a) generation of electrons and holes; (b) electron and hole trapping; (c) electron release due to thermal stimulation; (d) recombination. Solid circles are electrons, open circles are holes. Level T is a electron trap, level R is a recombination centre, E_f is Fermi level, E_g is the energy band gap.

The one trapping – one recombination centre model:

- Electrons/hole pairs become excited when exposed to radiation
- If the electron is given enough energy, it moves into the conduction band
- When the electron tries to return to the ground state, there are two possibilities:
  - It returns directly
  - It gets trapped in an imperfection within the crystal structure (deliberately made from the doping process)

How TLDs work



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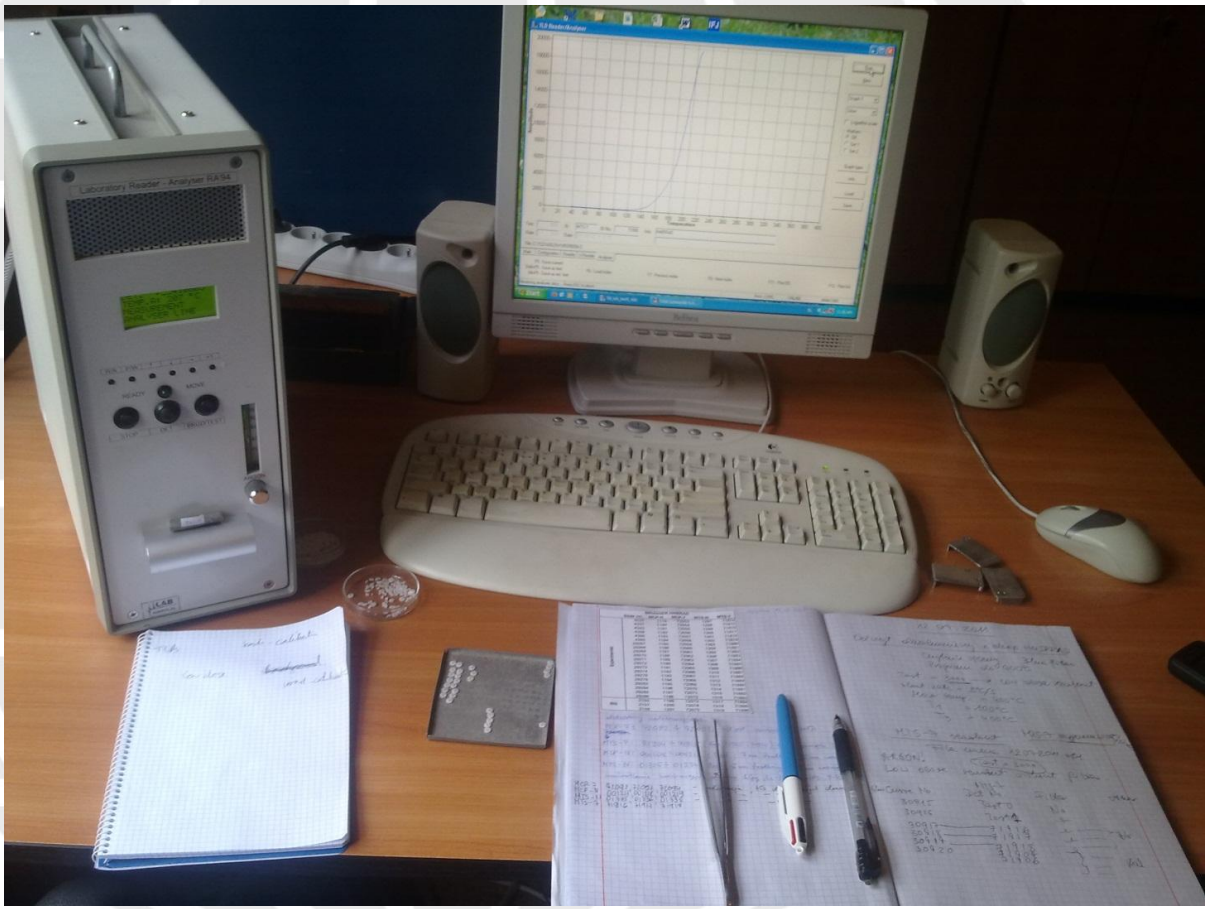
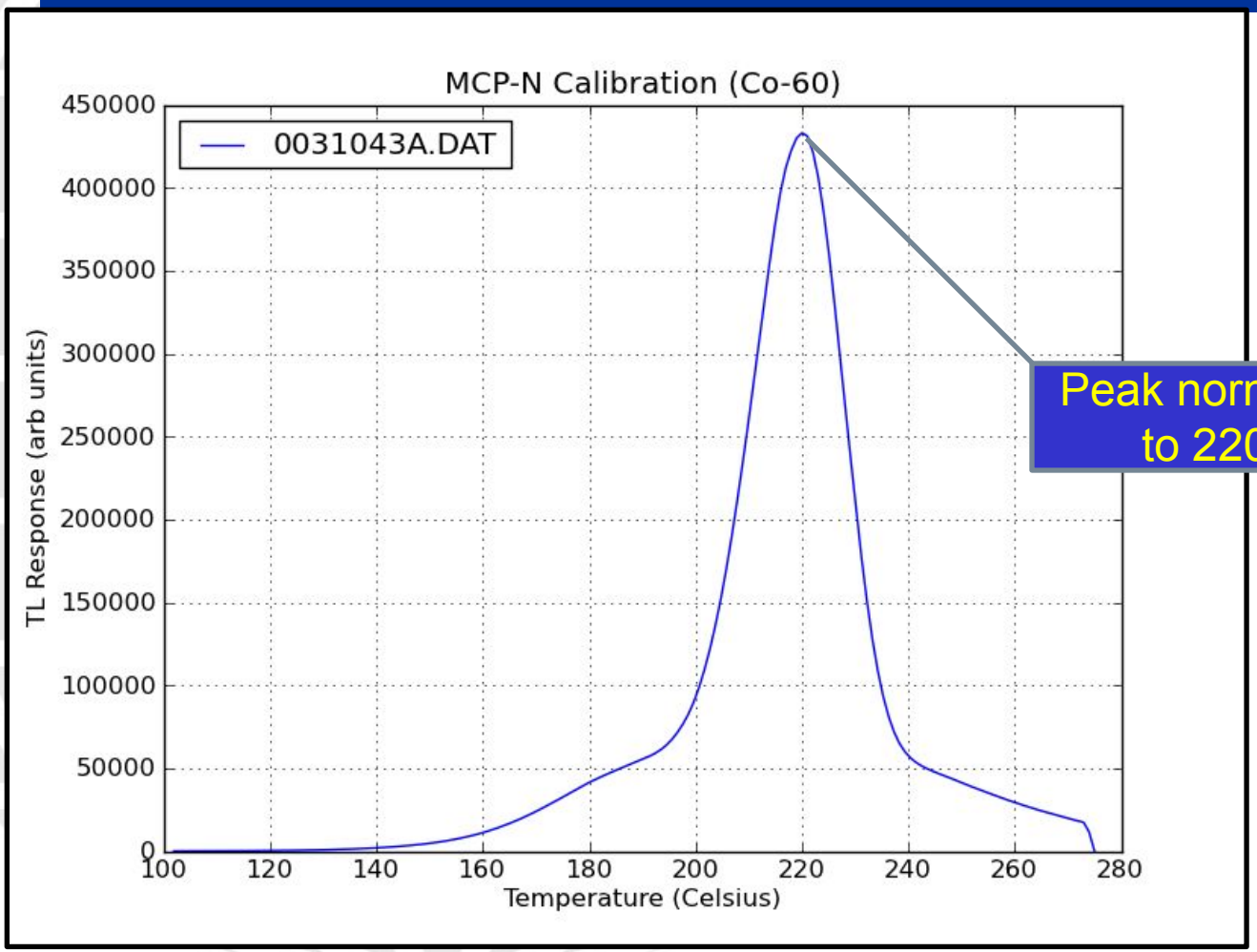
- When the sample is heated, the electron receives enough energy to escape from the trap and recombine with the hole -> this process emits light
- This light can be measured by a photomultiplier and the TLDs exposure to radiation can be calculated
- The trapped energy states can last for long time (if the trap depth is high) which make them a good a passive measuring device for radiation
- After reading, the TLD signal is eliminated, so can only be read once
- Sensitive between µGy to MGy

