Radioactivity

Historical review; fundamentals; artificial and natural; detection; doses

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Overview

1. General Information
2. Introduction
3. Radioactivity: fundamentals
4. Radioactivity: Detection methods
5. Radioactivity: Doses

General Information

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Education

B.Sc. in Physics

University of Valladolid

Valladolid, Spain

Sept. 1995 - Feb. 2002

PhD. in Physics

University of Valladolid

Valladolid, Spain

Mar. 2002 - Jul. 2008

Thesis entitled: Radon concentrations in air, soil and water in a granitic area: instrumental development and measurements

Introduction

Once upon a time …

- X- rays
- Some materials emit radiation
- Wow ! we can penetrate our body

Once upon a time …

Once upon a time …

- Photographic plates can get dark in the presence of material called Uranium
- It must a property of the matter itself
- Such a material emits a type of radiation

Once upon a time …

MARIE SKLODOWSKA and PIERRE CURIE

Once upon a time ...

A wonderful marriage

- Marie: a physicist and mathematician but . . . a Polish Woman
- Pierre: professor of Physics in Paris
- Studies on pitchblende

Once upon a time …

Their work with pitchblende

- They began separating elements and reducing sample's size
- They observe an increase on the intensity of emitted radiation
- They discovered **Polonium** in 1898

Their work with pitchblende

- After separation of Plonium . . . emitted radiation increases more and more
- It must be another element different from Uranium and different from Radium. This element emits radiation too.

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  - Very poor materials and infraestructures to do the task
  - Laboratory: a simple shed
  - From pitchblende to radium: years and years of hard work

Once upon a time …

Their work with pitchblende

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- … the Radium
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  - Very poor materials and infraestructures to do the task
  - Laboratory: a simple shed
  - From pitchblende to radium: years and years of hard work
  - 10^3kg pitchblende $\Longrightarrow$ few grams of radium

Once upon a time …

Milestones

- 1903: Nobel prize on Physics: Marie, Pierre and Becquerel (15000 $!!!)
- 1906: Pierre Curie passed away in a street accident in Paris on 19 April 1906 (*Crossing the busy Rue Dauphine in the rain at the Quai de Conti, he slipped and fell under a heavy horse-drawn cart. He died instantly when one of the wheels ran over his head, fracturing his skull (Wikipedia)*)
- 1911: Nobel prize on Chemistry: Marie Curie

Once upon a time …

Once upon a time ...

Other names to bear in mind

- Ernest Rutherford (1871 – 1937): concept of radioactive half-life; model of the atom
- Sir James Chadwick (1891 – 1974): the discovery of the neutron
- Frederick Soddy (1877 – 1956): radioactivity and nuclear reactions
- Friedrich Ernst Dorn (1848 – 1916): see later . . .
- Rolf Maximilian Sievert (1896 – 1966): biological effects of radiation
- Max Karl Ernst Ludwig Planck (1858 – 1947): quantum theory

Once upon a time …

Credit

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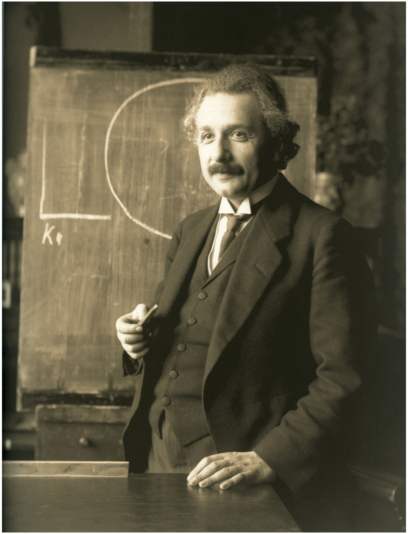
Credit

Once upon a time …



By Ferdinand Schmutzer

Learnings so far

Let's remember

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- Radioactivity: new phenomenon discovered at the end XIX century

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- Radioactivity: new phenomenon discovered at the end XIX century
- Curie: key name on the development of knowledge XX century

Learnings so far

Let's remember

- Radioactivity: new phenomenon discovered at the end XIX century
- Curie: key name on the development of knowledge XX century
- The beggining of XX century gathered a fantastic pool of scientist as ever

Radioactivity: fundamentals

Ionizing radiation

Radiation with enough energy to detach electrons from atoms or molecules, thus ionizing them

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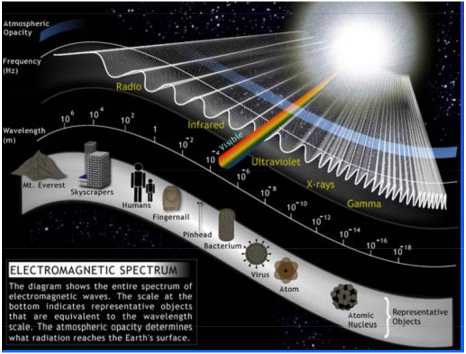

Numbers and names

Symbol	Definition	Fingerprint
Z (atomic number)	The atomic number of an atom is the number of protons it contains	ATOM
A (mass number; atomic mass number or nucleon number)	Total number of protons and neutrons (together known as nucleons) in an atomic nucleus	ISOTOPE

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radon: ${}^{222}_{86}Rn$; ${}^{220}_{86}Rn$; ${}^{219}_{86}Rn$

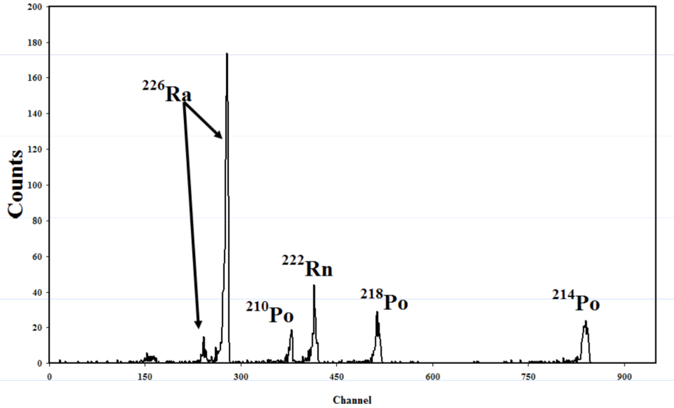
Decay modes

Alpha decay: Emission of an alpha particle ($^{4+}_{2}He$) by a nucleus

Characteristics of the alpha decay mode

- High enery (MeV)
- Heavy particles: they can be stopped in some cm
- Elements heavy nucleus
- Examples: $^{222}_{86}Rn$, $^{238}_{92}U$, $^{210}_{84}Po$

Example of alpha spectrum



Decay modes

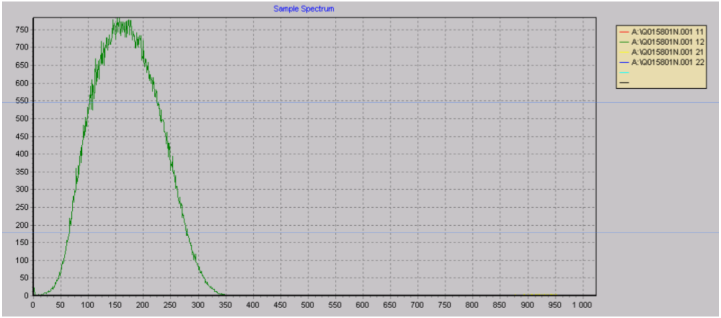
Beta decay: Emission of beta particle (positive or negative) by a nucleus. Also electron capture by a nucleus.

