

Radiation Basics

Nuclides & Isotopes

Elements are identified by atomic numbers, the number of protons (Z) in its nucleus. The nuclide is denoted by the **atomic number as a subscript** and the **mass number (number of protons + neutrons), A, as superscript** on the element's symbol, for example



Isotopes are nuclides of a given element with a different number of neutrons (N).

Example: Hydrogen and hydrogen isotopes

Atomic # # neutrons Mass #

	Z	N	A
${}_1\text{H}^1$	1	0	1
	99.985% of ordinary hydrogen		
${}_1\text{H}^2$	1	1	2
	Deuterium, 0.015% of ordinary hydrogen		
${}_1\text{H}^3$	1	2	3
	Tritium, radioactive, 12.3 year half-life		

- **The periodic table of 108 elements has a total of around 2500 different isotopes.**
- **Of these, 270 are stable isotopes and the rest are radioactive, most of which being artificially-made, i.e. they do not naturally exist, they are produced by nuclear means.**

The Nucleus, Mass Defect and Binding Energy

- The nucleus is composed of Z protons and N neutrons is held together by a strong nuclear force which overcomes the electrostatic repulsion of the positively charged protons.
- The energy that holds this together is called the binding energy, which comes from the mass difference "mass defect".

Example

Aluminum atom has 13 protons, 13 electrons and 14 neutrons.

It has a mass of 26.981538 amu.

One atomic mass unit (amu) = 1.66×10^{-27} kg

It is defined such that the carbon-12 atom has a mass of exactly 12.000000 amu.

Aluminum-13

- Proton weight $1.007276 \text{ amu} \times 13 = 13.095588 \text{ amu}$
- Electron weight $0.000549 \text{ amu} \times 13 = 0.007137 \text{ amu}$
- Neutron weight $1.008665 \text{ amu} \times 14 = 14.121310 \text{ amu}$

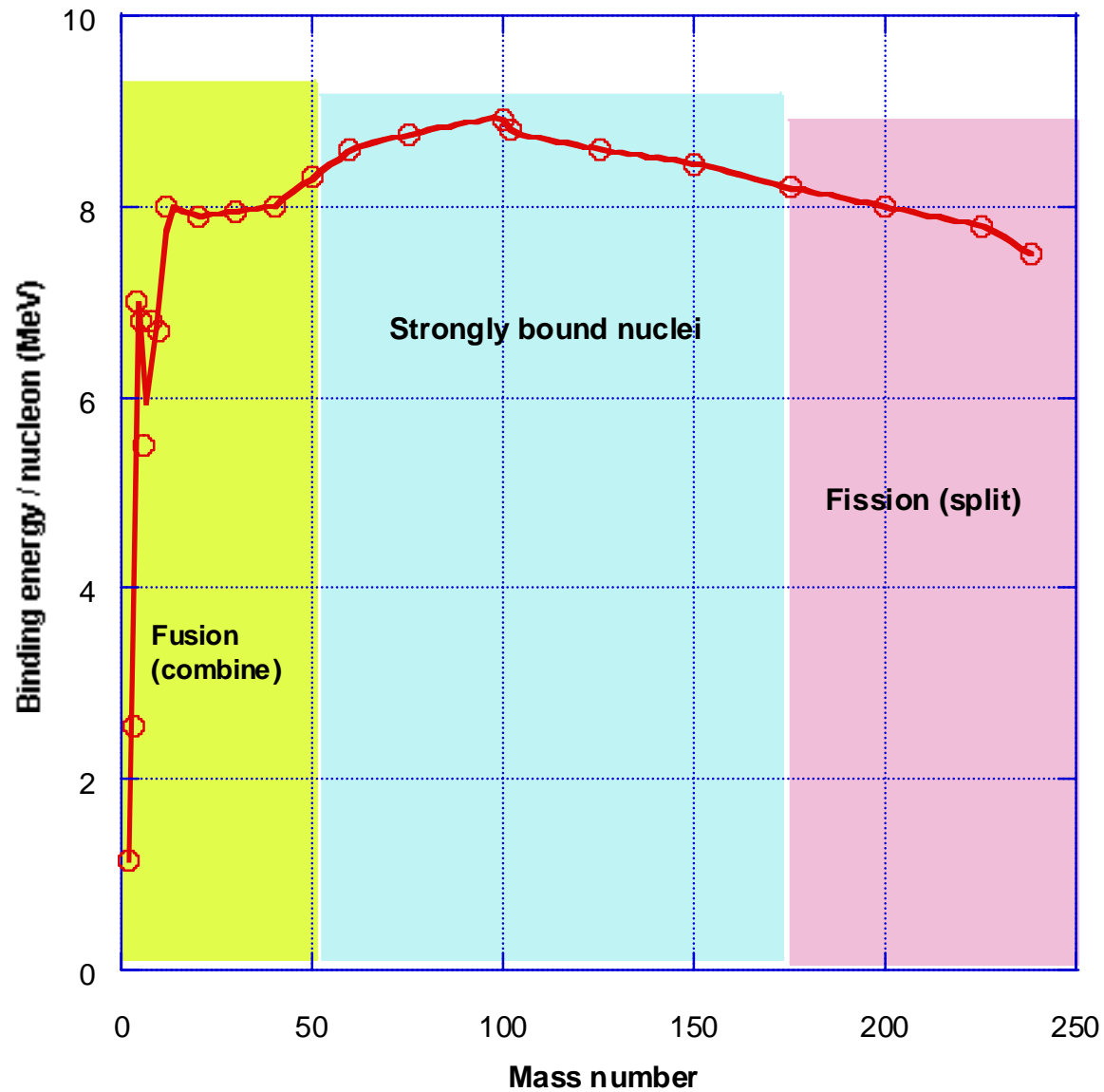
- Total weight 27.224035 amu

- True weight 26.981538 amu

- Difference 0.242497 amu

The missing mass, 0.242497 amu, is the binding energy and can be related by Einstein's famous equation, $E = mc^2$, where E is energy, m is that mass and c is the speed of light. In this example, the missing mass corresponds to **225MeV**, which is the energy given up by assembling a loose collection of protons, electrons and neutrons into an atom, also it is the energy required to break up the atom and nucleus into its constituent parts.

Binding energy per nucleon versus mass number



Radioactivity

- About 340 nuclides found in nature
 - About 70 of them are naturally radioactive
 - ‘normally in heavy elements’
- All elements with atomic number > 83 are
- radioactive
- Some light elements are naturally radioactive:
 - Tritium (${}_1\text{H}^3$)
 - Beryllium-10 (${}_4\text{Be}^{10}$)
 - Carbon-14 (${}_6\text{C}^{14}$)

- Some of the combinations of protons and neutrons are not stable. Combination has too few or too many neutrons for the number of protons.
- To become more stable, the atom may release some of its extra energy by emitting radiation.
- Three basic types of radiation are:
alpha (α), beta (β) and gamma (γ).

Alpha (α) radiation

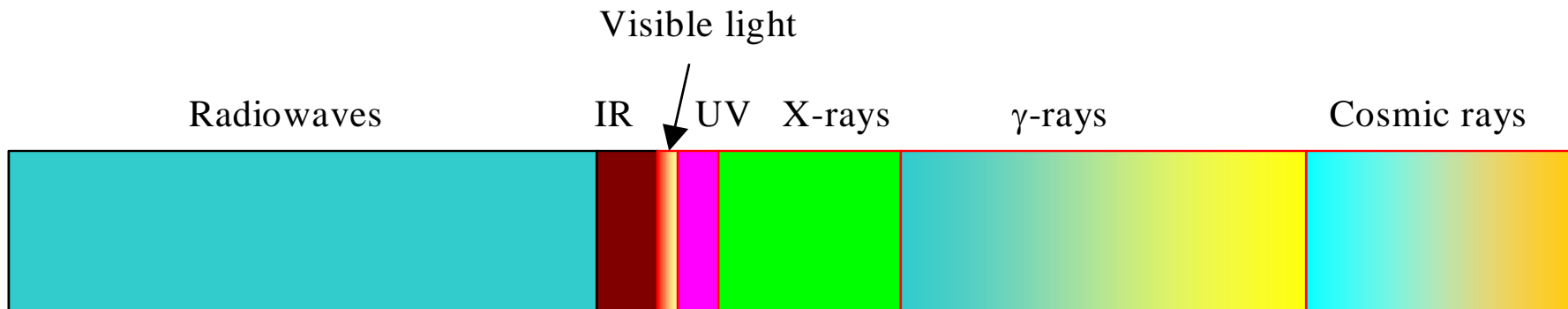
- Particles made of 2 protons and 2 neutrons, which is the Helium nucleus. This is the heaviest (about 4 amu) of the radiations and has an electrical charge of +2.
- Symbols used for alphas are α and He^4 .
- The range of alpha particles in air is about 2.5cm for 4MeV alphas and about 7.3cm for 8MeV alphas. In aluminum, it is about 0.015 and 0.055 cm for 4 and 8Mev, respectively.

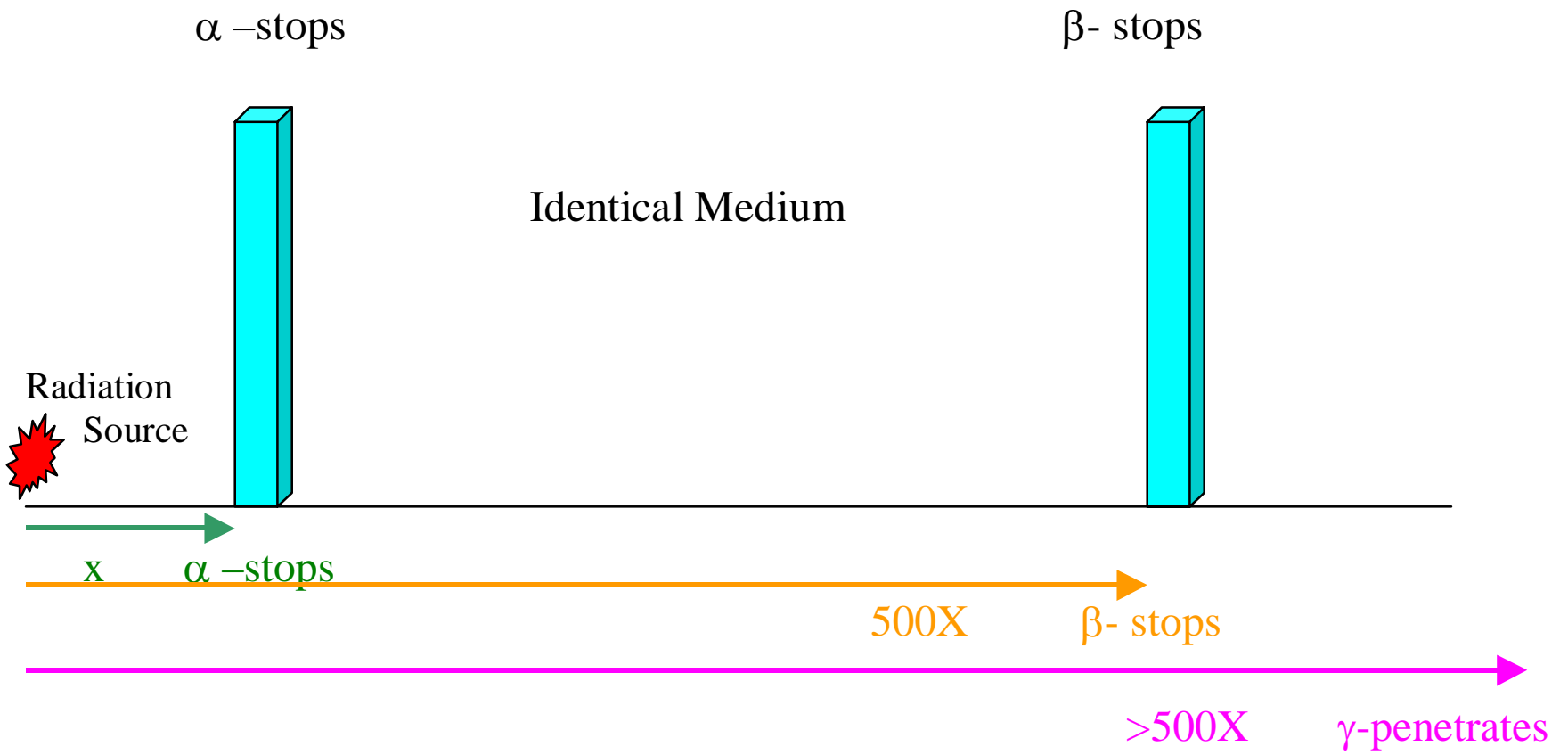
Beta (β) radiation

- Particles identical to normal electrons. They originate from the nucleus of the atom, not the group of electrons surrounding the atom. They are lighter than alphas and have a charge of -1.
- Symbols for betas are β^- and e^- .
- The positively charged electrons, **positrons**, can be emitted by an unstable nucleus.
- The symbols for positrons β^+ and e^+ .
- The range of beta particles is about **500** times that of alphas. In air, it is about **1.5 meters for 0.5MeV** and **8.5 meters for 2MeV** betas. In aluminum, it is about **6.5 millimeters** and **4 centimeters** for **0.5 and 2MeV** betas, respectively.