Reading the TLDs



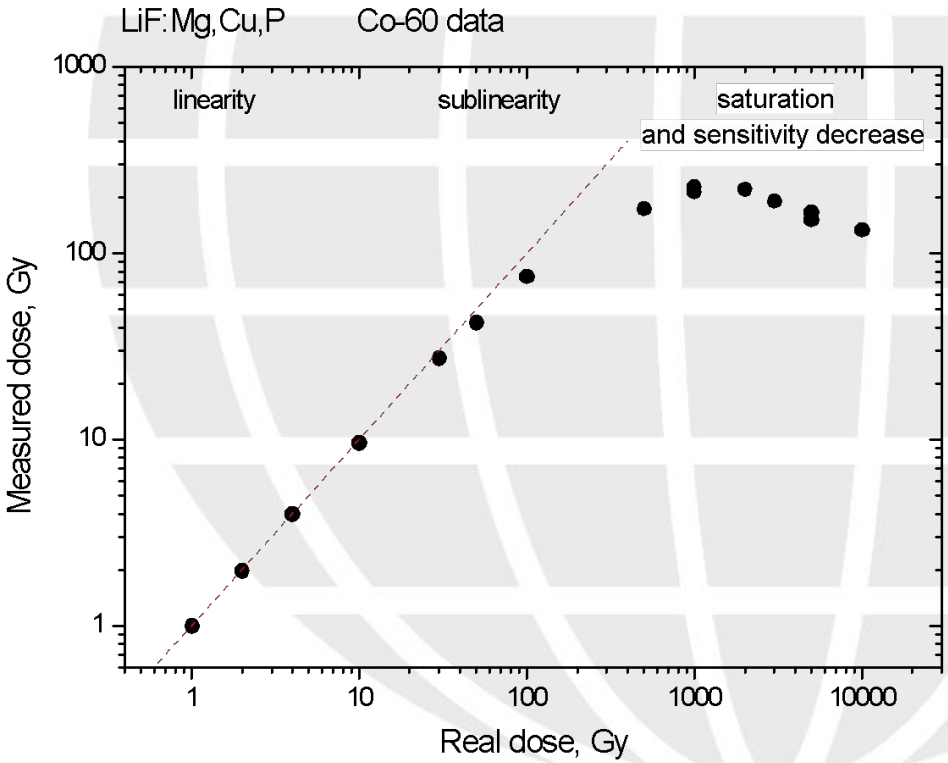
Reading the TLDs (Glowcurve)

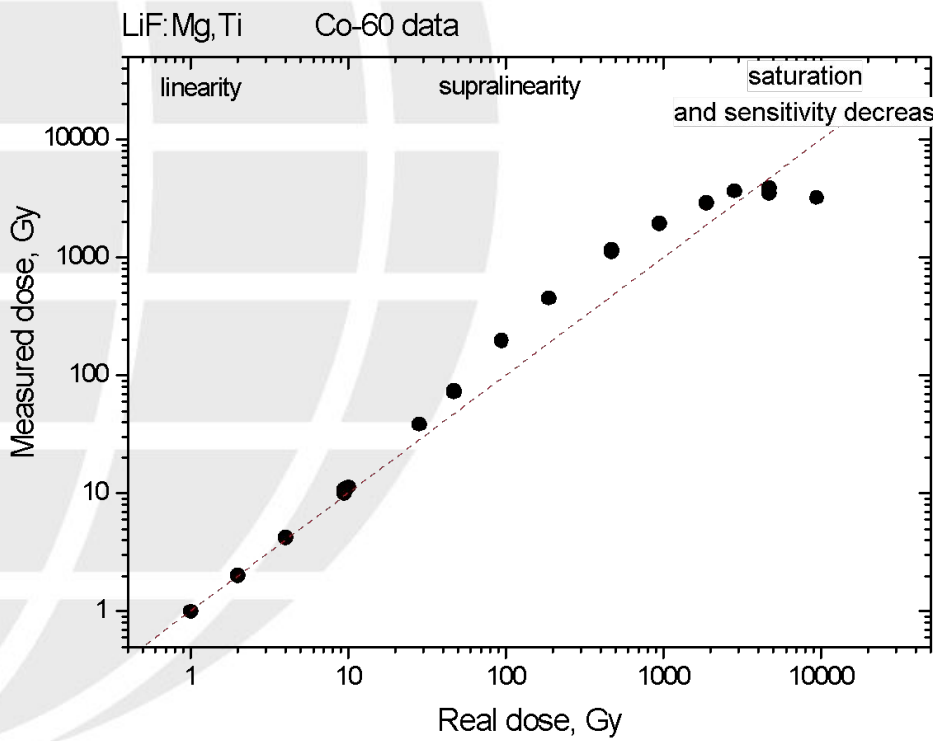


Peak normalised to 220°C

TLD Response

- Dose >1Gy is non linear





Use of TLDs

- Used in along side other detector types for additional comparison
- Sensitive to small doses, more so than the other kinds of active detectors
- Not effected by electric/magnetic fields
- Small size and mobile so can be placed anywhere

TLD

Advantages

- Lithium Fluoride is almost tissue equivalent.
- No darkroom processing / chemicals required to obtain result.
- Small size o Reusable
- Excellent resistance to environment (i.e. temperature, humidity)
- Can distinguish between types of radiation by using different lithium isotopes.

Disadvantages

- Re-usable: stored signal is cleared. The process of reading out eliminates the dose effect, so it can only be done once. Not permanent record.
- Dust on the detector will glow when heated and will be recorded by the phototube as a false reading.
- The TLDs are sensitive to exposure by ultraviolet light and therefore must be sealed in a light-tight badge.

Principle of application of ESR for dosimetry

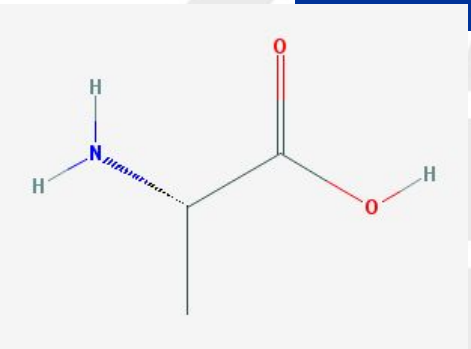
Ionizing radiations release energy in matter

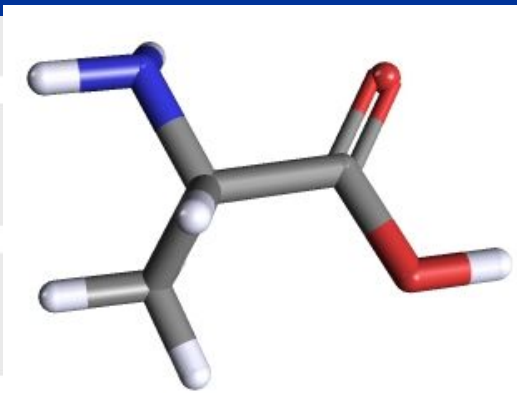
Production of paramagnetic centers (*i.e.* free radicals, point defects, etc)

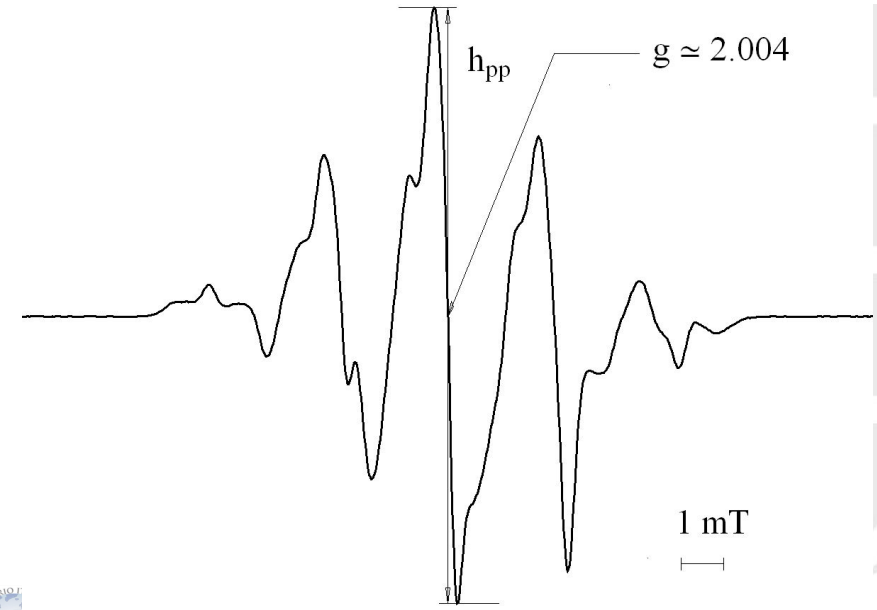
Electron Spin resonance (ESR) can detect paramagnetic species