Characteristics of the beta decay mode

- Less energy than alpha emission
- Longer distance before stopping
- Continuous spectrum of energy
- Examples: ${}^{3}_{1}\mathrm{H}$, ${}^{90}_{38}\mathrm{Sr}$

Decay modes

Example of beta spectrum



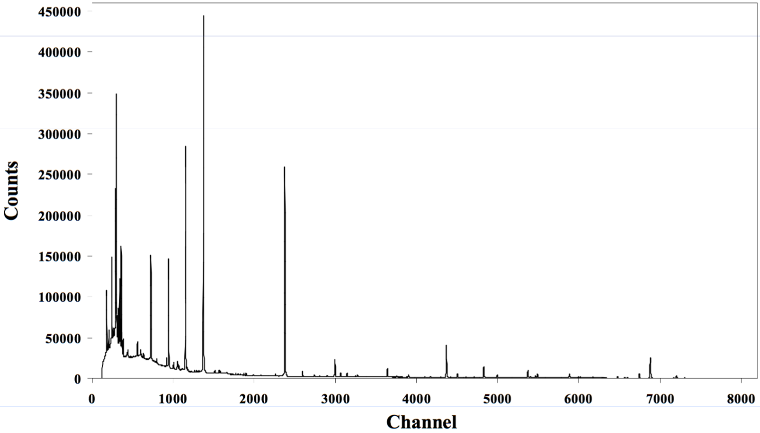
Decay modes

Gamma decay: Photon's emission by a nucleus when reaching steady state of energy.

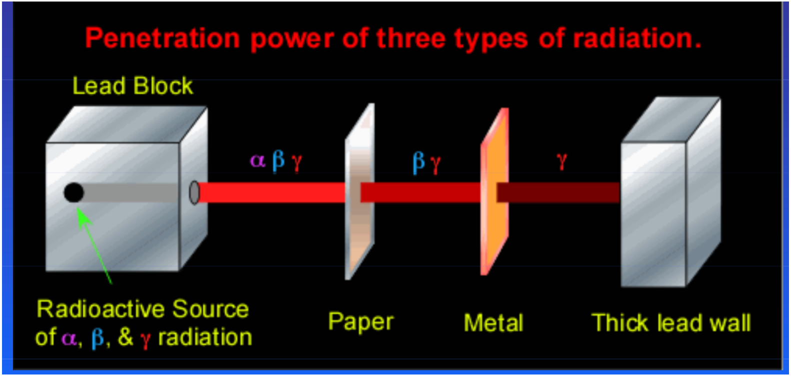
Characteristics of the gamma decay mode

- Photons with different energies
- X Rays
- Gamma Rays (with different energies)
- Gamma rays = Nucleus
- X Rays = Atomic crust
- Examples: $^{99}_{43}Tc$, $^{60}_{27}Co$

Example of gamma spectrum



Penetration power



Definitions

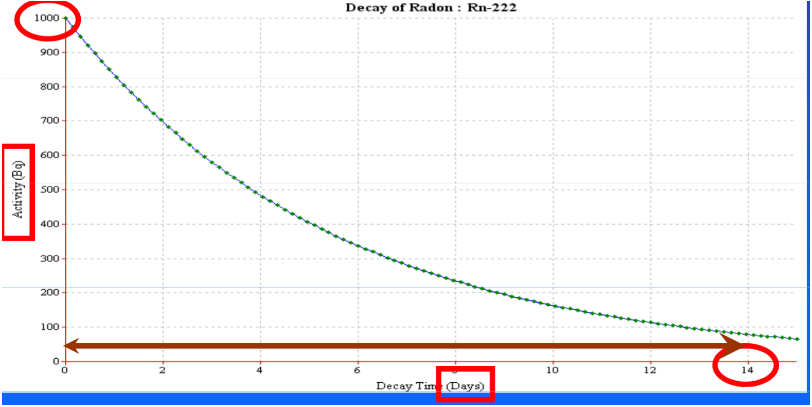
- Activity (A): Number of disintegrations per second
- Half life ($T_{1/2}$): Neccesary time for an isotope to decrease its nucleus by half (s)
- Decay constant (λ): Probability of disintegration by time (s^{-1})
- Decay chain: chained series of transformations (4 Natural decay chains)

Units

- Becquerel (Bq) : unit of activity in the International System of Units: 1Bq = 1 DPS (disintegration / second)
- Curie(Ci):Old unit of activity: 1Ci=$3.7 \cdot 10^{10}$ Bq
- Concentration : Bq/kg, Bq/l, Bq/m3
- Sievert (Sv) : Unit for equivalent dose
- Working Level Month (WLM): Occupational exposure (1 WLM is approximately equivalent to an exposure of 150 Bq m^{-3} in a year)

Exponential's decay law

$$A = A_0 e^{-\lambda \cdot t}$$



Half-lives

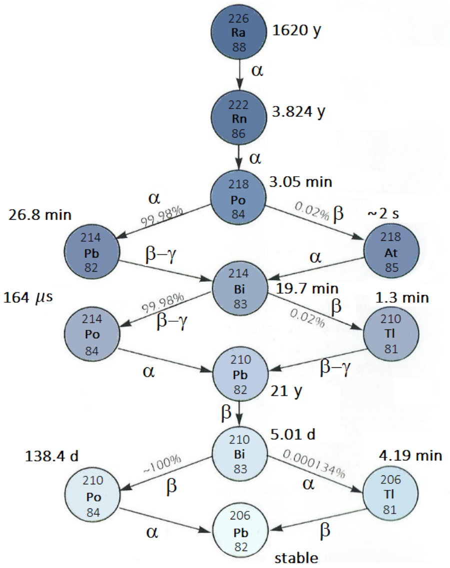
Isotope	Half life
^{238}U	$4.5 \cdot 10^9$ y
^{14}C	5730 y
^{3}H	12.4 y
^{131}I	8.03 d
^{222}Rn	3.8 d
^{99}Tc	6 h
^{219}Rn	3.96 s

Natural decay series

Series	Start	Half life (y)	Final product
Thorium	^{232}Th	$1.41 \cdot 10^{10}$	^{208}Pb
Neptunium	^{237}Np	$2.14 \cdot 10^{6}$	^{209}Pb
Uranium	^{238}U	$4.51 \cdot 10^{9}$	^{206}Pb
Actinium	^{235}U	$7.18 \cdot 10^{8}$	^{207}Pb