Gamma (γ) radiation

- Electromagnetic radiation made of photons and is similar to X-rays, microwaves, light and radio waves.
- Gammas have no weight but they do carry energy and momentum, just like any other photon from the electromagnetic (EM) spectra.





- Other types of radiation do exist but usually only in nuclear reactors and high energy physics particle accelerators. The most important of these is the **neutron**.
- For nuclei that have a large excess of energy, a neutron can be emitted. It is rare in nature for this type of decay to happen. Most neutron sources in laboratories contain two elements; one that emits alpha particles and one that emits a neutron after being struck by that alpha.

Radiation Interactions

- Each form of radiation has a distinctive feature when interacting with matter. The response to such interaction determines the way with which such radiation can be detected.
-
- Ionizing radiation means the form of radiation that ionizes a certain medium, such as the α , β and γ radiations. But first, what is ionization? When an electron is removed from the atom, it leaves the atom positively charged and thus the atom becomes an ion. Each ion and electron forms an ion-pair. A gas can simply be ionized by means of an electric field to form plasma, but ionizing radiation is due to the interaction of radiation particles (α , β) or radiation quanta (γ) with matter.

α -particles

- passing through matter loses their energy via electrostatic interactions with atomic electrons, and thus α -particles produce excitation and ionization. Their range of penetration into matter is limited by their energy.

β -particles

- have a continuous energy spectrum, which is a characteristic of the isotopes. β 's lose their energy via collision with atomic electrons and this results in excitation and ionization. Slowing of β 's produces electromagnetic radiation (**x-rays**), known as Bremsstrahlung. Their range is longer than α 's.

γ -rays

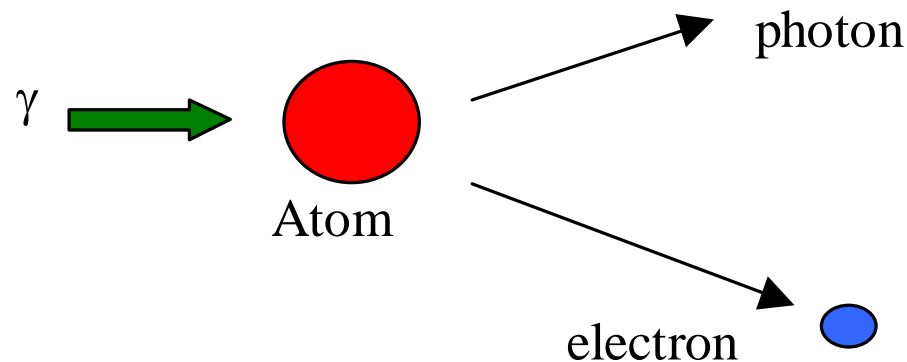
- are not particles and thus the mechanism is different than α 's and β 's. Let see how γ 's interact:

- *Photoelectric Effect:*

Here γ provides all its energy to eject an electron from the atom's inner shell, and the ejection of electron causes ionization.

Compton Scattering:

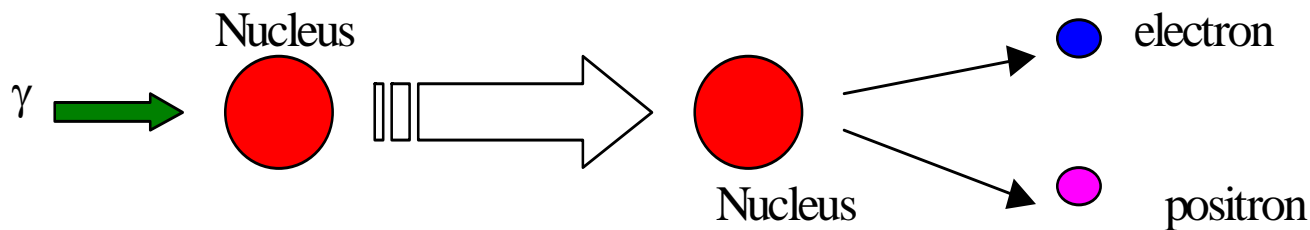
Here, only part of gamma energy is consumed to eject an electron from the outer shell and a photon is scattered. This is the predominant mechanism for gammas in the energy range 1-2MeV.



Pair Production:

Here, energy is converted to mass, gamma's energy is totally consumed and electron-positron pair appears. This can only occur for γ -energy > 1.02 MeV.

(1.02MeV = mass of 2 electrons, or the mass of an electron and a positron)



We have seen that γ attenuates into matter by the exponential law: $I(x) = I_0 e^{-\mu x}$ and μ is the attenuation coefficient. More precisely, it is the linear attenuation coefficient, and it is the summation of **ALL** attenuations due to γ -interactions:

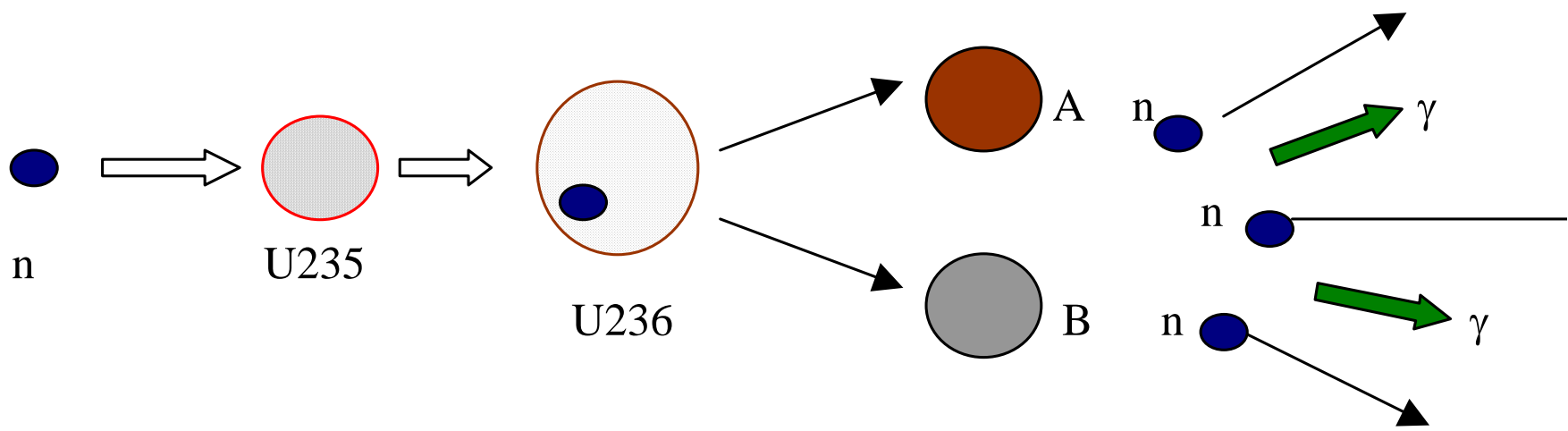
$$\mu = \mu_{\text{(photoelectric)}} + \mu_{\text{(Compton)}} + \mu_{\text{(pair production)}}$$

$$\mu = \tau + \sigma + \kappa$$

Neutrons

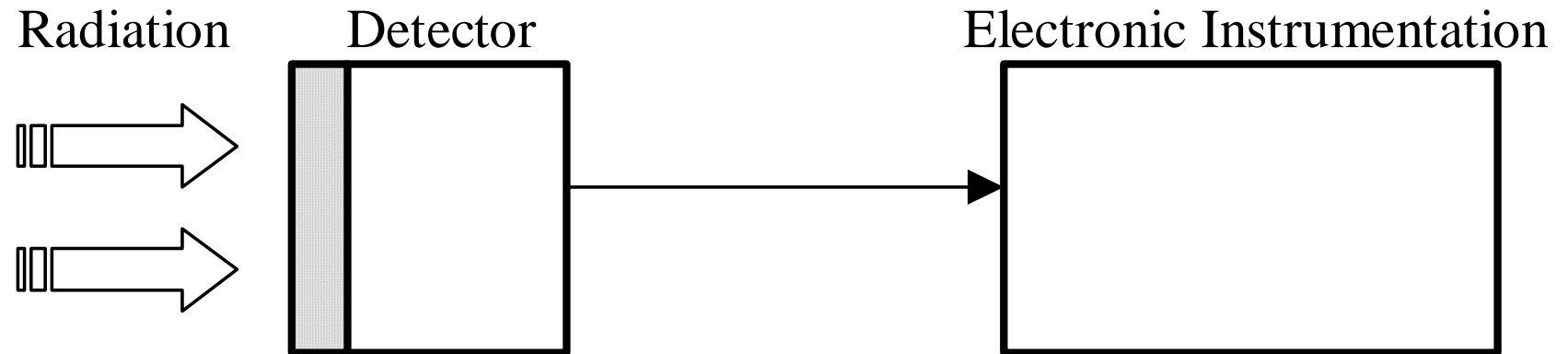
They also interact with matter, and they:

- May scatter by elastic or inelastic collisions.
- May be captured, which results in gamma emission.
- May cause Fission.
- May, if energy high enough, induce neutron-proton (n,p) and neutron-alpha (n, α) reactions



Radiation Detection

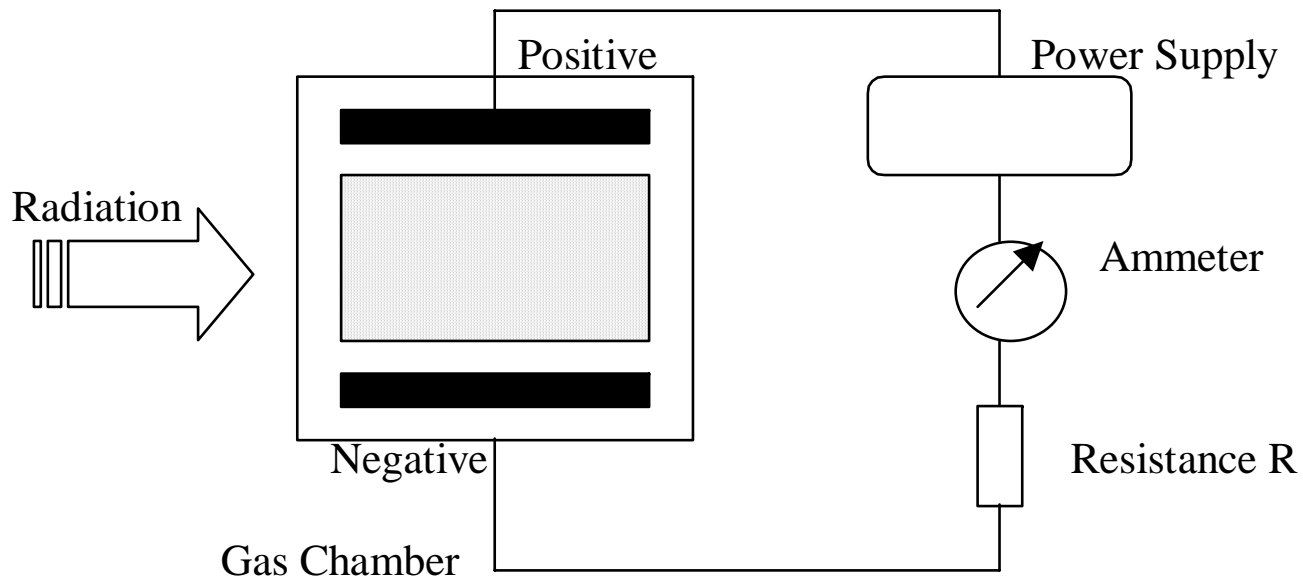
Detection of radiation is a consequence of radiation interaction with matter. A detector is 'some' kind of material that interacts with radiation, and the result of such interaction can be sensed by instrumentation and recorded by a data acquisition system (DAS).