Since the readout does not affect the ESR signal, it is possible to exploit additive dose response and repeated readings can be performed

ESR dosimetry – Alanine ($C_3H_7NO_2$) dosimetry







The alanine at present it is formally accepted by

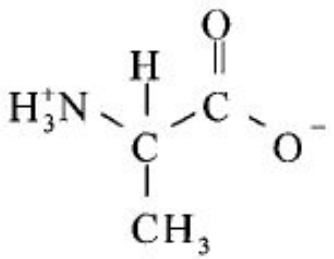
- IAEA (International Atomic Energy Agency, Vienna, Austria)
- NIST (National Institute for Standards and Technology, USA) and
- NPL (National Physical Laboratory, UK)

as a secondary reference and transfer dosimeter for high dose irradiation.

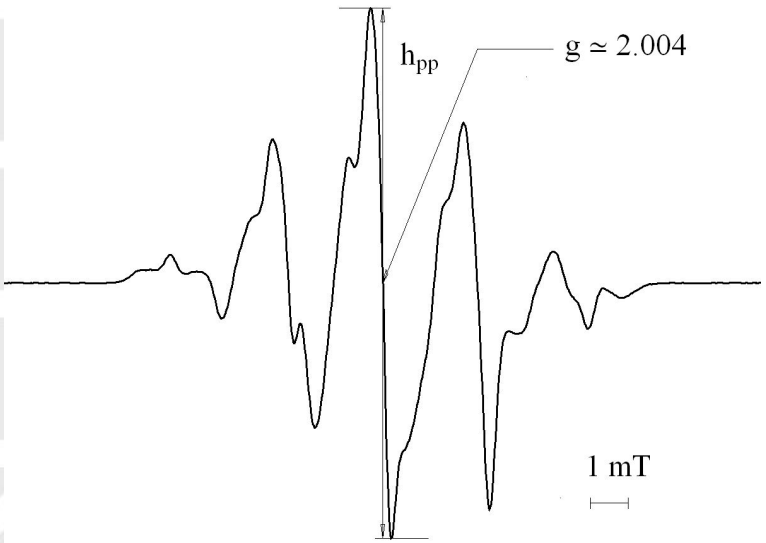
ESR/alanine dosimetry

Features of the amino acid alanine:

- The linearity of the EPR response in a wide range of doses from 10 up to 5×10^4 Gy.
- near tissue equivalence
- high radiation chemical yield
- near invariant response to
  - variations in photon energy
  - minor temperature variations
  - other variations in ambient conditions
- high stability of radiation products



ℓ-α-Alanine



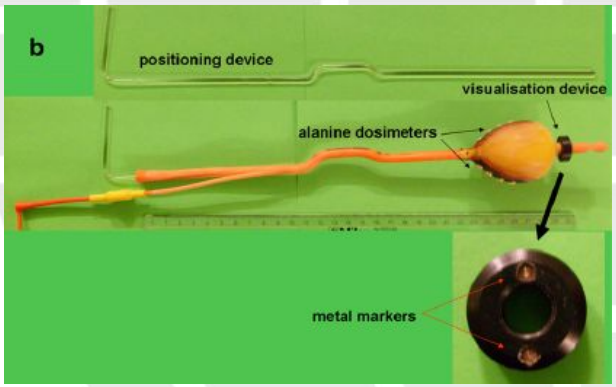
MAIN DRAWBACK

The ESR instrumentation is very expensive...

… even though in the last years many bench-top (much less expensive) instrumentation are also produced.

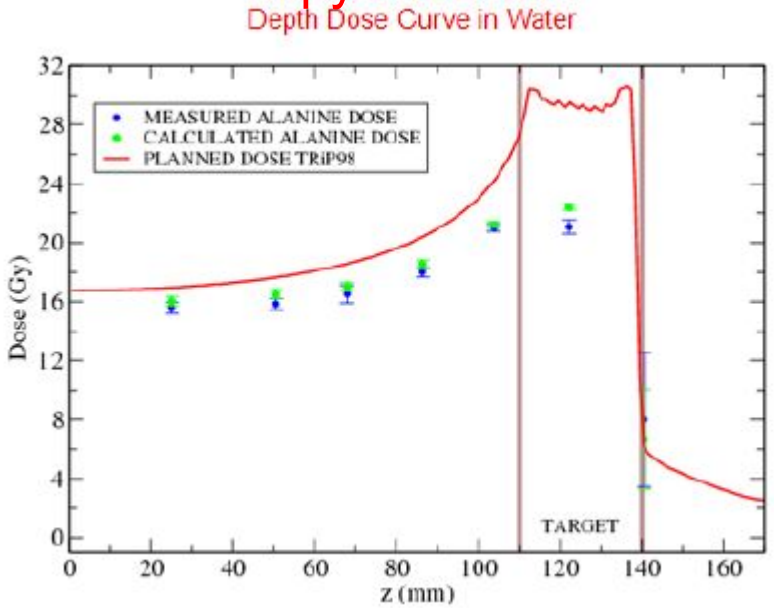
Applications in radiotherapeutic field

Applications for radiation therapy:
Brachitherapy for prostate cancer
Brachitherapy for uterus cancer
Therapy for breast cancer
...



D. Wagner et al. Radiotherapy and Oncology 88 (2008) 140–147

Hadrontherapy with Carbon ions

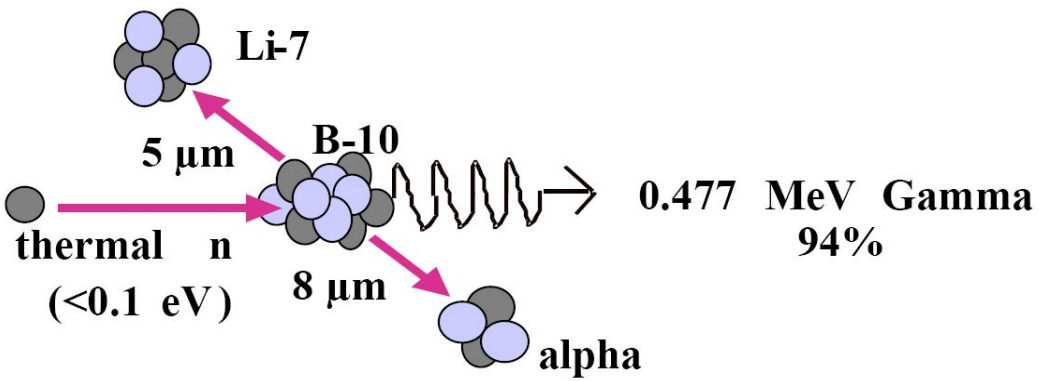


La Tessa C. et al *^{12}C ion beam dose distribution in presence of medium inhomogeneities: comparison between different measurements and simulations with treatment planning system for particles TRiP98.* ERRS2012 abstract