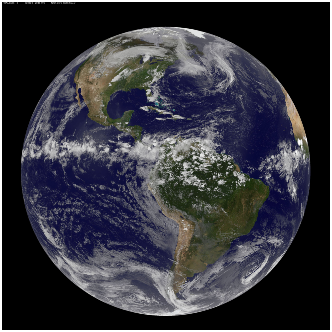
Earth's age: $4.65 \cdot 10^{9}$

Natural decay series Uranium



Natural radioactivity

- Since the Earth Earth's birth
- Every second values are lower and lower : Exponential decay In our bodies
- ^{40}K In the rocks, air, water, food, clothes, EVERYWHERE
- More than 50 % of dose is NATURAL RADIATION



Credit: NASA Goddard Space Flight Center

Natural radioactivity

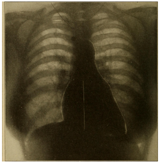
COSMIC RADIATION

Credit: Radiation, people and the environment (IAEA, February 2004)

Artificial radioactivity

- Radioactive isotopes can be created
- Fission and fusion = Energy AND/OR destruction
- X-ray detectors
- Medical applications
- Industrial applications

Credit: Xiquinho Silva



Learnings so far

Let’s remember

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- Radiactivity: natural and artificial

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- 3 decay modes: alpha, beta and gamma

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Learnings so far

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- Radiactivity: natural and artificial
- 3 decay modes: alpha, beta and gamma
- Units: activity (Bq, Ci); WLM
- 4 Natural decay series

Radioactivity: Detection methods

Thinking over …

Key questions

- What do we need to measure?
- How can we do the measurements?
- Which parameters are important ?

Thinking over …

Key questions

- What do we need to measure?
- How can we do the measurements?
- Which parameters are important ?

Boundary conditions

- Facilities
- Staff's training
- Accuracy and precision
- Deadline for results
- Our budget

Available techniques

- Alpha spectrometry
- Liquid Scintillation counting (LSC)
- Gross alpha / beta
- Gamma spectrometry
- Others (i.e., ICP-MS and others)

Advantages and disadvantages

Alpha spectrometry I

Characteristics

- High resolution surface barrier detectors
- Low Detection limits possible in a reasonable measurement time
- Good definition of peaks
- Possible to measure a lot of natural radionuclides (uranium and thorium series)
- Calibration is easy, no problem with geometries

Alpha spectrometry II

Problems

- Radiochemistry (separation)
- Adsorption (i.e., radium isotopes)
- Chemical interferences (barium)
- Interferences in spectrum
- Costly technique

Alpha spectrometry III

LIQUID SCINTILLATION COUNTING I

Characteristics

- α/β Discrimation
- Low detection limits can be reached
- Not long measurement times
- Possibility to handle a large number of samples

LIQUID SCINTILLATION COUNTING II

Problems

- Problems with spillover
- Correct Set up of the LSC counter can be difficult
- When measuring ^{226}Ra seqular eqilibrium with ^{222}Rn is needed: time consuming
- LSC counter is very expensive

LIQUID SCINTILLATION COUNTING III

Gamma spectrometry I

Characteristics

- Instrumentation (HPGe) available in most of labs
- No radiochemistry is needed
- Pretreatment of the sample is very simple
- A large number of radionuclides can be measured
- Detection limits acceptable for environmental determinations

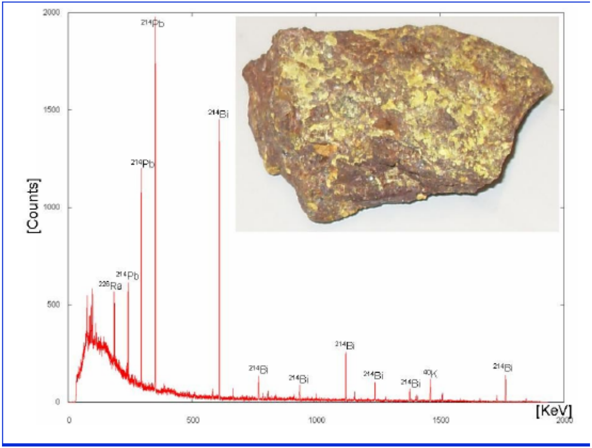
Gamma spectrometry II

Problems

- Each geometry needs different efficiency calibration
- Very dependent on density of sample
- Time consuming (several days in some cases)
- Maintenance of detector is critical (refrigeration)
- Monitoring of background levels is necessary

Gamma spectrometry III

Short intro to gamma spectrometry



The gamma-ray spectrum of natural uranium, showing about a dozen discrete lines superimposed on a smooth continuum, allows the identification the nuclides ^{226}Ra, ^{214}Pb, and^{214}Bi of the uranium decay chain. (*Credit: wikipedia*)

Short intro to gamma spectrometry I

Gammna decay: Photon's emission by a nucleus when reaching steady state of energy

- Gamma line is the fingerprint of a radionuclide
- One radionuclide can have several gamma lines with different probabilities and different energies
- X Rays and Gamma Rays (with different energies)
- Gamma rays = Nucleus
- X Rays = Atomic crust

Short intro to gamma spectrometry II

INTERACTION OF RADIATION WITH MATTER

- Charged particles produce a signal within a detector by ionization and excitation of the detector material directly.
- Gamma photons are uncharged and consequently cannot do this
- Gamma-ray detection depends upon other types of interaction which transfer the gamma-ray energy to electrons within the detector material

Short intro to gamma spectrometry III

INTERACTION OF RADIATION WITH MATTER

- Excited electrons charge and lose their energy by ionization and excitation of the atoms of the detector medium, giving rise to many electron–hole pairs
- The absorption coefficient for gamma radiation in gases is low and all practical gamma ray detectors depend upon interaction with a solid
- The electron–hole pairs can be collected and presented as an electrical signal.

How do radiation and matter interact?

How do radiation and matter interact?

PHOTOELECTRIC EFFECT

How do radiation and matter interact?

PHOTOELECTRIC EFFECT

COMPTON EFFECT

How do radiation and matter interact?