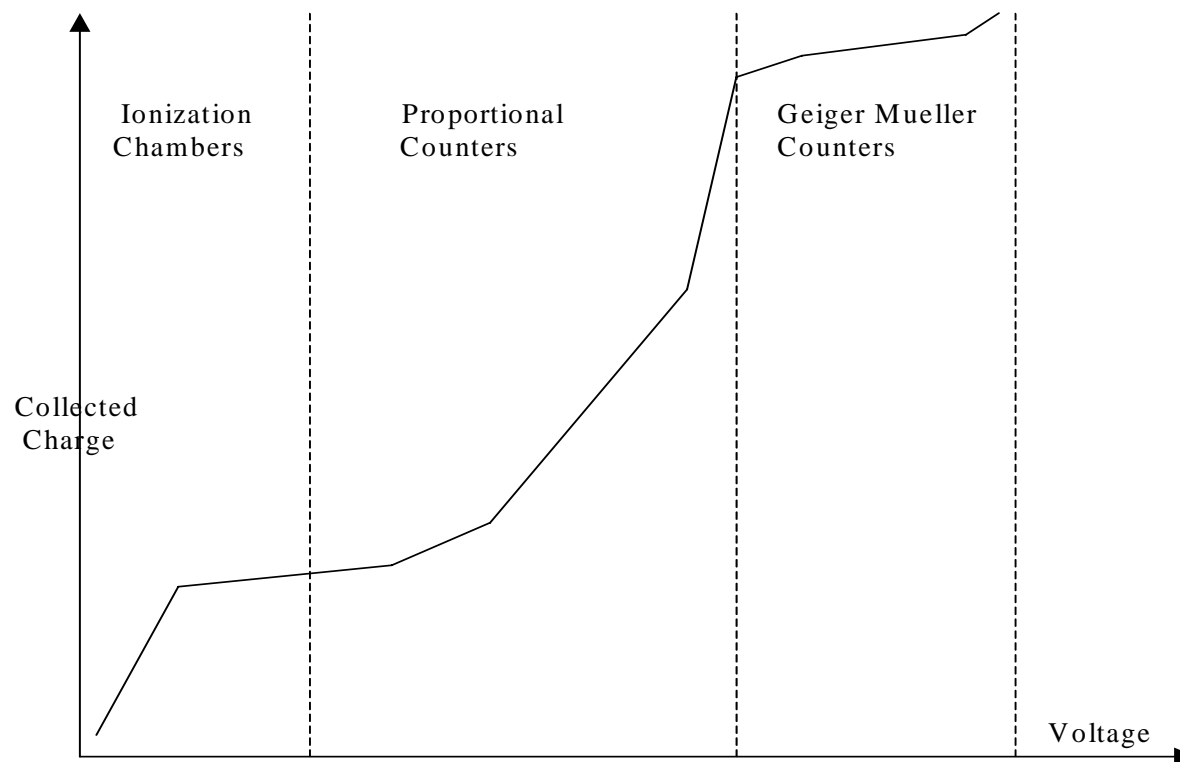
- **The Detector**: Gas-ionization or Scintillation or Semiconductor detectors
- **Electronic Instrumentation**: High voltage supply, signal amplifier, scalar and DAS.

Gas Counters (gas ionization detectors)

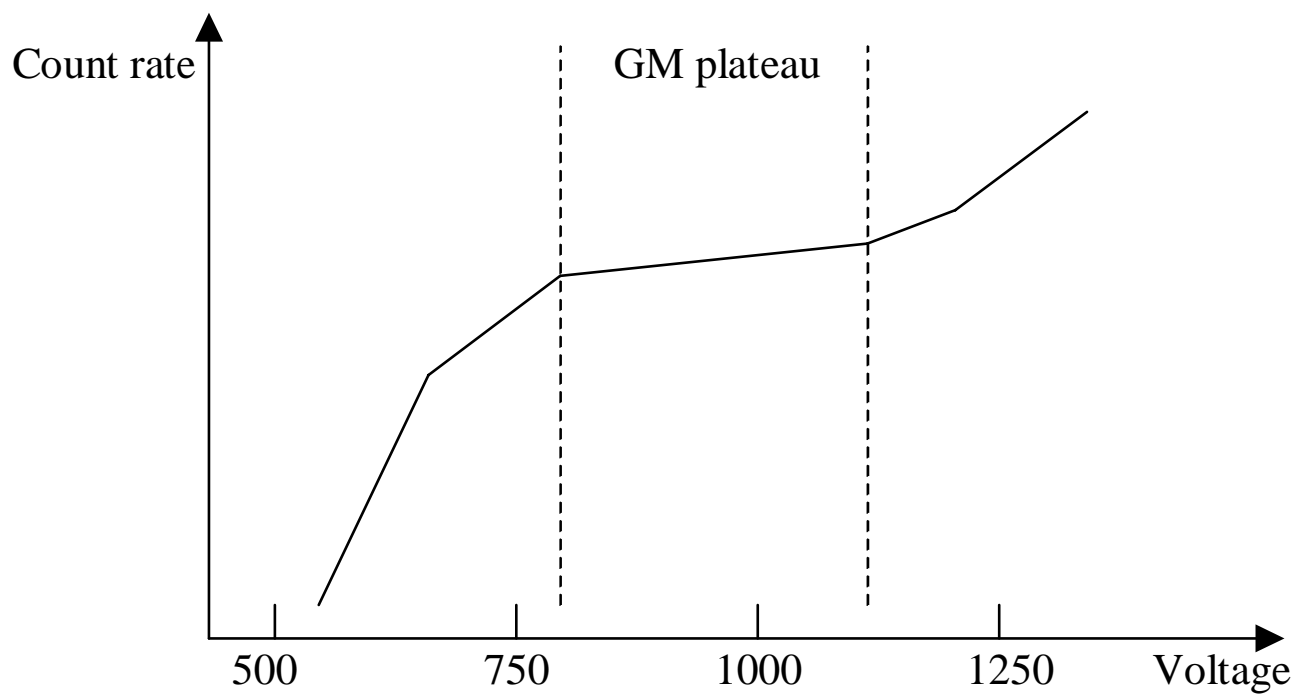
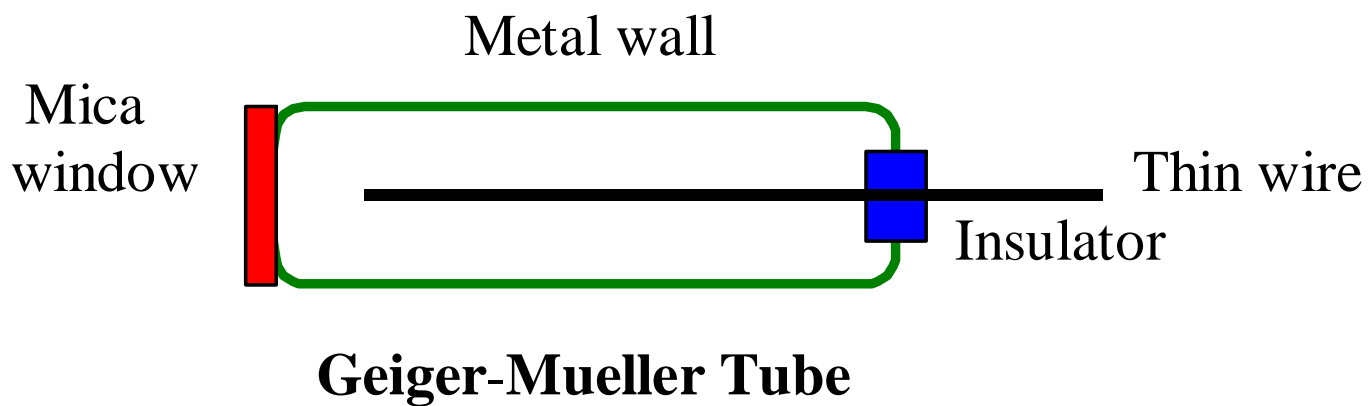
A gas chamber filled with a chosen gas. Two electrodes are installed inside of the chamber, one positive (anode) and one negative (cathode), connected to a power supply (battery). The electric current measured by the ammeter is a measure of radiation.



This is a current-type detector used for measuring radiation level or dose rates. It can be a pulse-type counter to measure individual ionizing events. It also can be a charge-collection (voltage measurement) to measure radiation dose

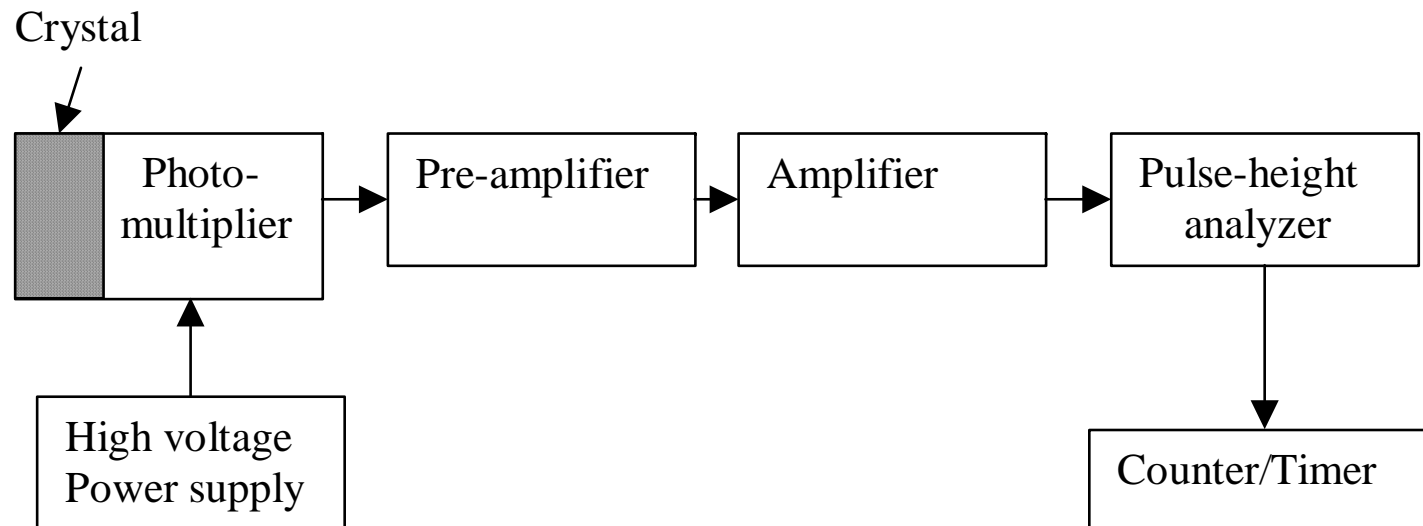


- **Ionization Chambers:** Current-type detectors providing integrated measure.
- **Proportional Counters:** Used for heavy particles that can produce enough ionization. The pulse height is proportional to energy deposition. Distinguishes between α and β .
- **Geiger-Mueller Counters:** Pulse height is no longer proportional to amount of ionization. Pulses are quite high and may not be amplified. Gas multiplication is via runaway avalanche. Any further increase in voltage will induce internal discharge (arcing) and damage the tube.



Scintillation Counters:

The interaction of some particles with materials produces ‘scintillation’ or “flash of light”. This scintillation can be amplified in a photo-multiplier tube, then be analyzed for the pulse height and counted.