Cross sections and nuclear reactions with thermal neutrons

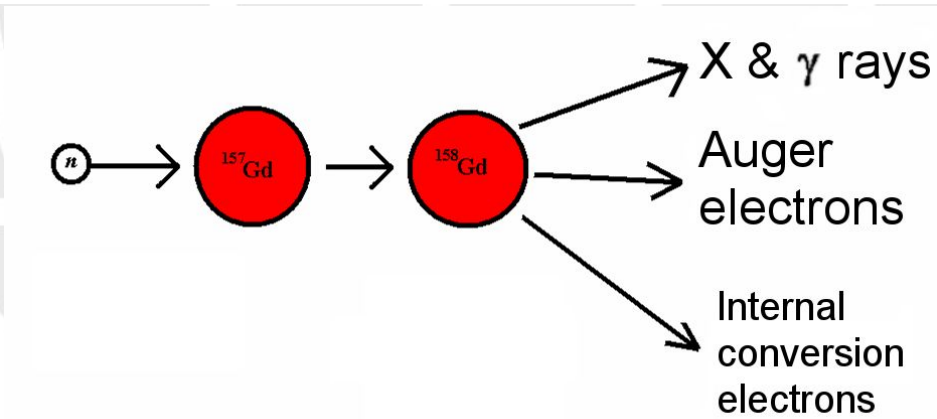
Nuclide	σ_{th} (barn)	Reaction
^{1}H	$3.33*10^{-1}$	(n,γ)
^{6}Li	$9.41*10^{2}$	(n,α)
^{10}B	$3.84*10^{3}$	(n,α)
^{12}C	$3.50*10^{-3}$	(n,γ)
^{14}N	1.83	(n,p); (n,γ)
^{16}O	$1.90*10^{-4}$	(n,γ)
^{23}Na	$4.30*10^{-1}$	(n,γ)
^{24}Mg	$5.30*10^{-3}$	(n,γ)
^{35}Cl	$3.27*10^{1}$	(n,γ)
^{113}Cd	$2.06*10^{4}$	(n,γ)
$^{135}Xe^{*}$	$2.72*10^{6}$	(n,γ)
^{157}Gd	$2.55*10^{5}$	(n,γ)
^{155}Gd	$7.50*10^{4}$	(n,γ)
$^{235}U^{*}$	$6.81*10^{2}$	(n,f)
$^{241}Pu^{*}$	$1.38*10^{3}$	(n,f)
$^{242}Am^{*}$	$8.00*10^{3}$	(n,f)

Interaction of ^{10}B and ^{157}Gd with thermal neutrons



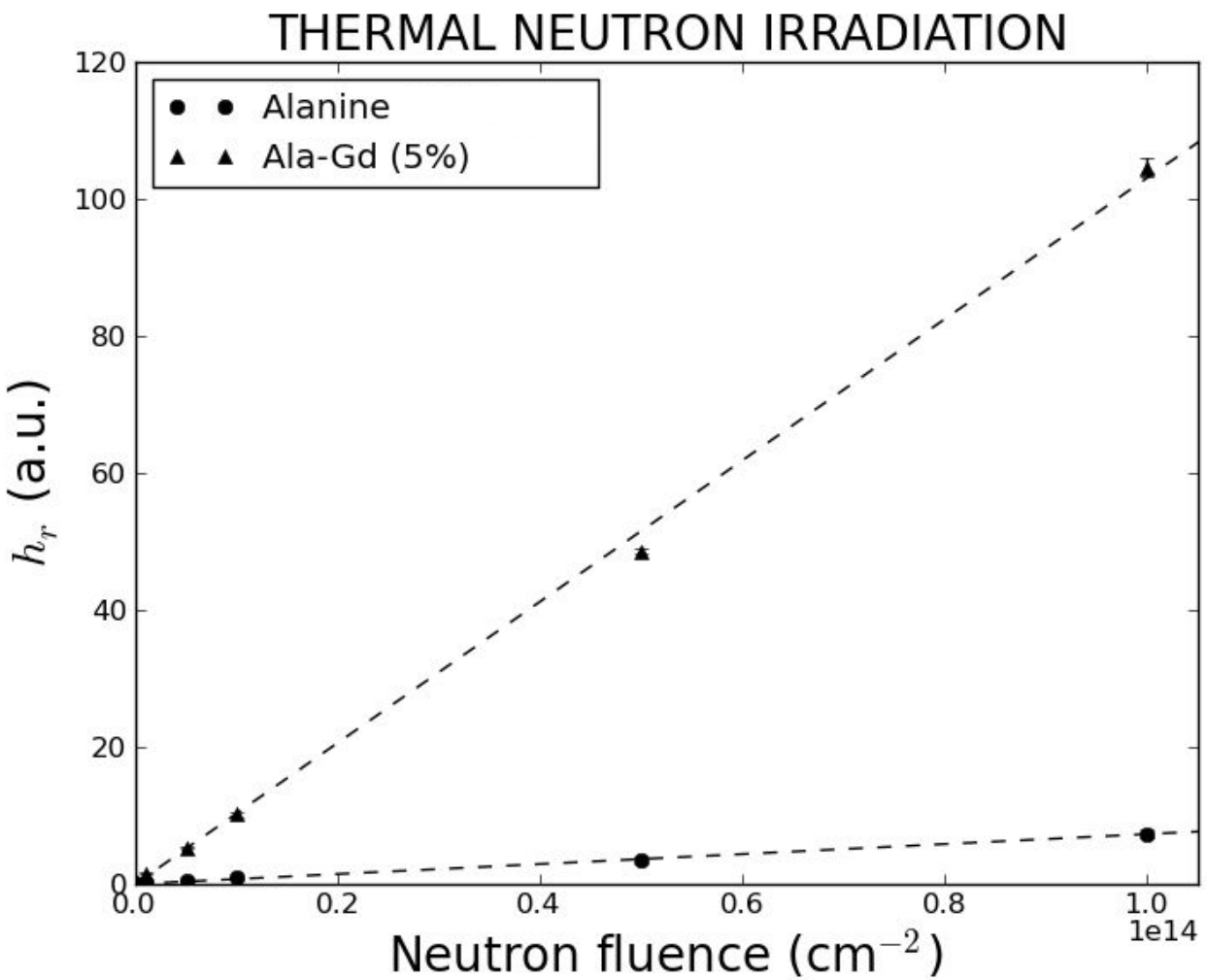
σ_{th} (barn)

3838



255000

Gd-Alanine – Neutron irradiation

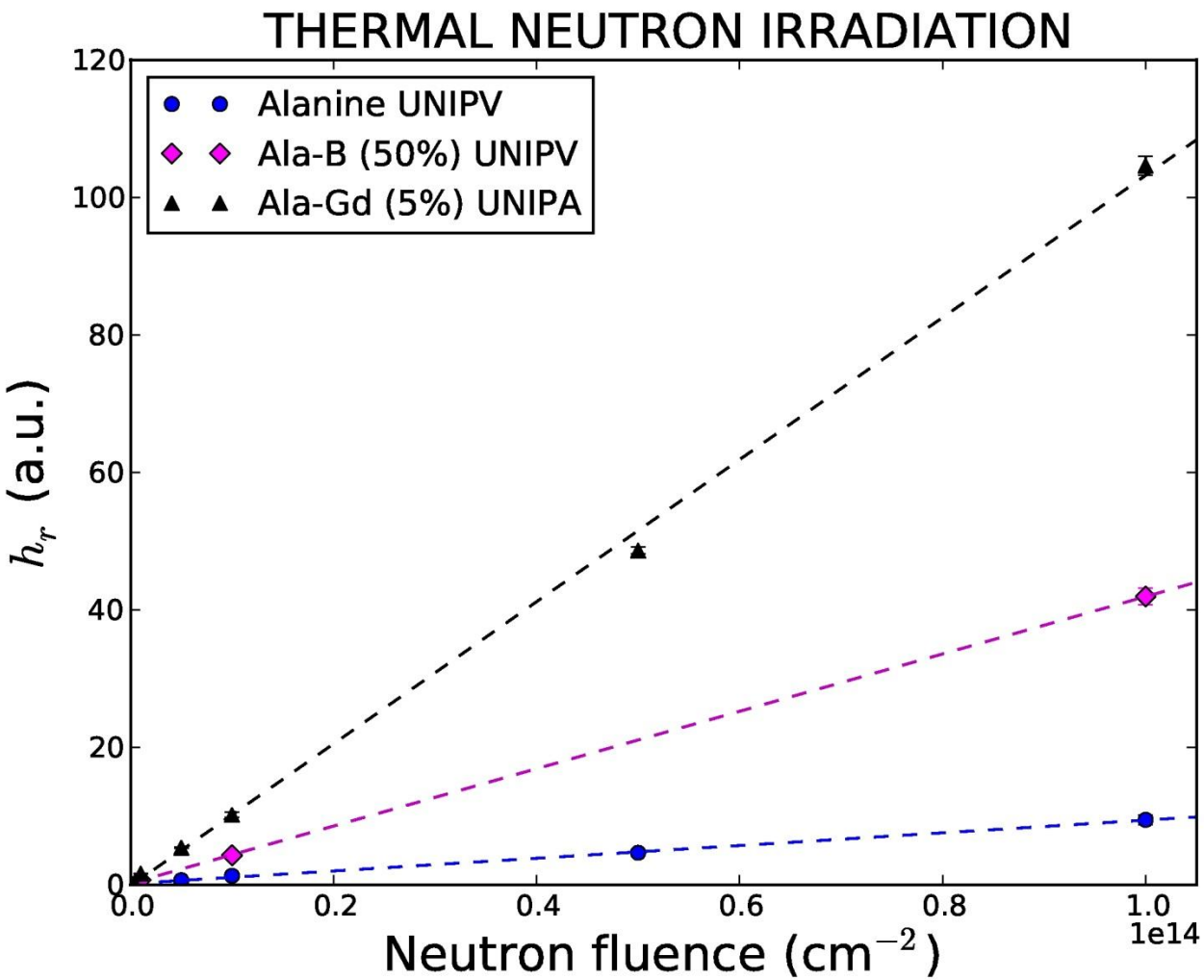


Linear response up to 10^{14} cm^{-2}

Sensitivity improvement of more than 10 times

M MARRALE et al. *Radiat. Prot. Dos.* (2014) 161 (1-4): 383-386.