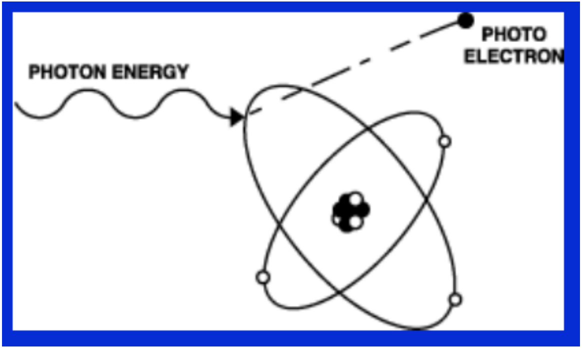
PHOTOELECTRIC EFFECT

COMPTON EFFECT

PAIR PRODUCTION

PHOTOELECTRIC EFFECT

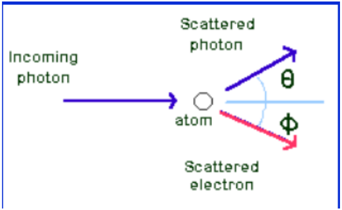
The photon interacts with the atom and gives ALL its energy to one electron: one part of the energy is used as kinetic energy and the rest is used to remove electron from the atom



COMPTON EFFECT

Characteristics

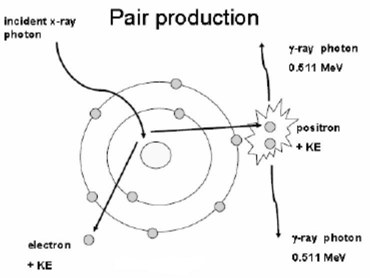
- "Elastic collision": pool balls
- Main interaction of gamma rays
- The photon collides with electron and hands over part of its energy to it. The angle through which the photon is scattered, the energy handed on to the electron, and energy lost by the photon are interconnected



PAIR PRODUCTION

Characteristics

- When the photon with energy in excess of 1.02 MeV passes close to the nucleus of an atom, the photon disappears, and a positron (e^+) and an electron (e^-) appear
- Annihilation reaction: positron interacts with electrons and creates 2 annihilation photons each of 0.51 MeV

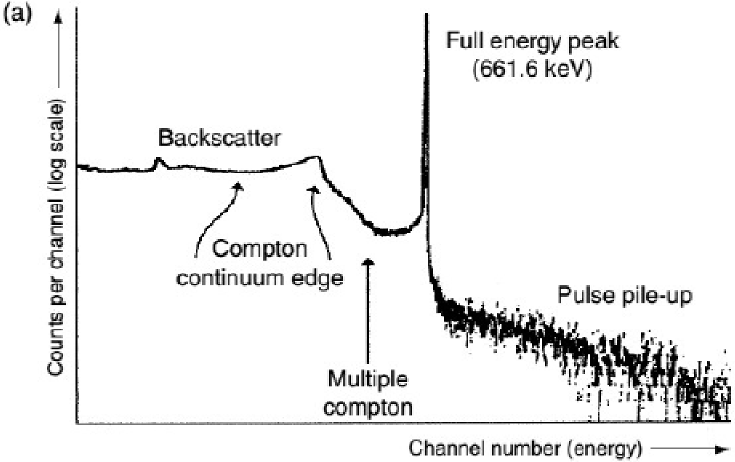


Interaction radiation and matter

Key facts

- Photoelectric interactions are dominant at low energy
- Pair production at high energy
- Compton scattering being most important in the mid-energy range
- In practice, evidence of pair production is only seen within a gamma-ray spectrum when the energy is rather more than 1022 keV

Let's study one spectrum I



Let's study one spectrum II

What can we infere?

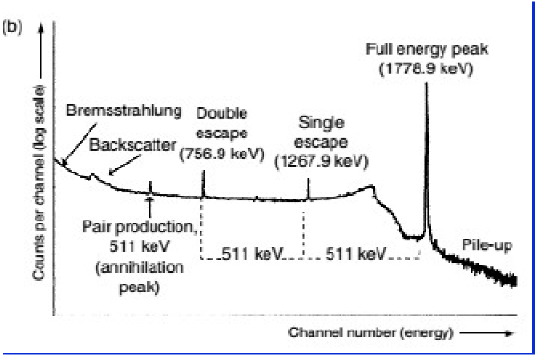
- Counts to appear in the spectrum above the full energy peak (apart from the natural background): due to random summing or pile-up, determined by the statistical probability of two gamma-rays being detected at the same time and therefore on the sample count rate
- The most troublesome photoelectric interactions will be those with the shielding, usually lead. There is a significant possibility that this fluorescent X-ray may escape the shielding and that it will be detected by the detector: generation of a number of X-ray peaks in the gamma spectrum in the region 70–85 keV (problems for low energy measurements that may be solved with Cd and Cu)

Let's study one spectrum III

What can we infere?

- The normal geometric arrangement of source–detector shielding means that most gamma-rays are scattered through a large angle by the shielding: backscattering (difficult to solve)
- Pair production: surroundings of the detector give rise to the annihilation peak at 511 keV in the spectrum. This is caused by the escape of one of the 511 keV photons from the shielding, following annihilation of the pair production positron. The annihilation peak is clearly visible in the spectrum of ^{28}Al (see Figure) but not in that of ^{137}Cs (Why?)

Let's study one spectrum IV



Practical points gamma detection

- Gamma spectrometry using germanium detectors is the best technique for identifying and quantifying radionuclides. This is due to the very sharply defined and characteristic energies of gamma-rays which are produced by the great majority of radionuclides.
- There are a small number of 'pure beta emitters', which do not emit gamma radiation. These cannot be identified by gamma spectrometry (^{3}H, ^{14}C, ^{90}Sr).
- X-ray energies will tell you the element present, but not which isotope.
- Decay schemes give vital information on whether gammas are in 'cascade'. This has great significance in true coincidence summing.

Practical points detection systems

Radiation INTERACTS with matter (detector's material)

Practical points detection systems

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Practical points detection systems

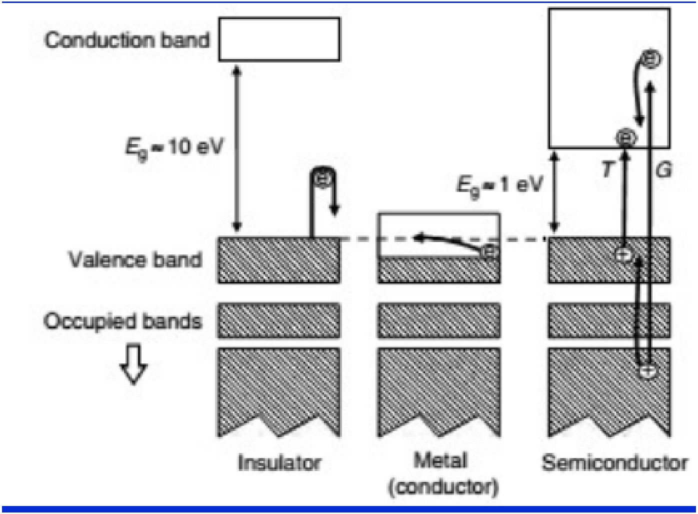
Radiation INTERACTS with matter (detector's material)

We must *translate* this interaction into an electrical signal that we are able to measure

Ideal properties of gamma spectrometry detector

- Output proportional to gamma-ray energy
- good efficiency, i.e. high absorption coefficient, high Z
- easy mechanism for collecting the detector signal
- good energy resolution
- good stability over time, temperature and operating parameters
- reasonable cost
- reasonable size

Band structure of solids



Charge carriers

- The interaction of a gamma-ray with the semiconductor material will produce primary electrons with energies considerably greater than thermal energies
- Electric field, carriers will migrate up (electrons) or down (holes) the field gradient.
- The number of electron–hole pairs produced, n, will be related directly to the gamma-ray energy absorbed
- One important component of the detector resolution is a function of n
- Avoid trapping centres which can make difficult mobility of carriers: the detector material must be available, at reasonable cost, with a high purity and as near perfect as possible crystalline state

Suitable materials?