Scintillation counter electronics

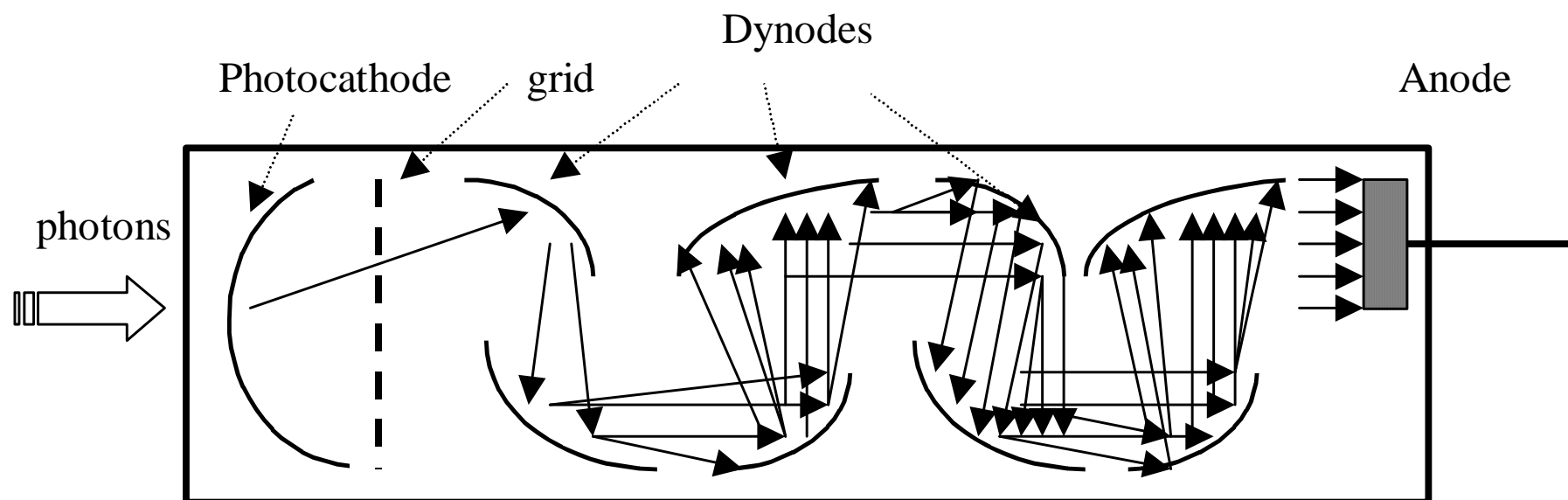
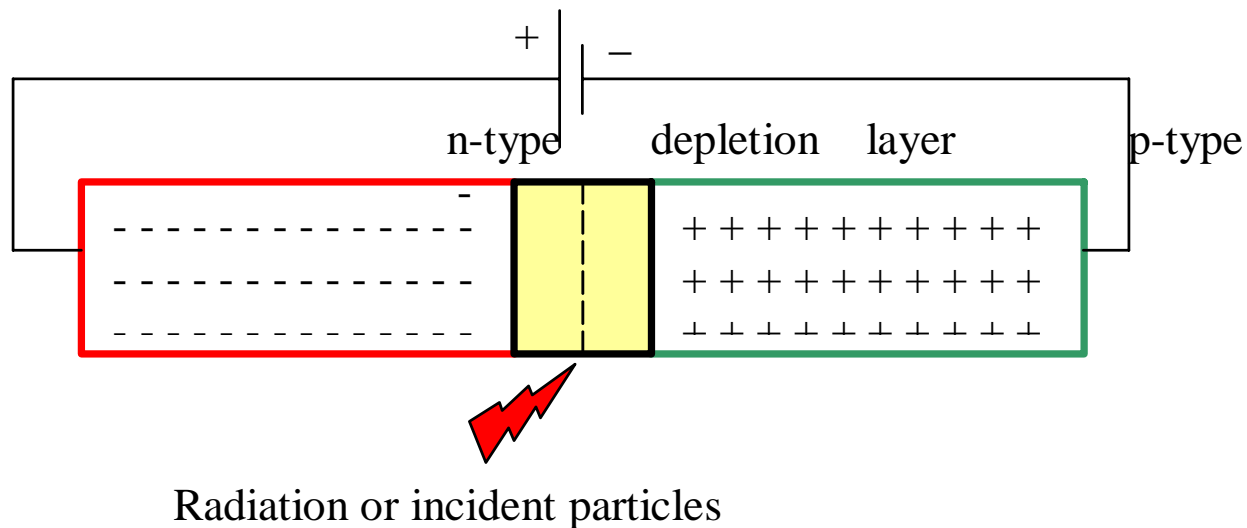


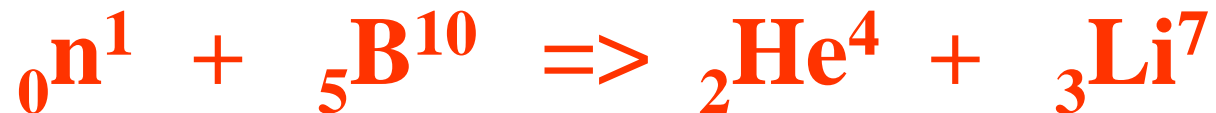
Photo-multiplier tube

Solid State Detectors:

They are semiconductors and compact. The electrical conductivity of the semiconductor is sensitive to presence of impurities. The depletion layer is sensitive to radiation and electric current flow through, thus the measured current is a measure of radiation.



Neutron Detectors: neutrons do not directly ionize a gas, and thus neutron reactions that can produce gases can be used, example:



In this reaction the neutron-boron interaction produces helium-4, then He-4 is the acting gas to operate as an ionization chamber. Boron trifluoride (BF_3) is usually used to induce the neutron-boron reaction. Neutron detectors measure the number of neutron incident on the detector.

Biological Effects and Medical Applications

- *Biological Effects*
- Biological effects are determined by the absorption of ionizing radiation in tissues. Indeed it differs between exposure to alpha, beta or gamma radiation.
- The range of absorption into materials is determined by the coefficient of absorption, or in other words, the attenuation coefficient.

Exposure to ionizing radiation has various effects on chromosomes

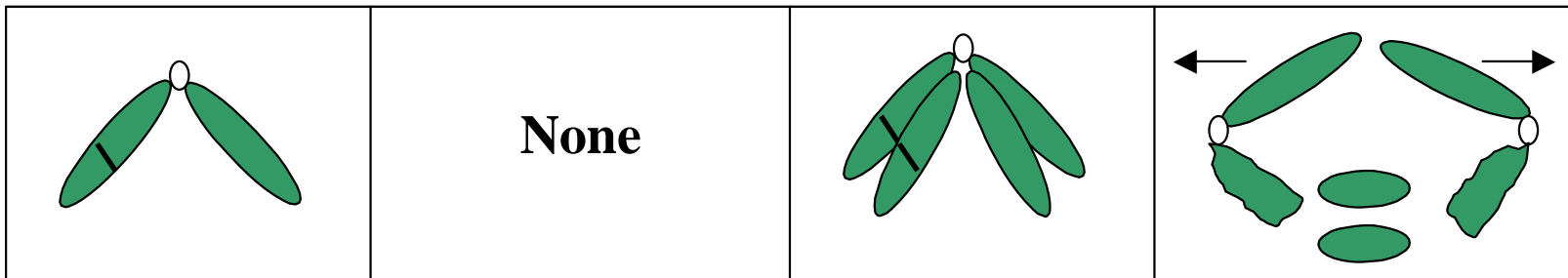
One break in one chromosome

Breakage

Recombination

Replication

Anaphasic separation



Single break in one chromosome, which results in centric and acentric fragments. The acentric fragments are unable to migrate and are only transmitted to one of the daughter cells. These fragments are eventually lost in subsequent divisions.

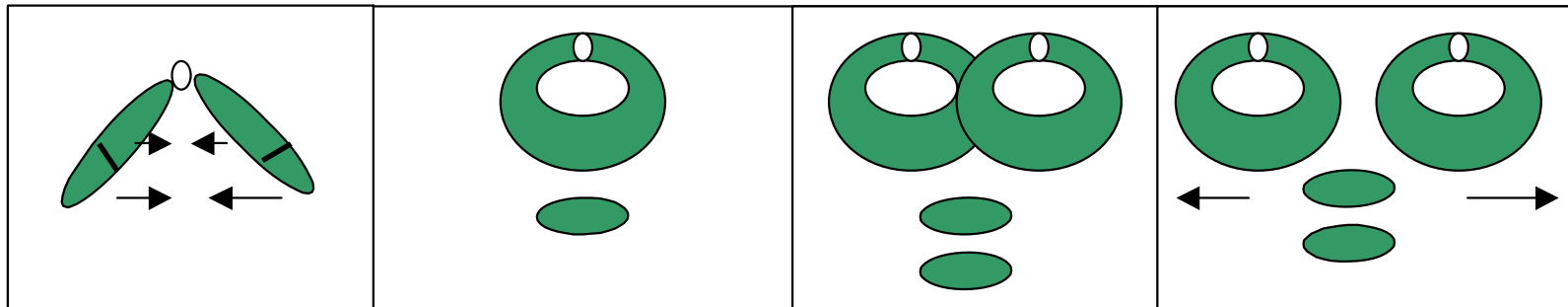
Two breaks in one chromosome rings

Breakage

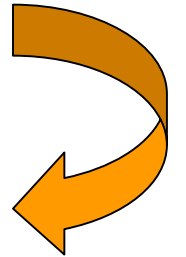
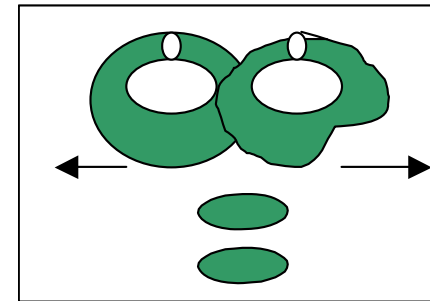
Recombination

Replication

Anaphasic
separation



OR



Ring formation may result from two breaks in the same chromosome in which the two broken ends of the centric fragment recombine. The ring-shaped chromosome undergoes normal replication, and the two ring-shaped sister chromatids will separate normally at anaphase, unless the centric fragment twists before recombination, in which case the sister chromatids will be interlocked and unable to separate.

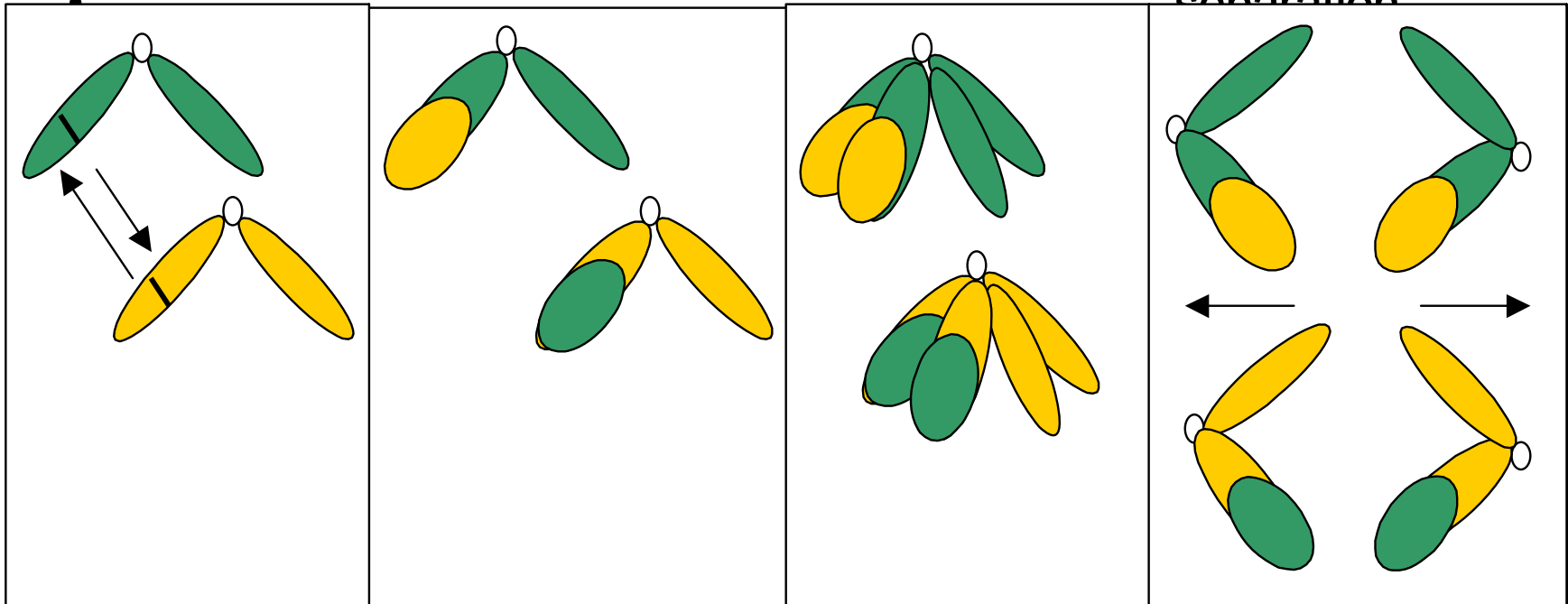
One break in two chromosomes translocation

- Breakage
Anaphasic

Recombination

Replication

separation



Translocation may occur when two chromosomes suffer one break; the acentric fragment of one chromosome combines with centric fragment and vice versa.

Medical Applications

- **Pharmacokinetics Research**
- **Radiation Therapy for Cancer**
- **Tomography**
- **Nuclear Medicine**

Pharmacokinetics Research

Study of the rate of transport of biomolecules through tissues at the cellular level, in organs, or in the whole body. Helps in understanding and predicting the behavior of pharmaceuticals or other biomolecules.

- **Principle**

- -Inject radioactive biomolecules into the blood.

- -Measure the rate of accumulation of it in the region(s) of interest as a function of time after the injection.

- -Develop predictive mathematical models based on the experimental observations.

Radiation Therapy for Cancer

To provide high localized dose to the tumor region and none to the healthy tissue. **But How?**

- High energy protons from accelerators.
- Electrons from accelerators.
- Gamma rays from externally placed radioactive sources (**Brachytherapy**).
- Neutron capture therapy.