Neutron irradiation - Comparison



Gadolinium addition (5%) increases neutron sensitivity than Boron addition (50%)

Alanine

Advantages

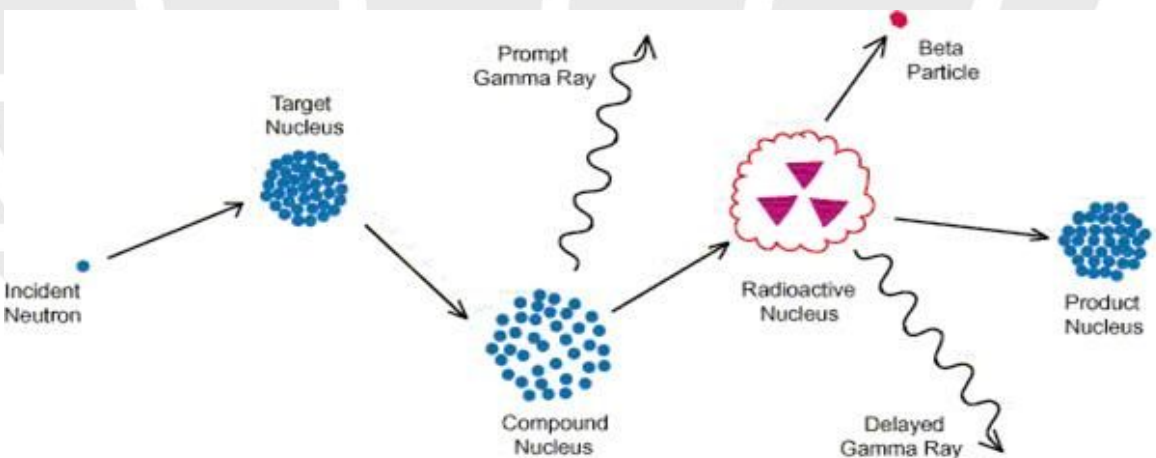
- Tissue-equivalent
- No energy correction within the quality range of typical therapeutic beams is required
- Very little fading for many months
- after irradiation.

Disadvantages

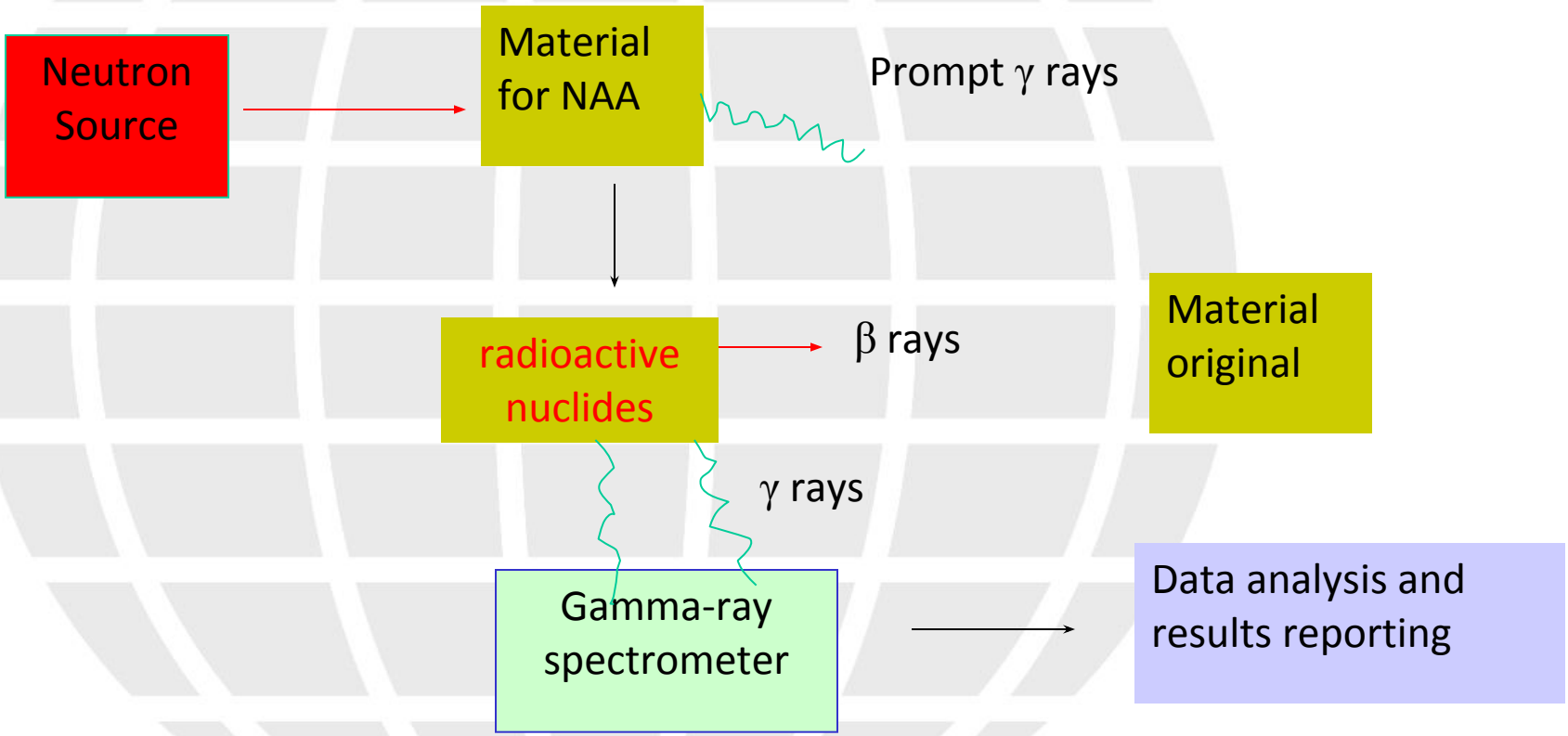
- The response depends on environmental conditions during irradiation (temperature) and storage (humidity).

What is Neutron Activation?

- Neutron activation is a process to produce artificial radioactivity
- Hit materials with neutrons
- Targets become radioactive
- Then decay in predictable ways