- To have as large an absorption coefficient as possible (i.e. high atomic number)
- To provide as many electron–hole pairs as possible per unit energy
- To allow good electron and hole mobility
- To be available in high purity as near perfect single crystals
- To be available in reasonable amounts at reasonable cost.

Type of HPGe detectors I

Intrinsic semiconductor: A semiconductor material containing equal numbers of electrons and holes

- acceptor impurities when distributed throughout the semiconductor material give rise to extra energy states just above the valence band, called acceptor states. Germanium with this type of impurity would be called p-type germanium ('p' for positive acceptor impurities)
- The impurity atom is a donor atom sitting in a donor site, it will introduce donor states just below the conduction band. Germanium with such impurities is n-type germanium ('n' for negative donor impurities)
- The p-type material has an excess of holes and the n-type an excess of electrons.

Type of HPGe detectors II

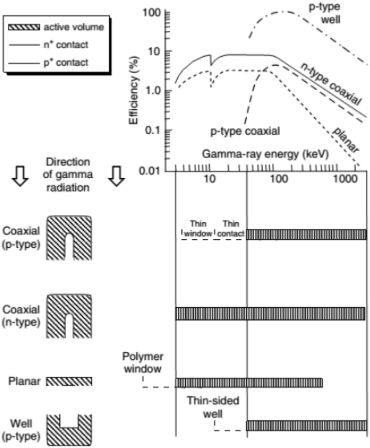


Figure 3.6 Configurations of detector generally available, together with schematic efficiency curves and an indication of the energy range over which they might be used

HPGe detectors I

Germanium detectors are operated at low temperature in order to reduce electronic noise and thereby achieve as high a resolution as possible

The most common means of providing a suitably low temperature is cooling with liquid nitrogen (boiling point 77 K)

HPGe detectors II

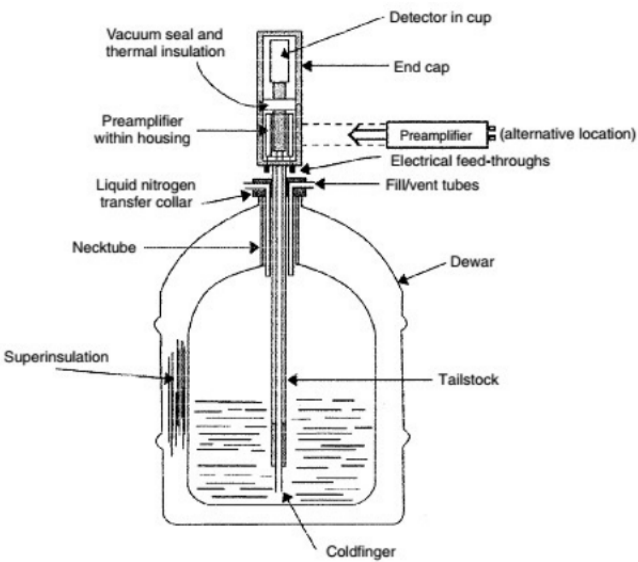
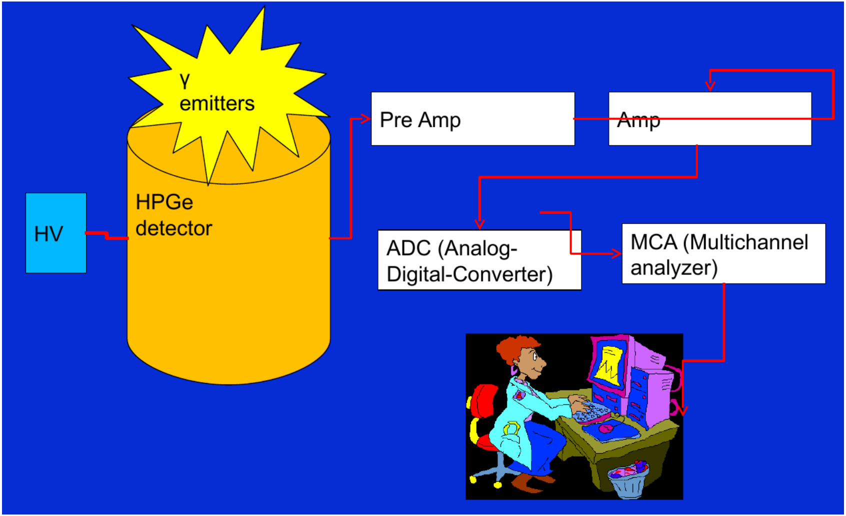


Figure 3.15 A typical germanium detector, cryostat and liquid nitrogen reservoir

HPGe detectors: example

HPGe detectors: Detection system



HPGe detectors

- The detector produces a signal proportional to the energy emitted by the source
- The measuring equipment accumulates on each channel the number of emissions corresponding to a certain energy

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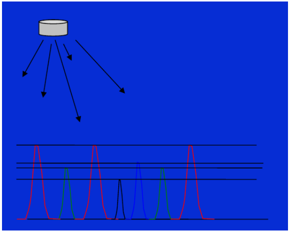
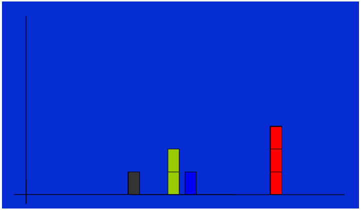
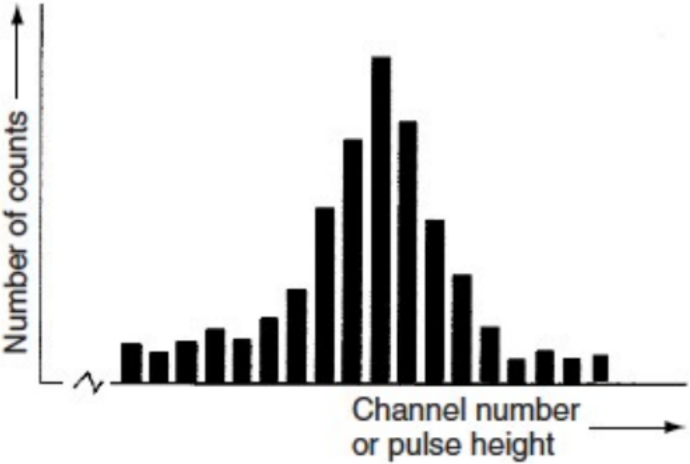




HPGe detectors: MCA (Multichannel analyzer)