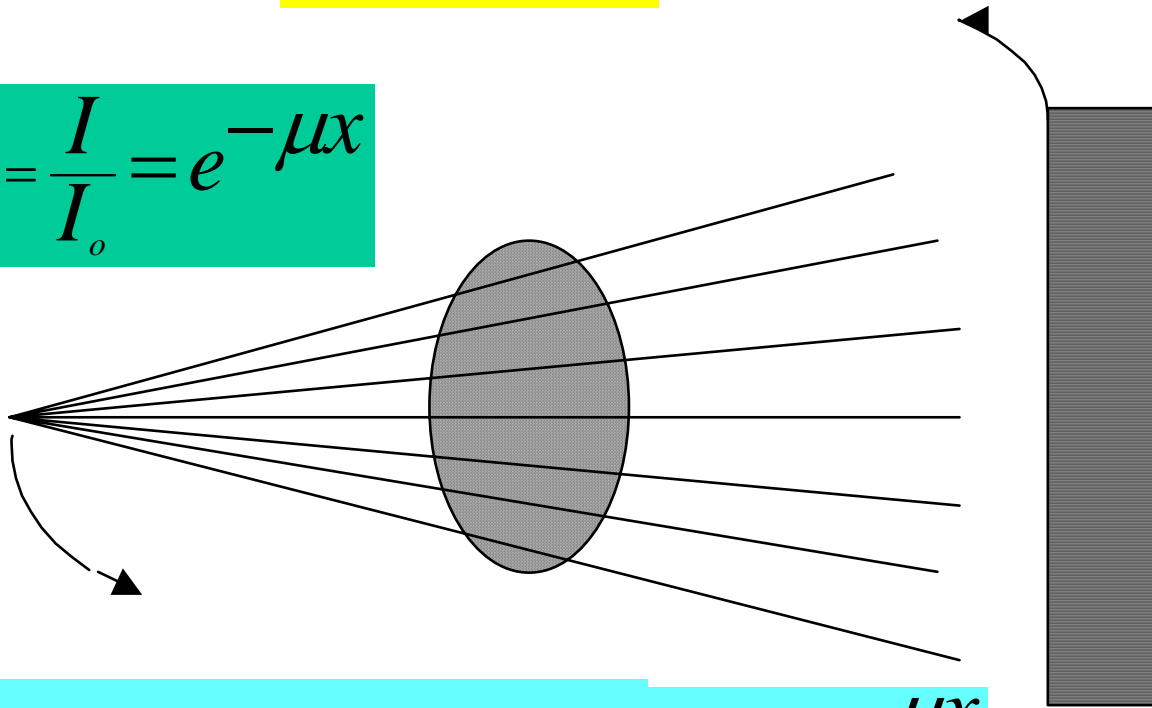
- **Problems**

- **-Kill ratio of tumor/normal cells.**
- **-Radiation resistant tumor cells.**
- **-Complete elimination of cancer.**

Tomography

- **X-ray Tomography**
- Commonly referred to as CAT scan or CT scan
No metabolic information, only structural information. $I = I_0 e^{-\mu x}$

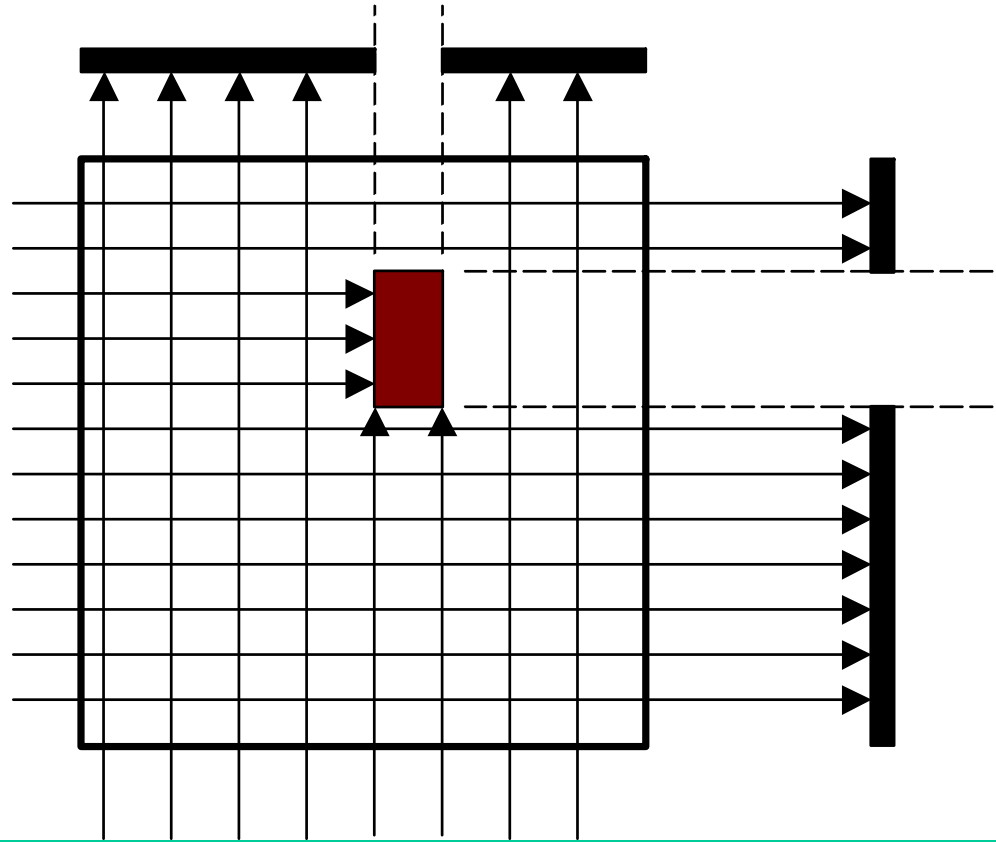
$$\text{Transmittance} = \frac{I}{I_0} = e^{-\mu x}$$



$$\text{Absorbance} = 1 - \text{transmittance} = 1 - e^{-\mu x}$$

Computed Tomography

Pioneers: radon, Hounsfield, Cormack

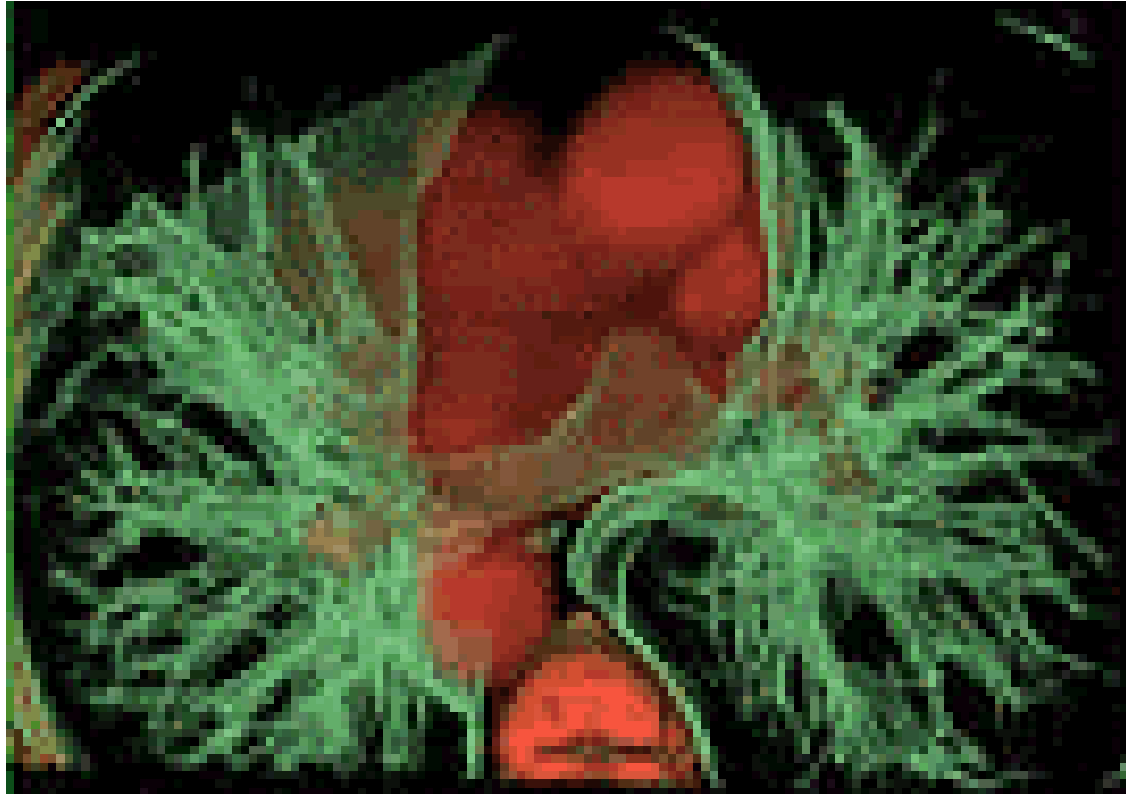
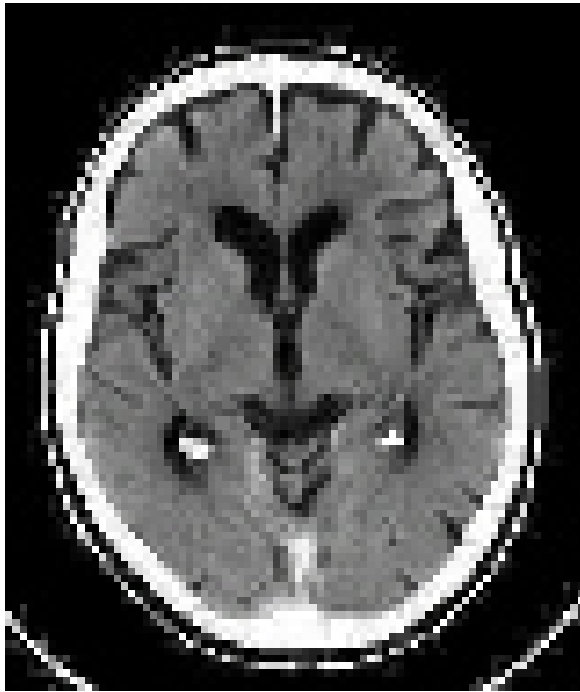


$$\text{Transmittance} = \frac{I}{I_0} = e^{-\mu x} = e^{-\left(\mu_1 x_1 + \mu_2 x_2 + \dots\right)}$$

CT Scanner and Spiral CT Scanner

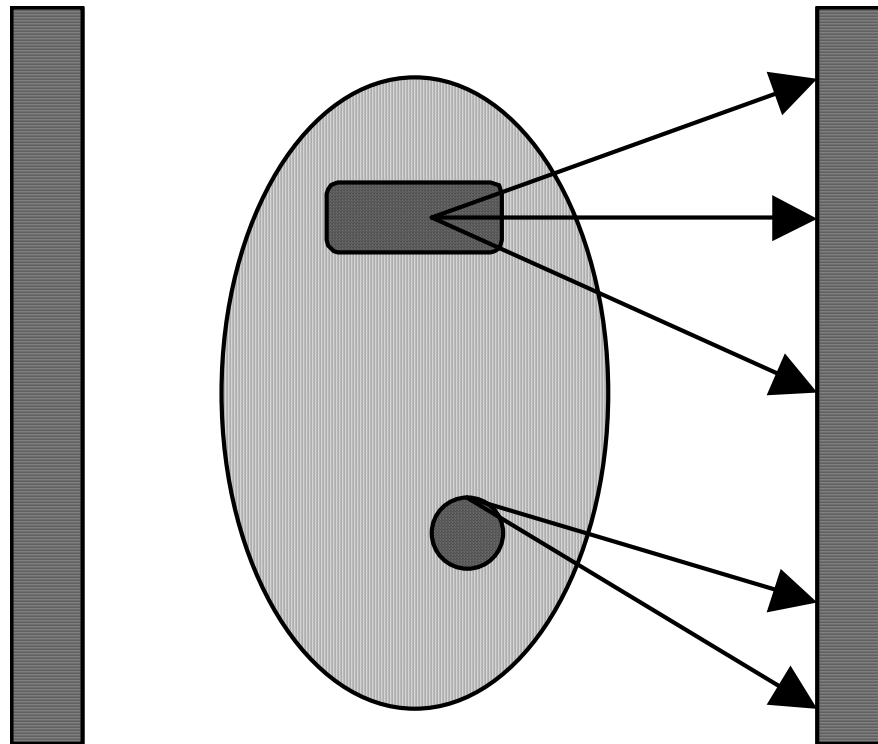
([http://www.bmimed.com/ct-imaging systems.asp?source=GOOG&keyword=computed+tomography](http://www.bmimed.com/ct-imaging%20systems.asp?source=GOOG&keyword=computed+tomography))