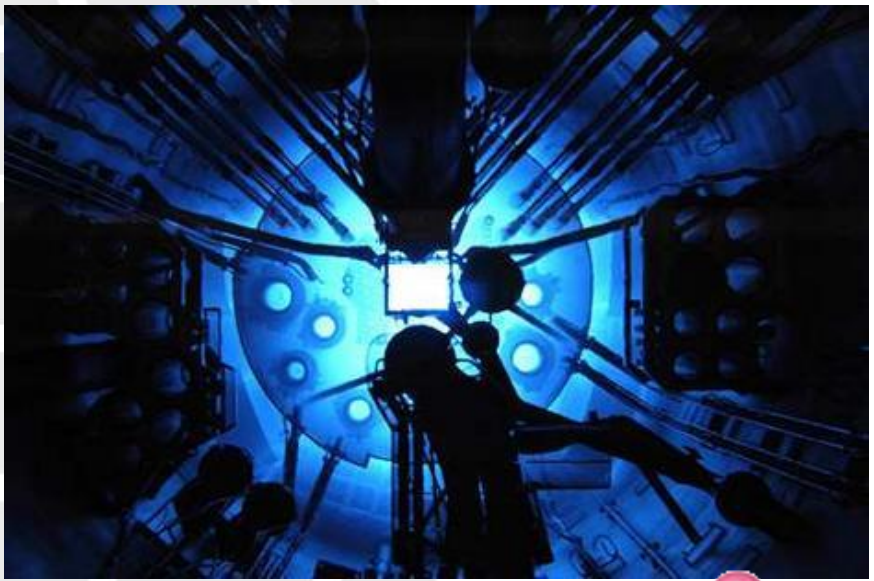
Neutron Activation Analysis Method

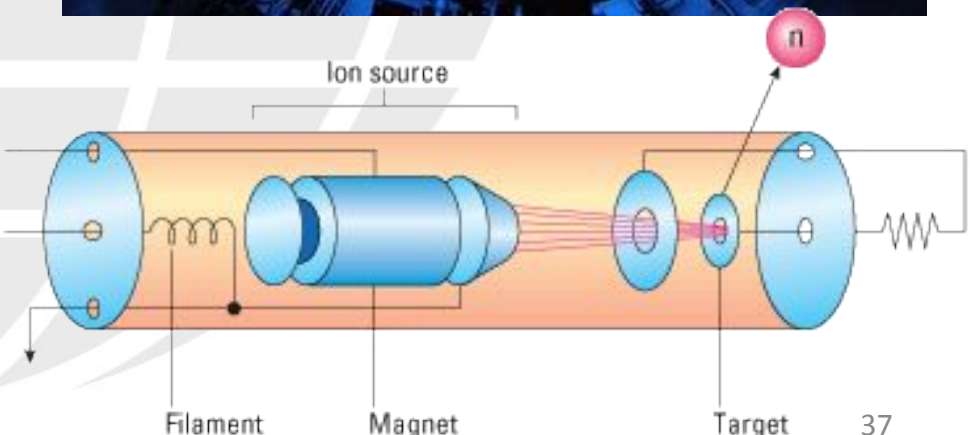


Block diagrams of the NAA method

Neutron sources

- A nuclear reactor
- A source that emits neutrons by fission (e.g. Californium)
- Alpha Source (like Radium) with Beryllium
- D-T fusion in a gas discharge tube





Neutron Activation

- production of a radioactive isotope by the absorption of a neutron, eg:
  - (n, γ) (n,p) (n,α) (n,n')
- if N_T target atoms with a cross-section σ are being neutron irradiated with a fluence of n cm^{-2} sec^{-1} then the production rate of daughter atoms is:

$$\phi \sigma N_T \ sec^{-1}$$

Neutron Activation

- the number of daughter atoms is N having a decay constant λ
- the rate of loss of daughter atoms is λN
- the rate of change is $\frac{dN}{dt}$
- the number of daughter atoms presented at any time while the target is bombarded is:

$$\frac{dN}{dt} = \phi\sigma N_T - \lambda N$$

Neutron Activation

- Assuming that the neutron fluence rate is constant and the original number of atoms is not being excessively depleted so N_T is constant, the solution of the previous differential equation is

$$\lambda N = \varphi \sigma N_T \left(1 - e^{-\lambda t}\right)$$

- where:

λN - represents activity of daughter as a function of t

$\varphi \sigma N_t$ - is called saturation activity representing maximum activity at time t $\rightarrow \infty$

- when neutrons are not monoenergetic as in a reactor, an average cross-section is used for σ

Neutron Activation

- the previous equation is the activity just at the end of production

- if one is interested in the activity sometime later the following terms must be added:

$$\lambda N = \phi \sigma N_T \left(1 - e^{-\lambda t_i}\right)\left(e^{-\lambda t_d}\right)\left(1 - e^{-\lambda t_c}\right)$$

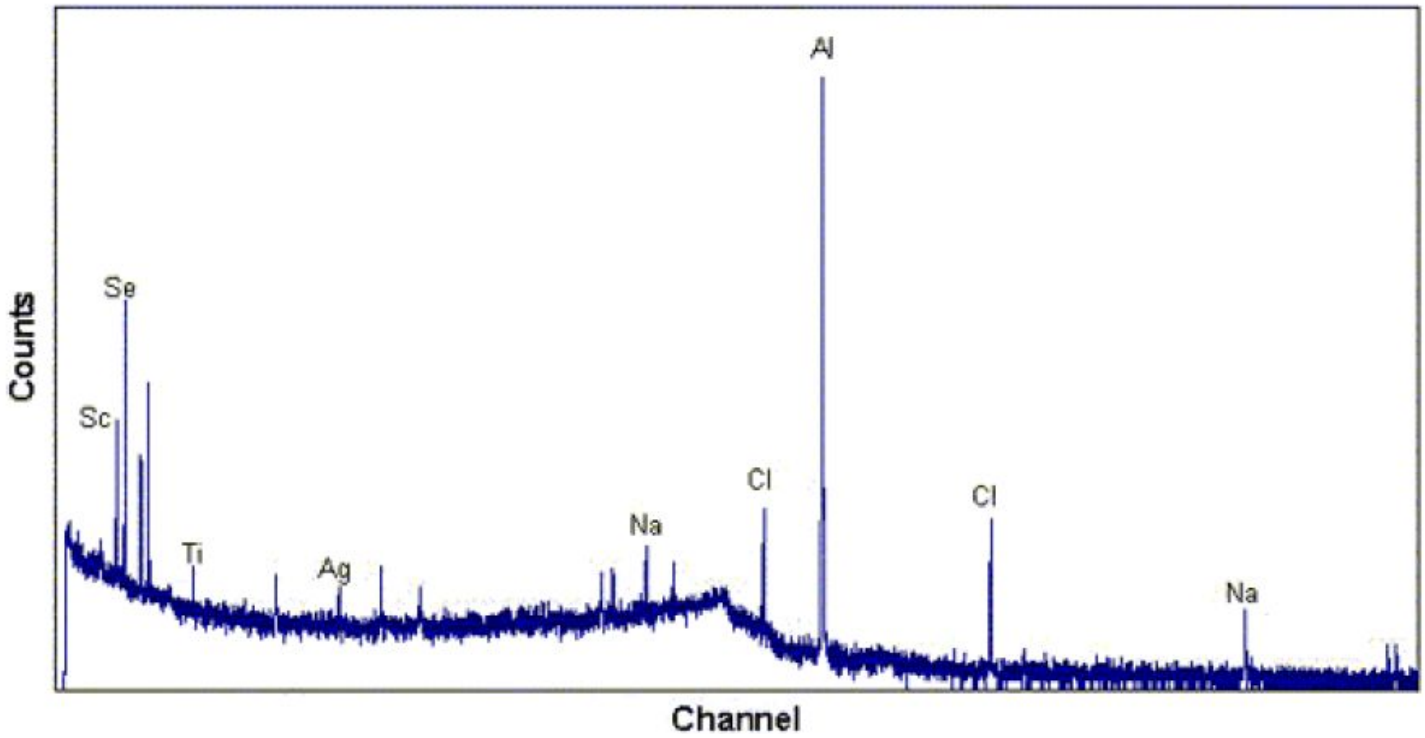
- where:
- t_i = irradiation time
- t_d = decay time
- t_e = counting time

The prepared sample and a standard sample are placed in a “detector” one at a time.

- The detector system counts and records gamma radiation emissions for a period of time.
- Time varies, but is usually in the range of 5 minutes to an hour.