- From the output from the amplifier, it rejects out-of-range pulses
- it measures the height of each of those accepted and adds a count into the memory location corresponding to the channel representing the voltage range
- it displays the data as a spectrum and allows the data to be printed or saved to a data storage device.
- In principle, the relationship between pulse height (and therefore energy) and channel number would be exactly linear, passing through zero

HPGe detectors: MCA (Multichannel analyzer)



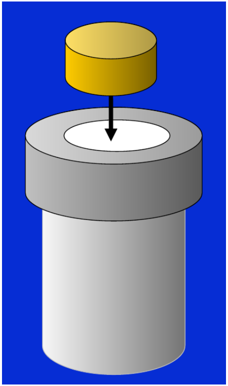
HPGe detectors: MCA terms and definitions

Lower level discriminator (LLD)	pulses below this level will not be analysed. Use this to reject electronic noise and low-energy X-rays
Upper level discriminator (ULD)	pulses above this level will not be analysed. Use this to reject very high energy pulses. This will often be left at its maximum, but still performs a useful function in rejecting high- energycosmic gamma-rays
ADC zero level	use this to adjust the energy calibration so that it passes through 0 keV. Not ideal for eliminating the effect of noise
Digital offset	this is a means of shifting the spectrum to lower channel numbers by subtracting a fixed number (the offset) from every channel number output by the ADC
Conversion range	the maximum pulse height the MCA can accept, typically 10 V
ADC resolution	is the total number of channels available within the ADC. It varies from model to model, but MCAs for germanium systems might incorporate a 16k (16384), 8k (8192), or 4k (4096) channels ADC
ADC conversion gain	is simply the number of channels actually used in a particular application – in everyday parlance, the spectrum size

Standards, calibrations

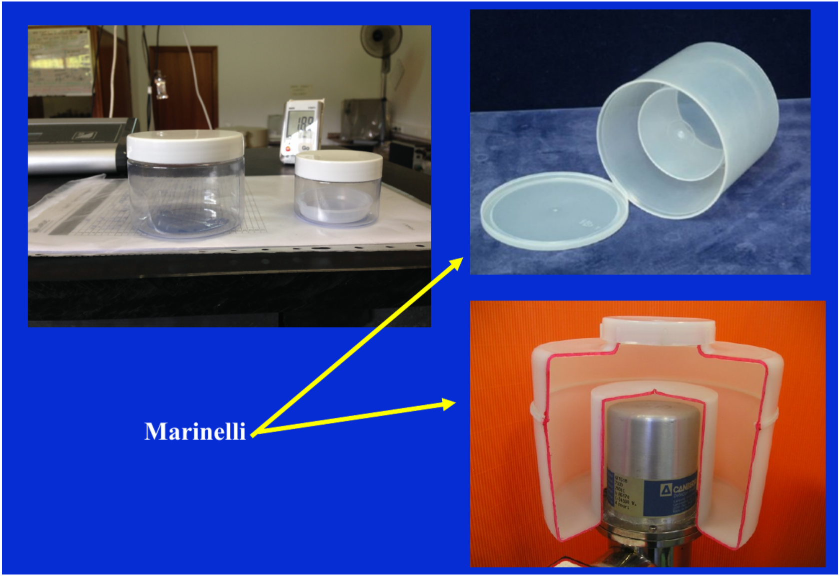
Geometry	the standard source shall have the same geometry as the sample to be measured.
Geometry	the standard radioactivy source shall be homogeneously distributed
Position	centered position
Software	the sorftware determines the presence of isotopes according to their energy. Thermal variations may cause spectrum shifts. Therefore it is necessary to carry out verifications frecuently

Calibration source



- Similar density of standard and analysis sample
- Standard shall be uniformly distributed over the entire volume (similar self-absorption as analysis samples)
- Centre the sample

Examples of geometries



Calibration steps

Calibration energy versus channel

Calibration efficiency versus enery

Energy vs. channel

The objective of energy calibration is to derive a relationship between peak position in the spectrum and the corresponding gamma-ray energy

Energy calibration is accomplished by measuring the spectrum of a source emitting gamma-rays of precisely known energy and comparing the measured peak position with energy. It matters not whether the source contains a single nuclide or several nuclides: ^{152}Eu source for routine energy calibration

Energy vs. channel

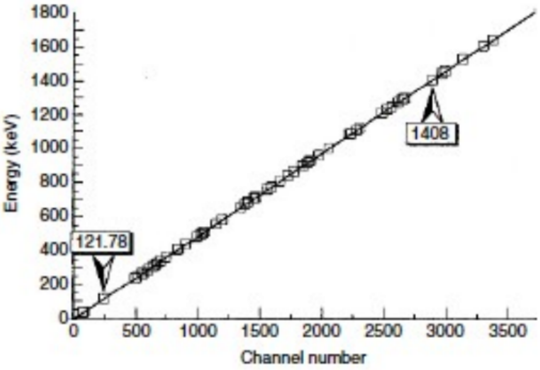


Figure 7.1 Energy calibration (55 points and the best fit straight line) using ^{152}Eu. The two marked points would be used for a two point calibration

Energy vs. channel

Efficiency vs. energy

Relative efficiency	general performance measure relating the efficiency of detection of the ^{60}Co gamma ray at 1332 keV of the detector to that of a standard sodium iodide scintillation detector
Absolute full energy peak	relation between the peak area in our spectrum to the amount of radioactivity it represents. This relates the peak area, at a particular energy, to the number of gamma- rays emitted by the source and must depend upon the geometrical arrangement of source and detector
Absolute total efficiency	relates the number of gamma rays emitted by the source to the number of counts detected anywhere in the spectrum. This takes into account the full energy peak and all incomplete absorptions represented by the Compton continuum
Intrinsic efficiency	relates the counts in the spectrum to the number of gamma rays incident on the detector. This efficiency is a basic parameter of the detector and is independent of the source/detector geometry. It is also called full energy peak or total

Energy vs. channel

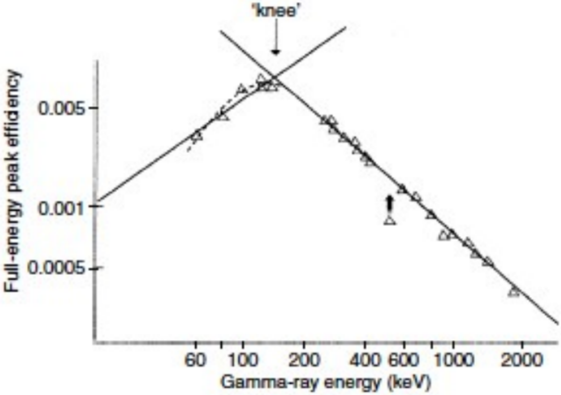
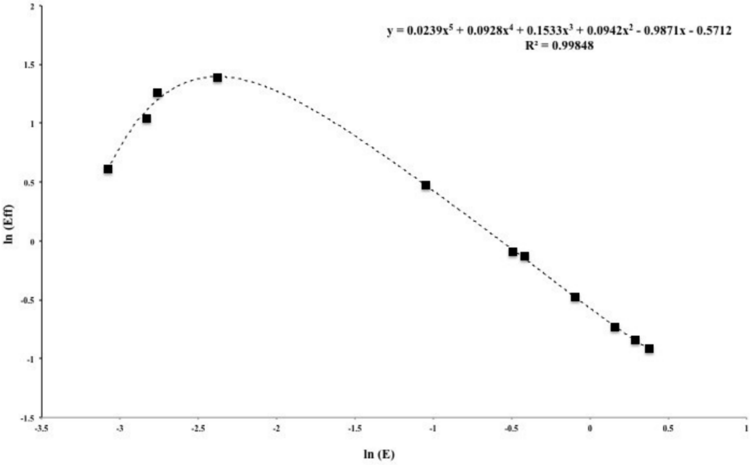