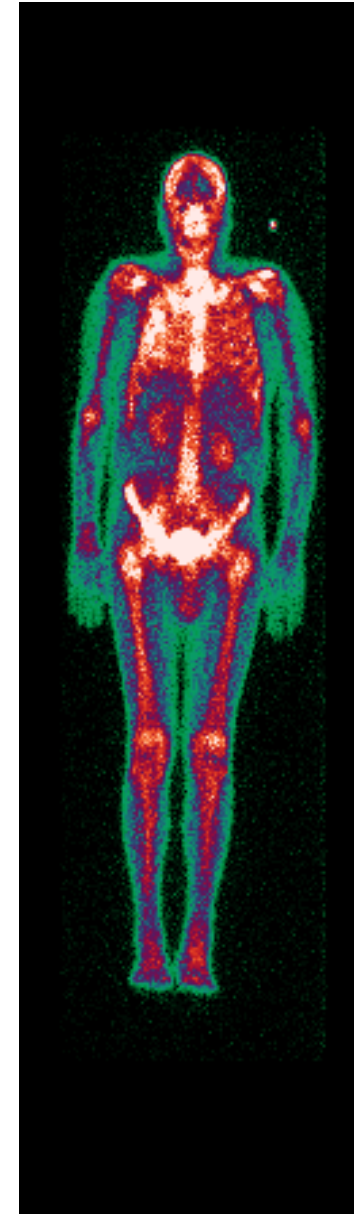
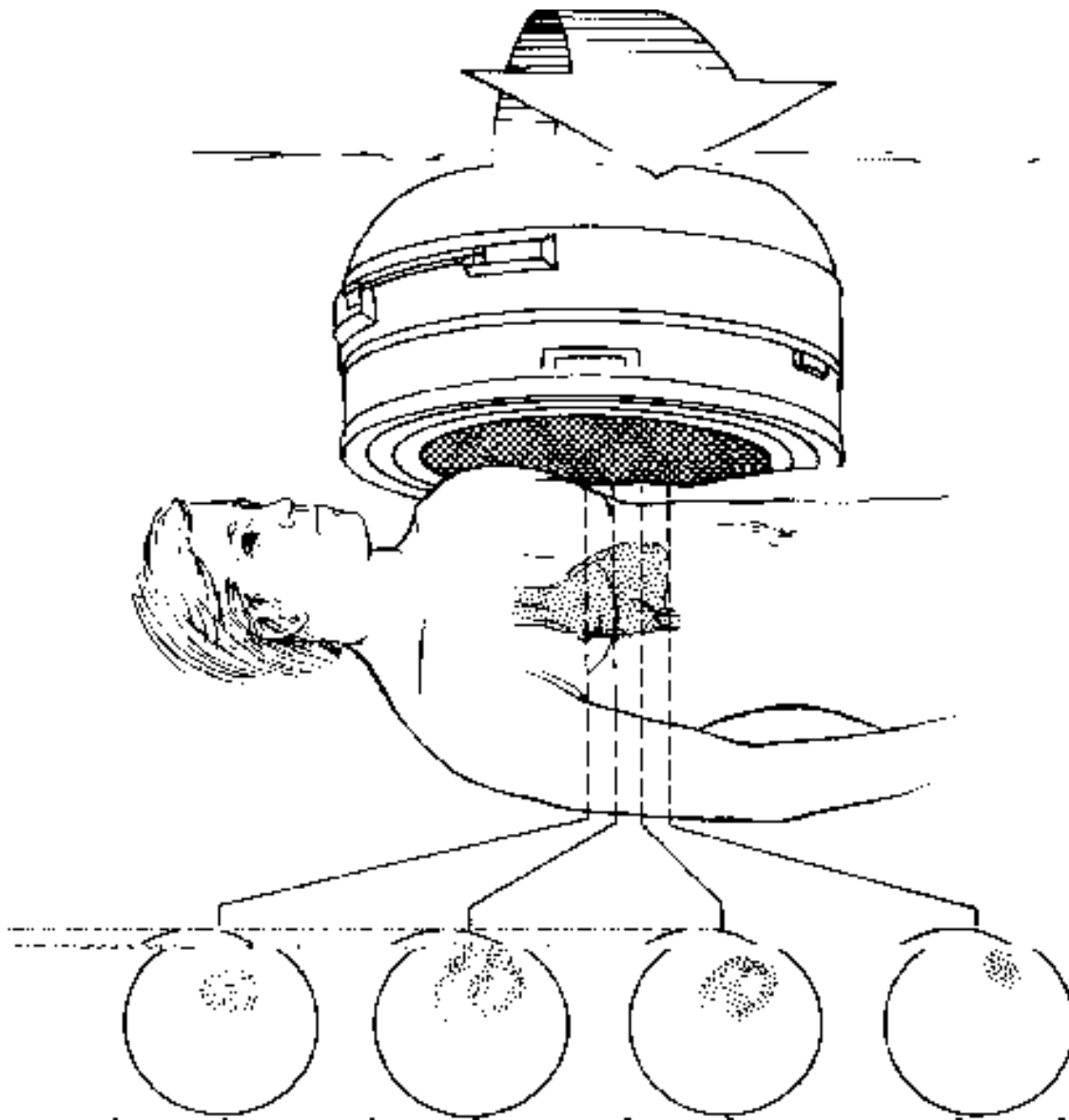
Single Photon Emission CT (SPECT)

- Proper choice of radioactive biomolecules gives metabolic information.



Example of a typical SPECT single-head cardiac scan

<http://www.bae.ncsu.edu/bae/courses/bae590f/1995/scarfone/>



- **Three-dimensional (3-D) emission computed tomography (ECT)** provides a qualitative and quantitative look at the volume distribution of biologically significant radiotracers after injection into the human body.

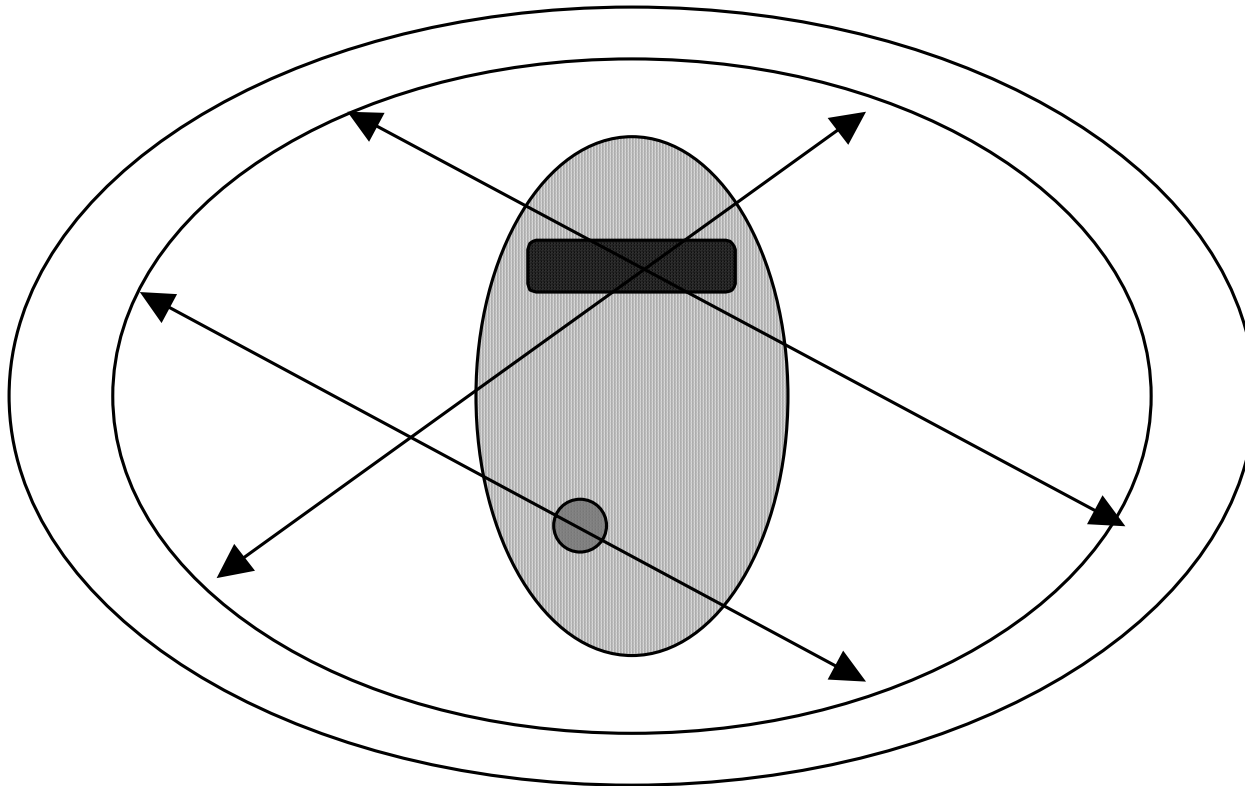
Emission computed tomography, together with two-dimensional (2-D) planar imaging, are the main imaging techniques used in any Nuclear Medicine department.

- **Three-dimensional ECT - a process involving rotation of up to three photon-sensitive cameras (Gamma cameras) around a patient - results in a 3-D image of the distribution of an injected radiotracer which is usually targeted for a particular organ, for example the heart. The 3-D image thus obtained is the result of reconstructing a series of 2-D projection sets, then "stacking" these one on top of the next to create the third dimension.**

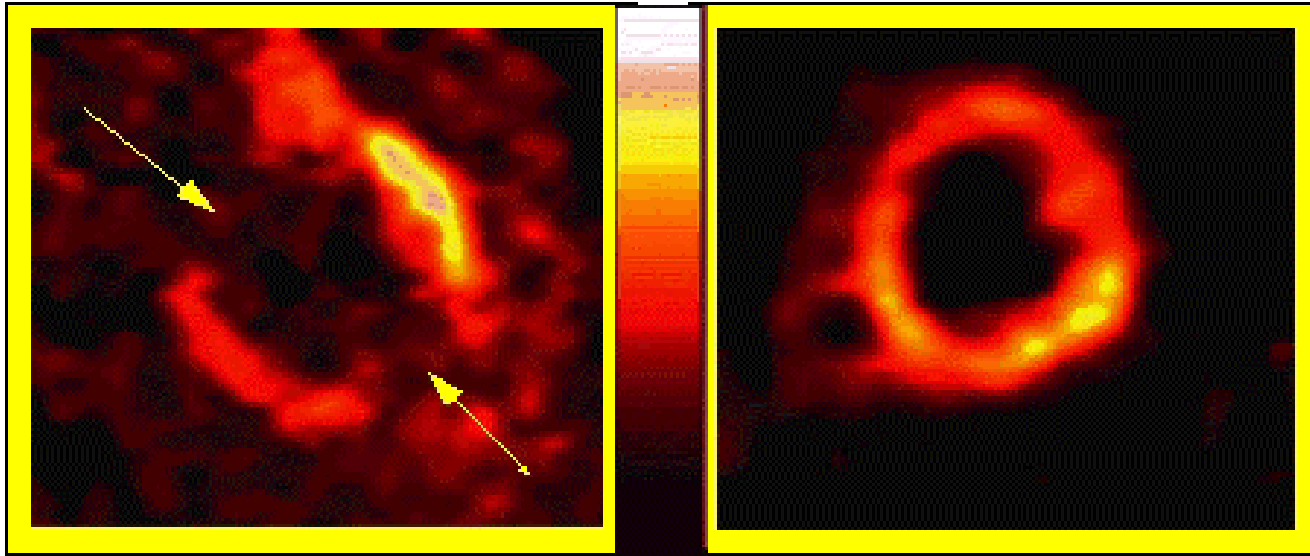
Positron Emission Tomography (PET)

- Use of radioactive biomolecules that emit positrons (anti-electrons) give metabolic information.

^{11}C
 ^{13}N
 ^{15}O
 ^{18}F



- **What Can PET Detect?**
(<http://www.biomed.org/pet.html#what>)
- **Coronary Artery Disease**
PET imaging is unique in its ability to determine whether a patient's heart muscle will benefit from coronary artery bypass surgery.
- **Example: Myocardial Viability**



Normal heart

- Image of heart which has had a myocardial infarction (heart attack). The arrow points to areas that have been damaged by the attack, indicating "dead" myocardial tissue. Therefore, the patient will not benefit from heart surgery, but may have other forms of treatment prescribed.