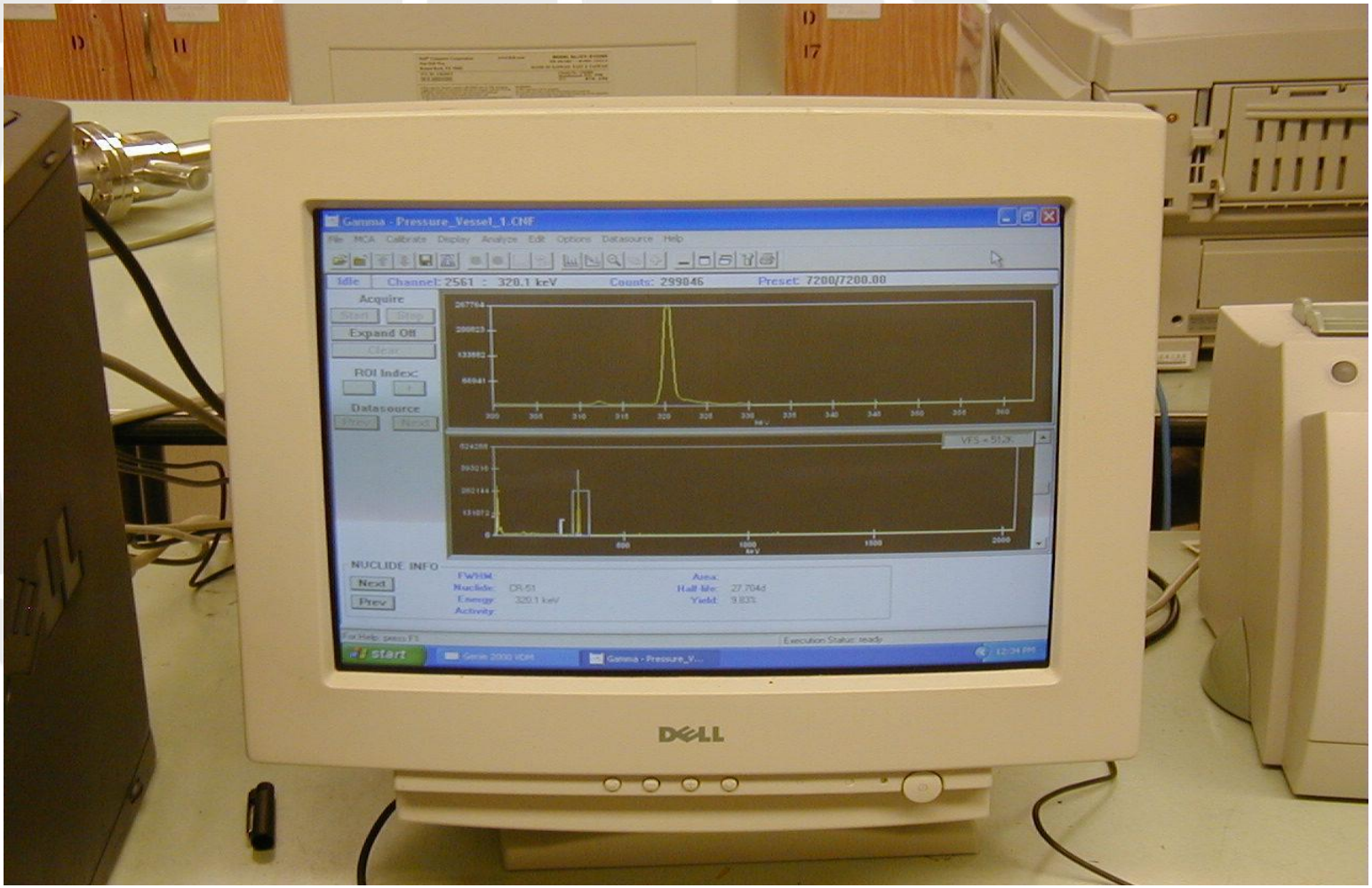
How?

- Detect the gamma-rays (prompt and delayed) - with gas detector, scintillators, semiconductors
- Bin number of counts at each energy



An example of gamma-ray spectrum from the activation of a human nail

Specialized software analyzes radiation peaks.
Peak data is correlated to specific elements for identification and quantification.



$$R = \varepsilon I_\gamma \quad A = \varepsilon I_\gamma n \varphi \sigma (1-e^{-\lambda t_i}) e^{-\lambda t_d}$$

R = measured gamma-ray count rate (cps)

A = absolute activity of isotope ^{A+1}Z in sample

ε = absolute detector efficiency

I_γ = absolute gamma-ray abundance

n = number of atoms of isotope ^{A}Z in sample

φ = neutron flux (neutrons·cm^{-2}·sec^{-1})

σ = neutron capture cross section (cm^2) for isotope ^{A}Z

λ = radioactive decay constant (s^{-1}) for isotope ^{A+1}Z

t_i = irradiation time (s)

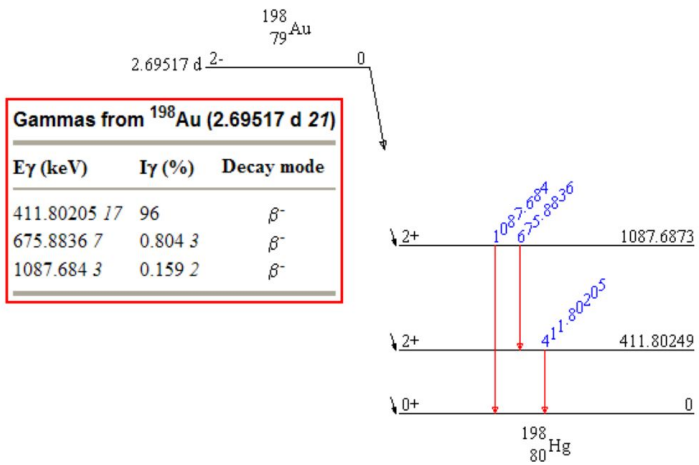
t_d = decay time (s)

$$^{109}\mathrm{Ag} + \mathrm{n} \longrightarrow {}^{110}\mathrm{Ag}$$

$$^{110}\mathrm{Ag} \longrightarrow \beta^- + {}^{110}\mathrm{Cd} + \gamma\ (658\ \mathrm{keV})$$

Applications

- Measurements of thermal neutron flux in a reactor with gold (^{197}Au) foils
- Measurements of epithermal and fast neutron flux in a reactor with ^{115}In and ^{63}Cu foils
- Determine the chemical composition of a sample
- Can identify up to 74 different elements in gases, liquids, solids, and mixtures