Figure 7.7 Efficiency curve for a p-type closed coaxial detector. The point lying below the line is that representing the 511 keV annihilation peak

Energy vs. channel



Energy resolution

Resolution is a measure of the width of the peaks in a gamma-ray spectrum – the smaller the width, the better the detector, the higher the resolution

FHWM: the Full Width of the peak at Half Maximum (keV)

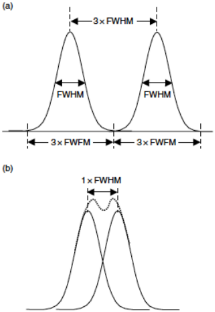


Figure 6.1 The influence of FWHM on the ease of discriminating between close energies: (a) centroids $>3\times$ FWHM apart should pose no problem; (b) centroids $1\times$ FWHM apart require deconvolution programs

Energy resolution

Table 6.3 Comparison of ultimate resolution of Ge and NaI(Tl) detectors

Material	ε(eV)[a]	F	FWHM at 661.67 keV	Resolution ratio	Source of data
Ge	2.96	0.058	0.794	0.031	Eberhardt (1970)
NaI(Tl)	170	1	25.0	0.031	See Knoll (1989), p. 312

[a] ε is the energy needed to create an electron–hole pair in germanium, or the energy needed to produce a photoelectron at the photocathode of the photomultiplier of the NaI(Tl) detector.

How to calculate activity

COUNTS

ACTIVITY (Bq kg^{-1}; Bq l^{-1} $\ldots$)

How to calculate activity

$$A = \frac{I}{T \cdot \epsilon \cdot P \cdot X}$$

- A: activity expressed in Bq kg^{-1}; Bq l^{-1} ...
- I: number of counts corrected
- T: time in seconds
- ϵ: efficiency
- P: emission probability
- X: mass (kg), volume (l), ...

In some cases it is necessary to include corrections due to radioactivity decay, summing effects, etc.

Some statistics

Binomial distribution

In principle, the statistics of radioactive decay are binomial in nature. If we were to toss a handful of coins onto a table and then examine the arrangement, we would find coins in one of two dispositions – heads up or tails up. Similarly, if we could prepare a radioactive source and, during a particular period of time, monitor each individual atom we would see that each has only one of two possible fates – to decay or not decay

Confidence limits

. . . we must quote our limits in such a way that we have a stated degree of confidence that the true value lies somewhere within them

Table 5.1 Coverage factors and the associated degree of confidence[a]

Coverage factor	Area within confidence limits (%)
1.0	68.3
1.645	90.0
1.96	95.0
2.0	95.5
2.326	98.0
2.576	99.0
3.0	99.9

[a] Confidence limit = coverage factor × s.

Counting Decision Limits

Critical limit (LC)	a decision level: 'Is the net count significant?'
Upper limit (LU)	'Given that this count is not statistically significant, what is the maximum statistically reasonable count?'
Detection limit (LD)	'What is the minimum number of counts I can be confident of detecting?'
Determination limit (LQ)	'How many counts would I have to have to achieve a particular statistical uncertainty?'
Minimum detectable activity (MDA)	'What is the least amount of activity I can be confident of detecting?'

Learnings so far

Let’s remember

Learnings so far

Let's remember

- Techniques to measure radioactivity: alpha, beta, gamma spectrometry and LSC and gross alpha/beta

Learnings so far

Let's remember

- Techniques to measure radioactivity: alpha, beta, gamma spectrometry and LSC and gross alpha/beta
- Interaction of radiation with matter

Learnings so far

Let's remember

- Techniques to measure radioactivity: alpha, beta, gamma spectrometry and LSC and gross alpha/beta
- Interaction of radiation with matter
- Gamma spectrometry: fundamentals, essential set up procedures

Learnings so far

Let's remember

- Techniques to measure radioactivity: alpha, beta, gamma spectrometry and LSC and gross alpha/beta
- Interaction of radiation with matter
- Gamma spectrometry: fundamentals, essential set up procedures
- Characteristics of HPGe detectors

Learnings so far

Let's remember

- Techniques to measure radioactivity: alpha, beta, gamma spectrometry and LSC and gross alpha/beta
- Interaction of radiation with matter
- Gamma spectrometry: fundamentals, essential set up procedures
- Characteristics of HPGe detectors
- Elementary estatistics of radioactivity

Radioactivity: Doses

Exposure (X)

Definition: is a measure of the ionization of air due to ionizing radiation from photons, that is, gamma rays and X-rays. It is defined to be the electric charge freed by the radiation divided by the mass of the air.

Units: coulomb per kilogram, however the roentgen is commonly used internationally in the nuclear industry (1R ~ 3876 C kg^{-1})

Exposure rate constant

The gamma ray field can be characterized by the exposure rate

$$X = \frac{\Gamma \cdot A}{r^2}$$

- X: exposure rate (R h^{-1})
- Γ: exposure rate constant
- A: activity
- r: distance

Exposure rate constants for various radionuclides

Radionuclide	Exposure rate constant (R cm^2 h^{-1} mCi^{-1})
^{60} Co	12.838
^{99}Mo	1.03
^{99m}Tc	0.720
^{137}Cs	3.400
^{226}Ra	8.25

Absorbed dose (D)

Definition: the mean energy imparted to matter per unit mass by ionizing radiation

Units: joules per kilogram (gray, Gy)

$$1\ \mathrm{Gy} = 1\ \mathrm{J\ kg^{-1}}$$

$$1\ \mathrm{Gy} = 100\ \mathrm{rad}$$

$$1\ \mathrm{rad} = 0.01\ \mathrm{Gy} = 10\ \mathrm{mGy}$$

Exposure and absorbed dose

$$D = f \cdot X$$

f: conversion coefficient depending on medium

The absorbed energy in a quantity of air exposed to 1 C kg^{-1} of X Rays is 0.869 Gy $f(\text{air}) = 0.869$

Conversion coefficients (*Credit: IAEA*)

Photon energy (keV)	f water	f bone	f muscle
10	0.91	3.5	0.93
100	0.95	1.5	0.95

Equivalent dose (H)