Example: Breast Cancer

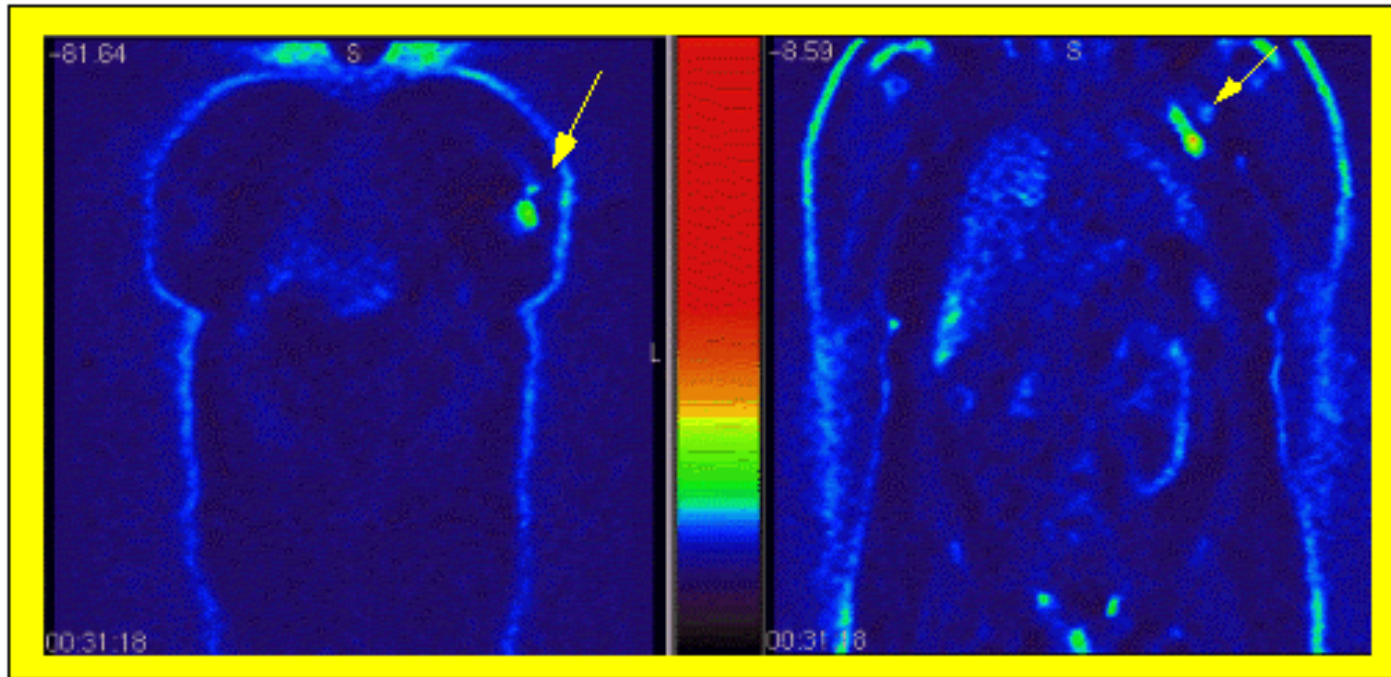
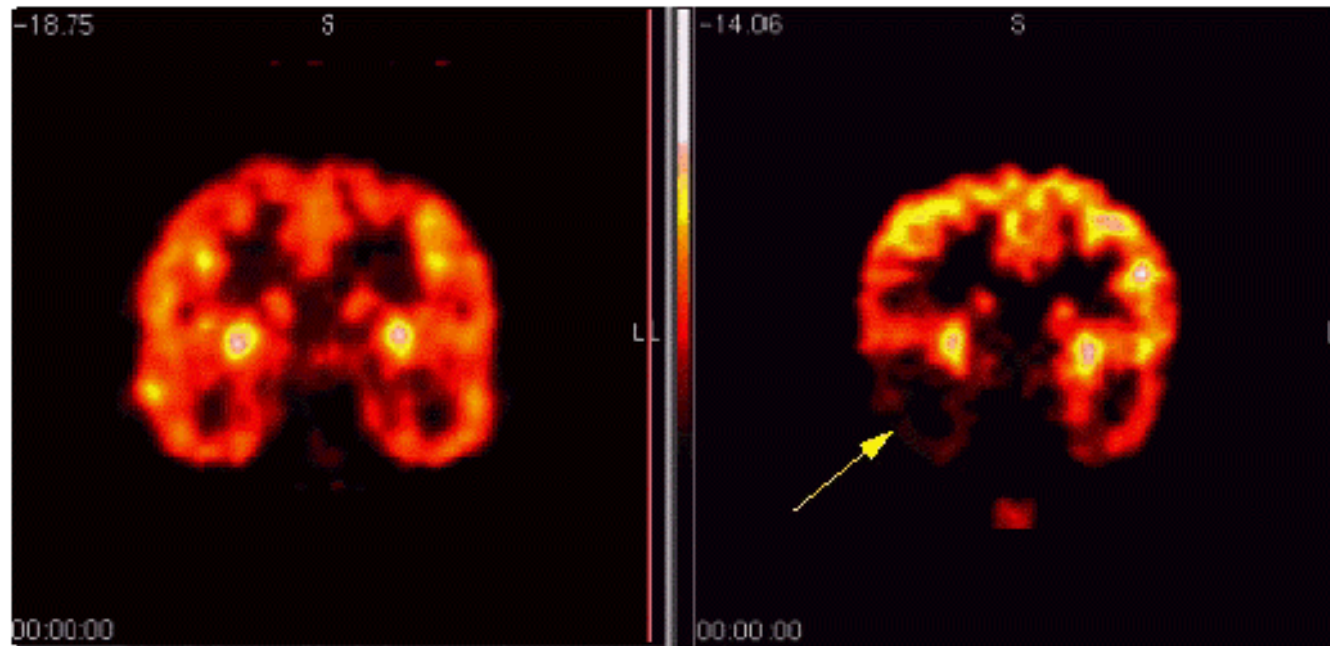


Image showing malignant breast mass that was not revealed by conventional imaging techniques such as CT, MRI, and mammogram.

Image of same patient with enlarged left axillary lymph nodes (indicated by arrows), which through biopsy were found to be metastatic (spread from another location). The whole body scan reveals a mass in the left breast (indicated by arrow), that was malignant and subsequently removed.

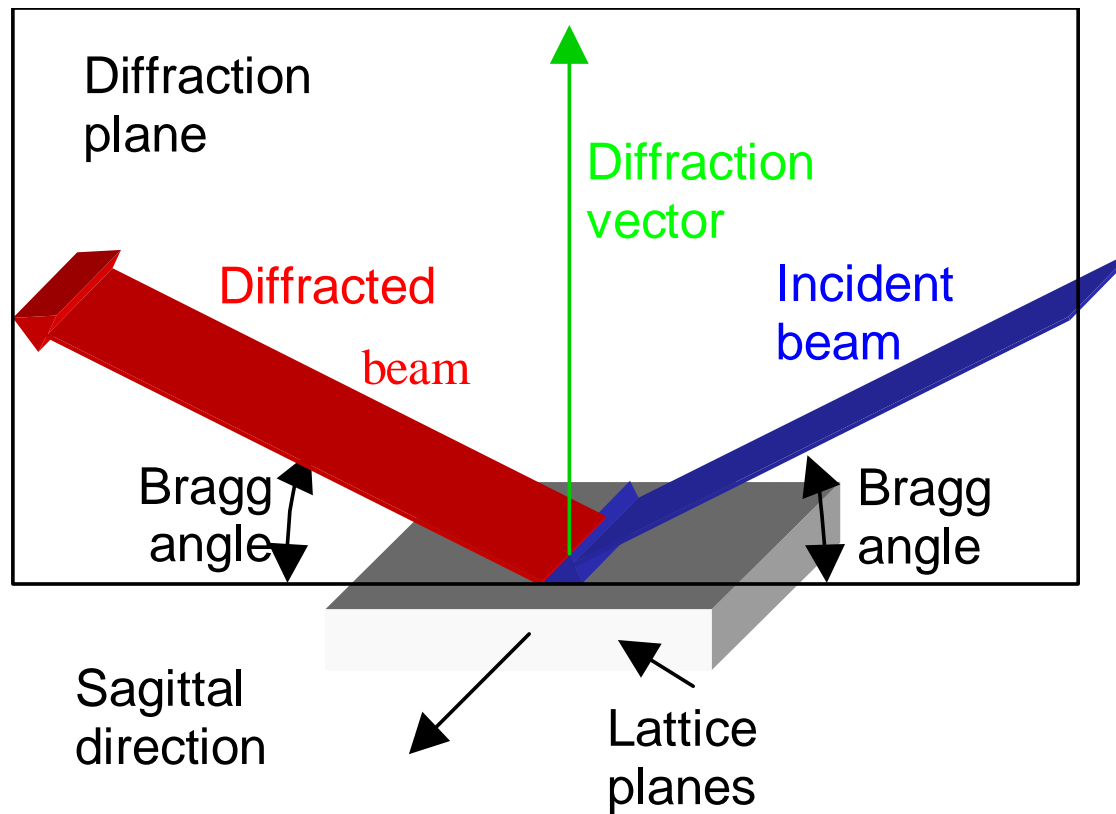
Example: Seizures



**Normal
Brain**

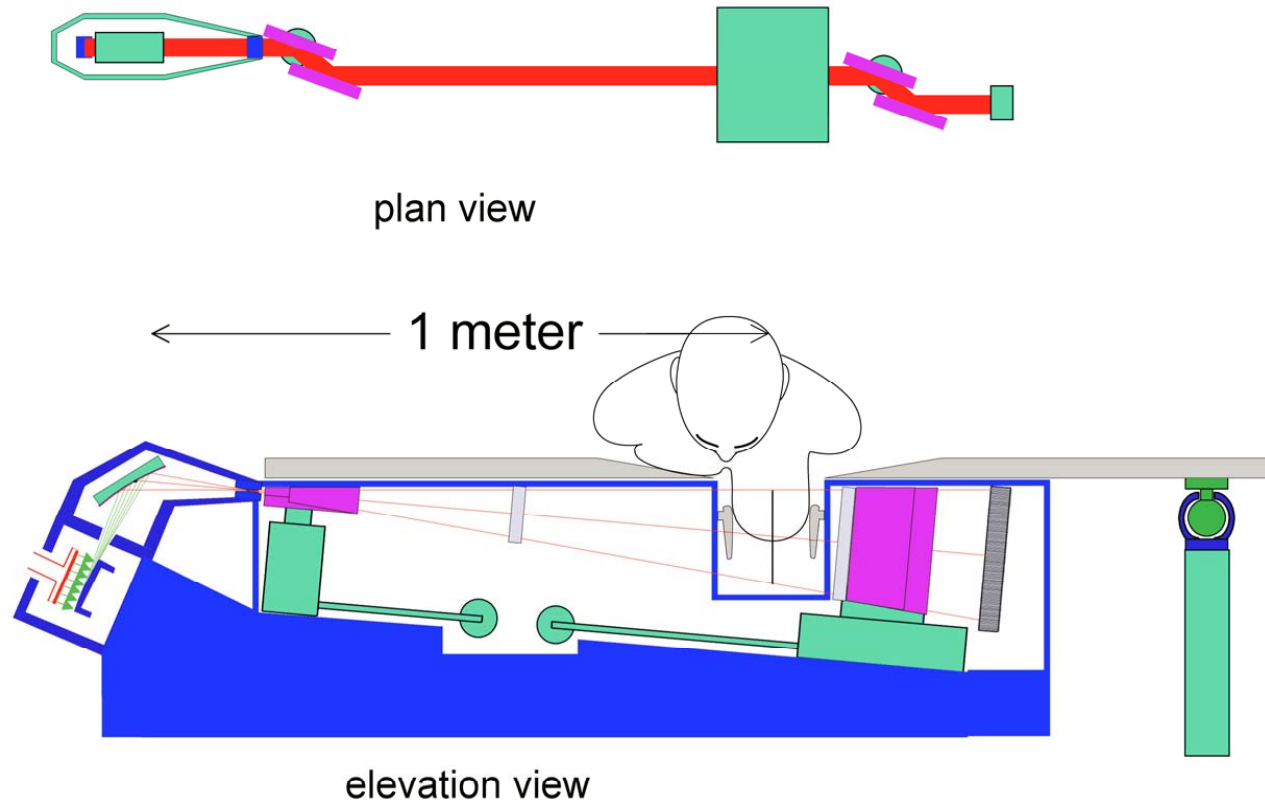
Image of the brain of a 9 year old female with a history of seizures poorly controlled by medication. PET imaging identifies the area (indicated by the arrows) of the brain responsible for the seizures. Through surgical removal of this area of the brain, the patient is rendered "seizure-free".