Advantages

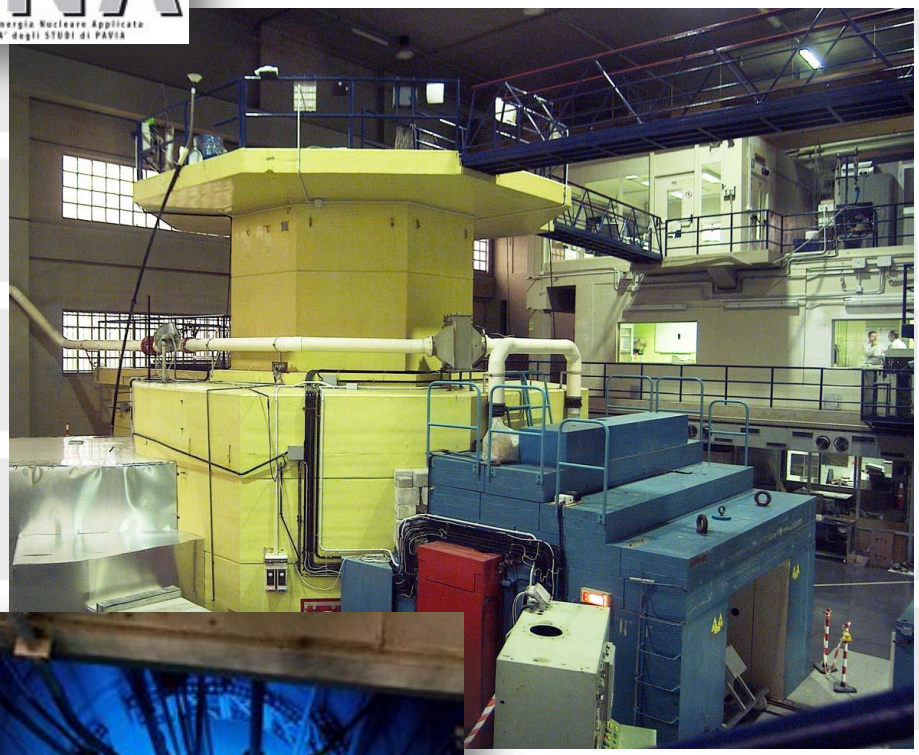
Advantages

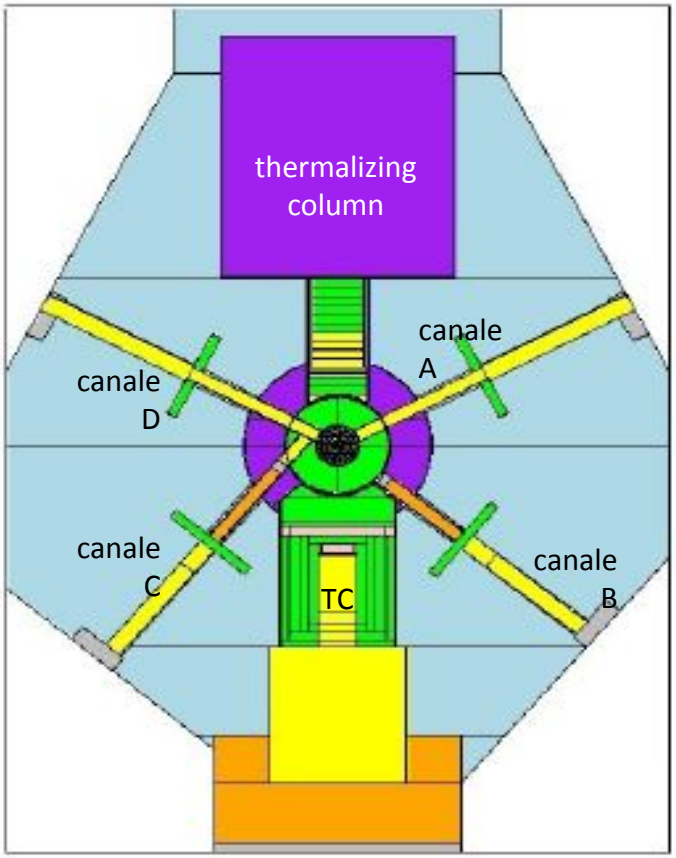
- Small sample sizes (.1mL or .001gm)
- Non-destructive
- Can analyze multiple element samples
- Doesn't need chemical treatment
- High sensitivity, high precision

Limitations

- Interferences can still occur when different component sample elements produce similar gamma rays.

Procedure to discriminate neutron and gamma components





Nuclear reactor TRIGA Mark II of Pavia

Other procedure to discriminate neutron and gamma components

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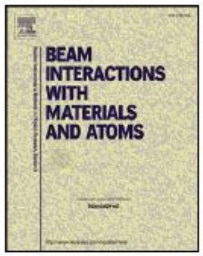

Neutron flux and gamma dose measurement in the BNCT irradiation facility at the TRIGA reactor of the University of Pavia

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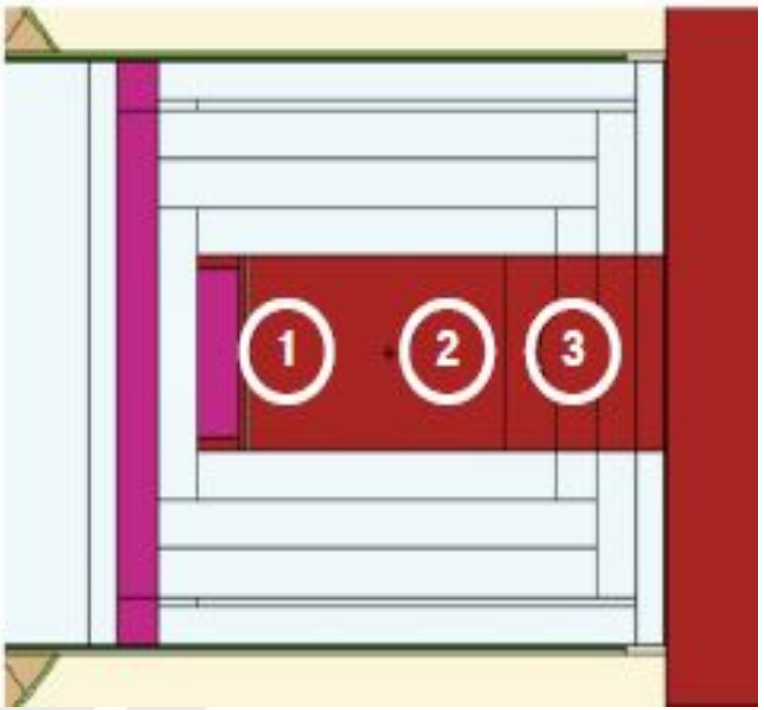
Other procedure to discriminate neutron and gamma components

Determination of the neutron spectrum by means of neutron activation analysis

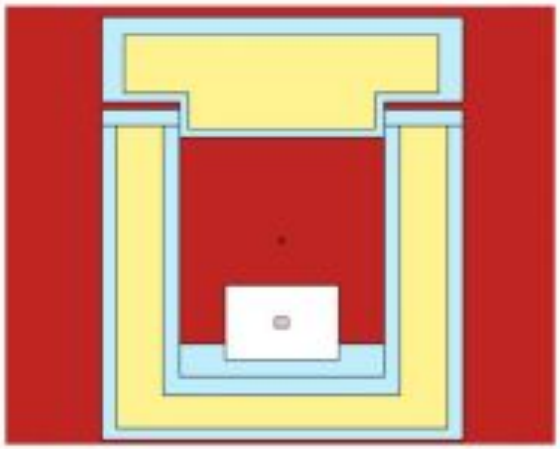
	Reaction	Energy range of primary response	Irradiation time
bare foils	$^{55}Mn(n, \gamma)^{56}Mn$	Thermal	10 min
	$^{197}Au(n, \gamma)^{198}Au$	Thermal	
Cd-cover	$^{115}In(n, \gamma)^{116}In$	1 eV resonance	2 h
B sphere	$^{197}Au(n, \gamma)^{198}Au$	5 eV res.	6 h
	$^{186}W(n, \gamma)^{187}W$	18 eV res.	
	$^{55}Mn(n, \gamma)^{56}Mn$	340 eV res.	
	$^{63}Cu(n, \gamma)^{64}Cu$	1 keV res.	
	$^{115}In(n,n')^{115m}In$	> 0.3 MeV	
Normalization	$^{197}Au(n, \gamma)^{198}$ Au $^{63}Cu(n, \gamma)^{64}Cu$	–	

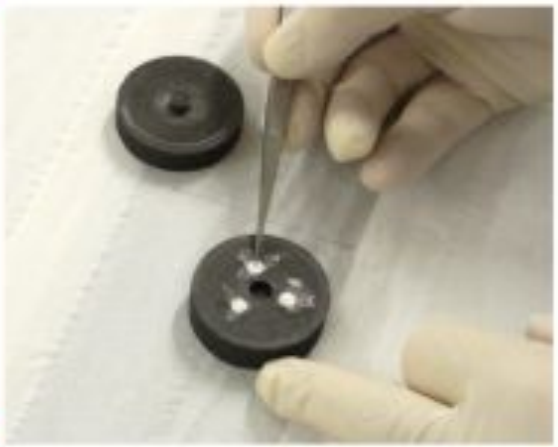
Other procedure to discriminate neutron and gamma components

- ✓ Monte Carlo simulation of the reactor, in particular of the thermal neutron column and calculation of the γ spectrum into three irradiation positions: POS 1, POS 2, POS 3;
- ✓ Determination through Monte Carlo simulations of the supports employed in measurements to ensure the equilibrium conditions of the secondary charged particles (CPE) and to separate the photon and neutron components in the mixed field;
- ✓ optimization of the irradiation setup for the calibration of the detectors;
- ✓ irradiation of the uncovered and covered detectors to separate the dose contributions due to the thermal neutron and photon components.



Irradiation setup to eliminate thermal neutron component





Shield for thermal neutrons composed of lithium carbonate enriched to 95% with ^{6}Li

Attenuation factor of the thermic component ~ 10^{-3}

Characterization of thermal column of TRIGA reactor of Pavia: total dose

Unshielded alanine samples

$$D_{\text{total}} = D_{\gamma} + D_{p} + D_{n}$$

- H(n, n')H ⟶ RE = 0.6
- γ from background ⟶ RE = 1
- $^{14}N(n,p)^{14}C$ ⟶ RE = 0.4

POS 1	Sim	34.82 Gy
	Exp	36.76 Gy
POS 2	Sim	14.27 Gy
	Exp	14.13 Gy
POS 3	Sim	6.89 Gy
	Exp	6.29 Gy

Conclusions (2)

- The use of alanine dosimeters allows to measure the gamma dose in a mixed (thermal neutron + gamma) field.
- The determination of the gamma dose is possible by following a procedure able to eliminate thermal neutron components.
- The experimental results should be aided by Monte Carlo simulations.
- The presence of fast neutron components involves the need to correctly evaluate the relative efficacy of alanine dosimeters.
- The protocol is effective as highlighted by the good agreement between the measured doses and simulated values

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Thank you for your kind attention!

Cathedral of Palermo