Definition: is the absorbed dose multiplied by a dimensionless radiation weighting factor, wR which expresses the biological effectiveness of a given type of radiation

Units: the SI unit of equivalent dose is called the sievert (Sv). The old unit was the “rem”

$$1 \text{ Sv} = 100 \text{ rem}$$

Radiation weighting factor wR

- For most of the radiation used in medicine (X Rays, γ, e^-) wR is = 1, so the absorbed dose and the equivalent dose are numerically equal
- exceptions
  - alpha particles (wR = 20)
  - neutrons (wR = 5 - 20)

Activity and equivalent dose

$$\dot{H} = \frac{K \cdot A}{r^2}$$

- $\dot{H}$: equivalent dose rate (mSv h^{-1})
- A: activity (Bq)
- r: distance
- K: factor

Effective dose (E)

Definition: Radiation exposure of the different organs and tissues in the body results in different probabilities of harm and different severity. The combination of probability and severity of harm is called “detriment”. o reflect the combined detriment from stochastic effects due to the equivalent doses in all the organs and tissues of the body, the equivalent dose in each organ and tissue is multiplied by a tissue weighting factor, WT, and the results are summed over the whole body to give the effective dose E

Units: Sievert (Sv)

Effecitve dose (E)

$$E = \sum T \cdot WT \cdot H_T$$

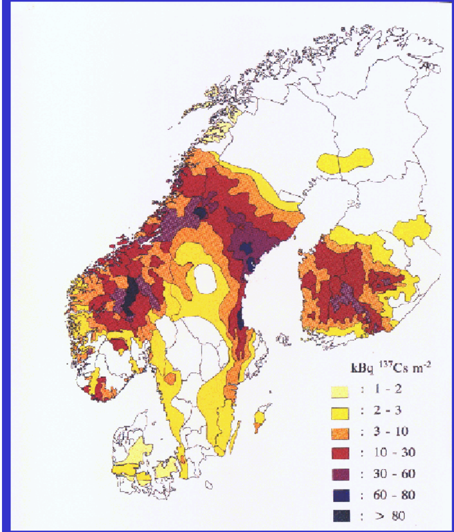
- E: Effective dose
- WT: weighting factor for organ or tissue T
- H_T: equivalent dose in organ or tissue T

Tissue weighting factors, wT

Conversion coefficients (*Credit: IAEA*)

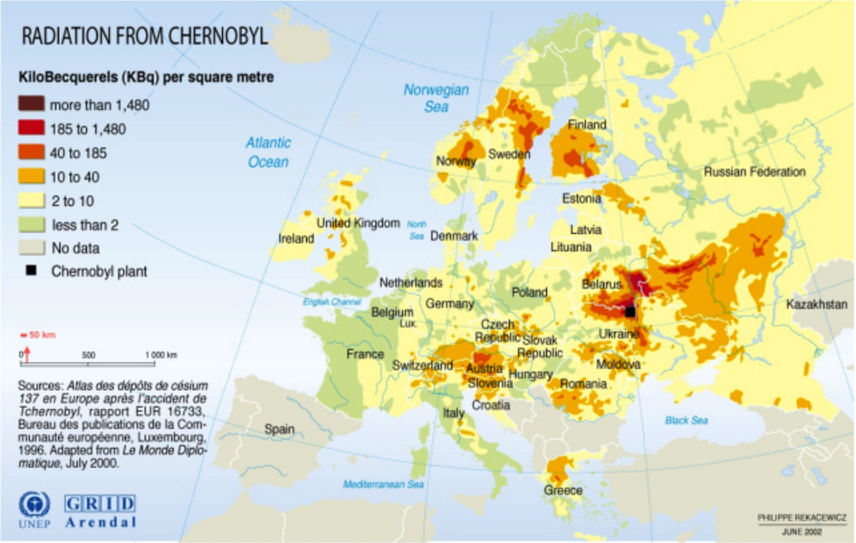
Organ/Tissue	*WT*
Bone marrow	0.12
Bone surface	0.01
Brain	0.01
Breast	0.12
Colon	0.12
Gonads	0.08
Liver	0.05
Lung	0.12
Skin	0.01
Stomach	0.12
Thyroid	0.04

Examples of doses due to artificial radionuclides



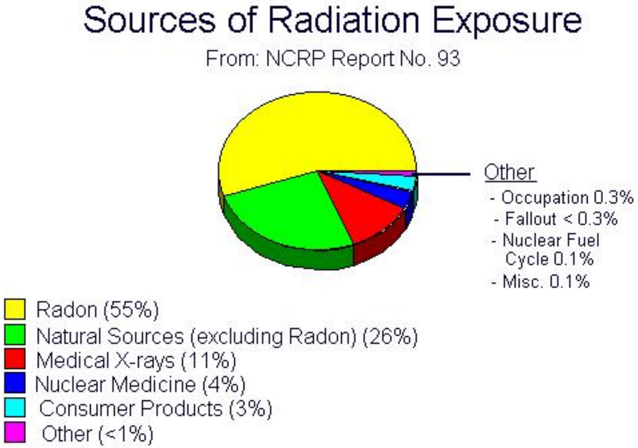
Deposition by the Chernobyl fallout in 1986 of ^{137}Cs in the Nordic countries

Examples of doses due to artificial radionuclides



Sources: UNEP/GRID-Arendal, European Environment Agency; *AMAP Assessment Report : Arctic Pollution Issues*, Arctic Monitoring and Assessment Programme (AMAP), 1998, Oslo; European Monitoring and Evaluation Programme (EMEP); Co-operative programme for monitoring and evaluation of the long range transmission of air pollutants in Europe, 1999. Adapted from *Le Monde Diplomatique, July 2000.*

Examples of doses due to natural radionuclides



Learnings so far

Let’s remember

Learnings so far

Let's remember

- Magnitudes use on radioactivity: Exposure (X), Absorbed dose (D), Equivalent dose (H), Effective dose (E)

Learnings so far

Let's remember

- Magnitudes use on radioactivity: Exposure (X), Absorbed dose (D), Equivalent dose (H), Effective dose (E)
- New units: Exposure (R), Absorbed dose (D), Equivalent and effective dose (Sv)

Learnings so far

Let's remember

- Magnitudes use on radioactivity: Exposure (X), Absorbed dose (D), Equivalent dose (H), Effective dose (E)
- New units: Exposure (R), Absorbed dose (D), Equivalent and effective dose (Sv)
- Relations between magnitudes: exposure and activity (exposure rate constant Γ); activity and equivalent dose (K)

Learnings so far

Let's remember

- Magnitudes use on radioactivity: Exposure (X), Absorbed dose (D), Equivalent dose (H), Effective dose (E)
- New units: Exposure (R), Absorbed dose (D), Equivalent and effective dose (Sv)
- Relations between magnitudes: exposure and activity (exposure rate constant Γ); activity and equivalent dose (K)
- Examples of doses due to natural radiation and artificial radiation (radioactive fallout)