Diffraction Enhanced Imaging

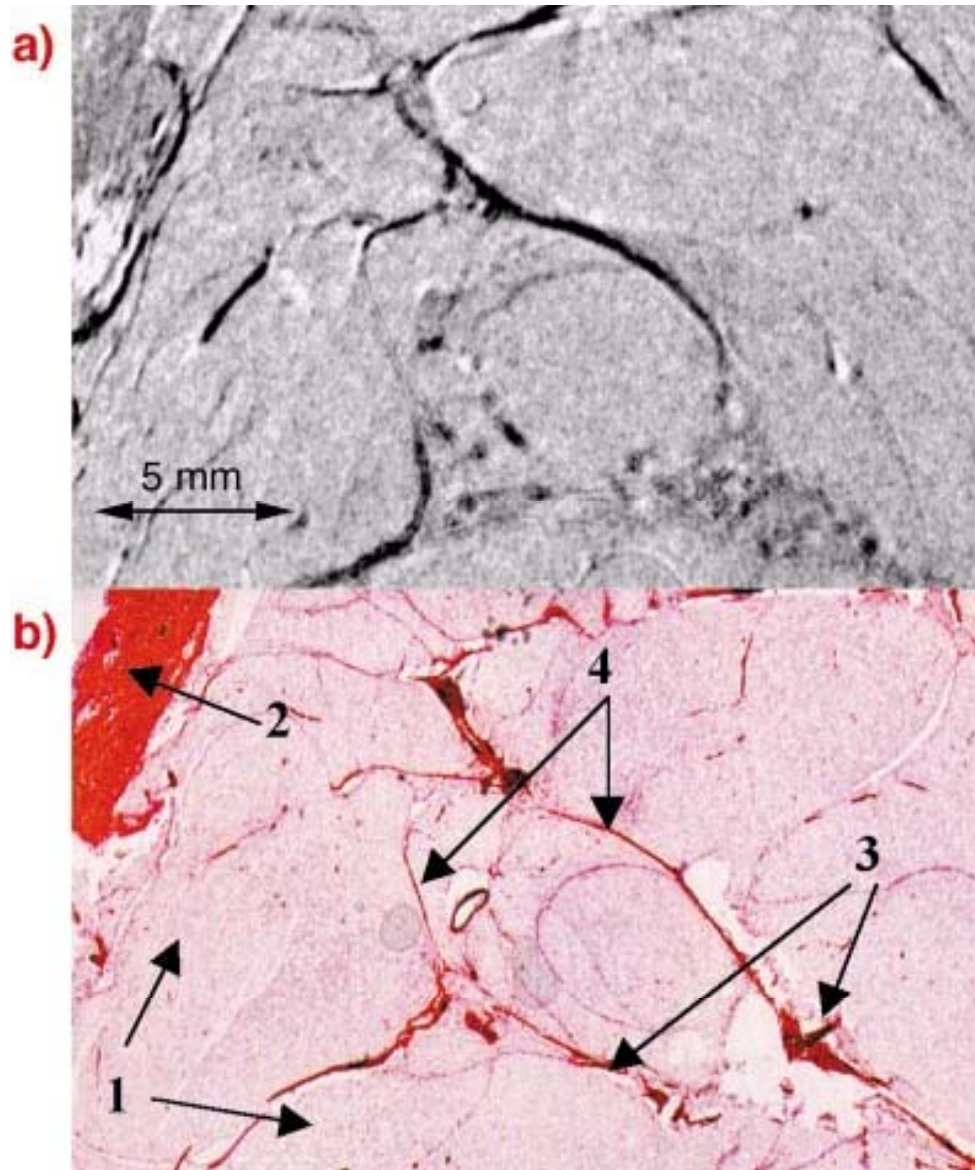


Schematic indicating diffraction geometry terms.
(Dean Chapman)

Integrated DEI system for mammography

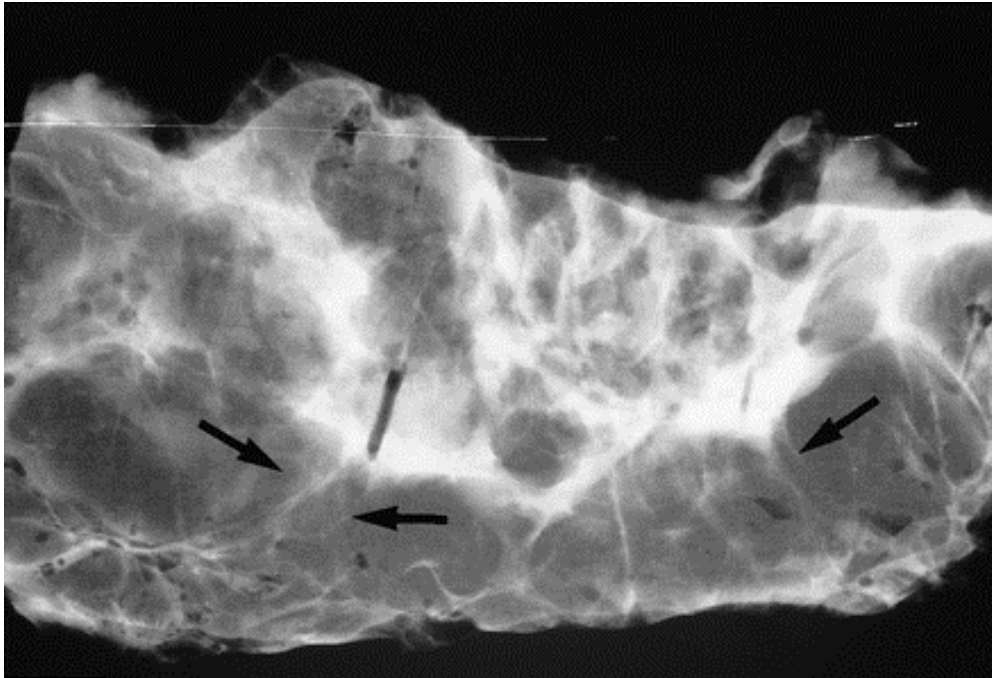


Integrated DEI system for mammography. Note that the patient lies prone and that two views of the breast are obtained by rotating the table so that the beam traverses the breast in different directions. Scans of the breast are made by moving the beam and detector together using a time-delay integration scheme.



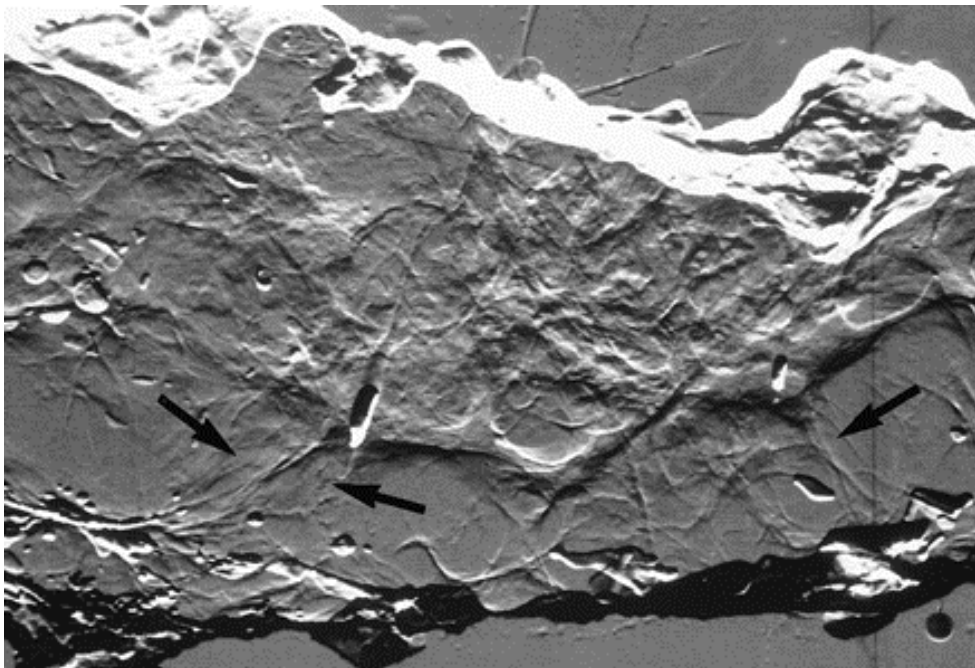
DEI-CT image of cancerous breast tissue showing excellent correspondence with the histological section b) taken at the same position. Arrows 1 indicate adipose tissue, arrow 2 skin and muscular tissue, arrows 3 cancer cells embedded in collagen, and arrows 4 collagen strands.

(<http://www.esrf.fr/UsersAndScience/Experiments/Imaging/ID17/dei/>)



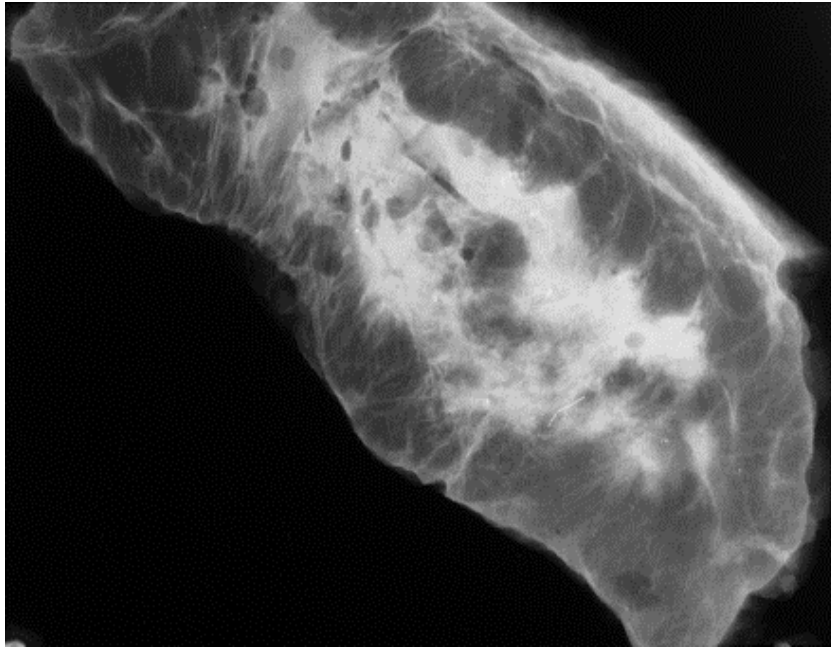
Digital radiography
image

Specimen with
invasive lobular
carcinoma

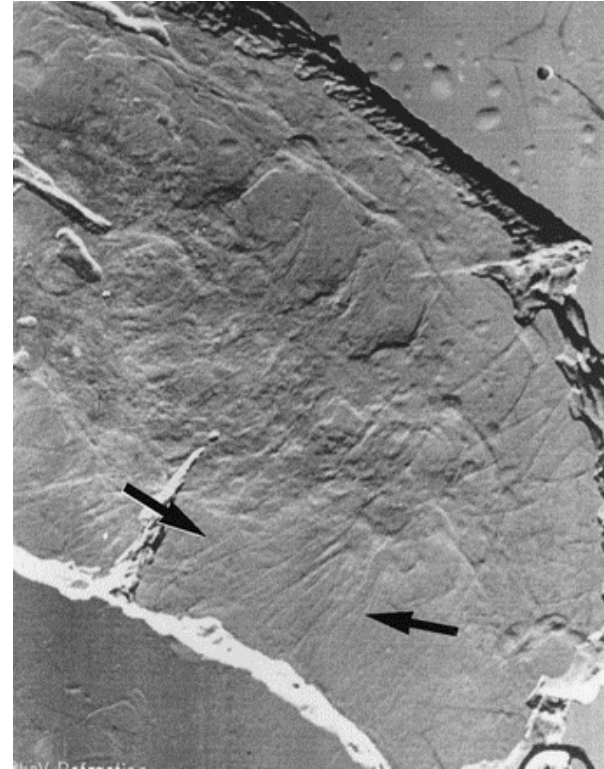


DEI image

[Pisano et al.,
Radiology 414(3),
895-901, 2000].



Digital radiography image



DEI image

**Specimen of infiltrating ductal cancer
[Pisano et al., Radiology 414(3), 895-901,
2000]**

Radiation Therapy

- **Major Use:**
- Cancer therapy typically using beams of gamma rays, electrons or protons to irradiate the tumor
- **Brachytherapy:**
- Radiation sources implanted within the tumor, e.g. prostate and cervical cancer.

Neutron Boron capture Therapy:

- Incorporates Boron-10 labeled compound into tumor, irradiate the tumor with low-energy neutrons produce He-4 and Li-7 depositing up to 2.78MeV in the tumor cell.