Applied Physics Primer: Structure of the course

Structure of the course

Programma:

1. Panoramica applicazioni fisica delle radiazioni
2. interazione radiazione materia: ionizzazione, effetto foto-elettrico, effetto compton
3. decadimenti radiattivi (beta, gamma e alpha)
4. reazioni nucleari
5. fisica dei neutroni
6. elementi di dosimetria
7. fondamenti di fisica degli acceleratori: focheggiamento, stabilita' di fase, ciclotroni, linac e sincrotroni

Esame finale

- Discussione di una tesina di fisica applicata
  - Tema concordato precedentemente
  - Interrogazione porta a qualunque argomento del programma
- Domanda su tema del programma non toccato dalla tesina

In itinere

- Pagina web del corso:

http://elearning2.uniroma1.it/course/view.php?id=2091

- Divisione in gruppi per esercitazioni. Segnarsi in https://docs.google.com/forms/d/e/1FAIpQLSdfsIyFrkq6tEsXQVHrBu2Aveo9DvdRJZhpf6M-rvr87YD1sw/viewform

Test di comprensione

Effettuati con Kahoot!

https://kahoot.it/

Oppure scaricate l'app prima della prossima lezione

Si useranno anche quiz in https://tinyurl.com/QuizFisApp

Materiale

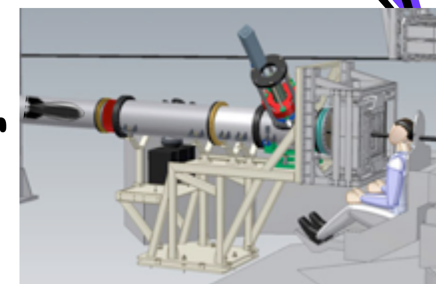
- Dispense ancora in via di sviluppo
  - Prima versione presente sull'e-learning del sito
- Ampia bibliografia e sitografia sull'e-learning

Medical Applications of radiation physics

Elementary particles and Medical Applications

Basic concept:

- ➔ "Inject" radiactive material or particles inside the patient



If the particle "escapes" the patient

- ➔ Diagnostics: SPECT, PET, Radioguided surgery

If the particle interacts inside the patient

- ➔ Radiotherapy: RT, Radio Methabolic Therapy, Brachitherapy, Hadrotherapy

Nuclear decays of interest

Gamma rays:
escape patient, interact outside it extracting electrons

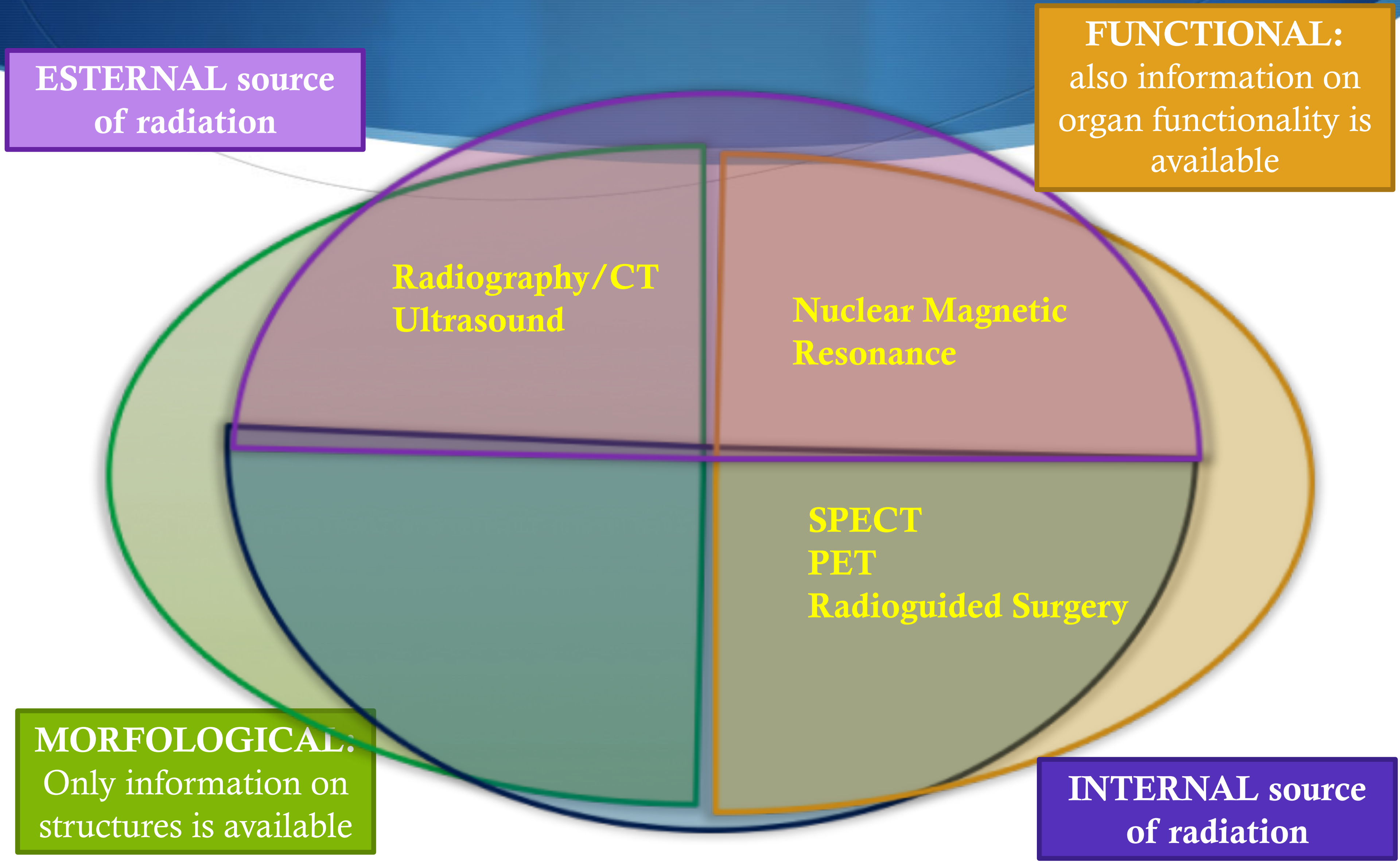
beta+ decays: positrons annihilate with e- and produce 2 photons that escape patient and interact outside

Beta- decays: electrons do not escape patient

Alpha decays: like electrons but even shorter path

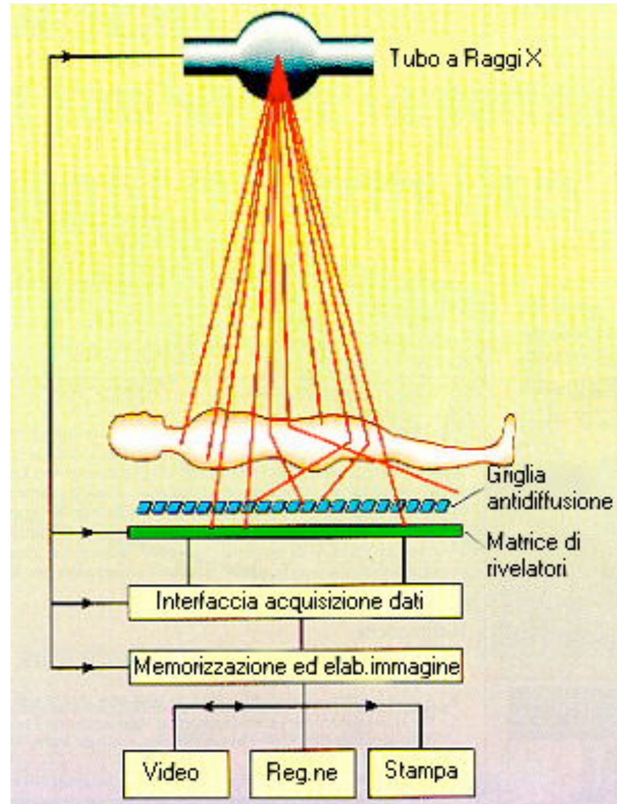
Diagnostics and therapy

DIAGNOSTICS



Diagnostics: radiography

- X-rays produced with a cathodic tube by Bremsstrahlung
- Interaction between matter and patient
- X-ray detection

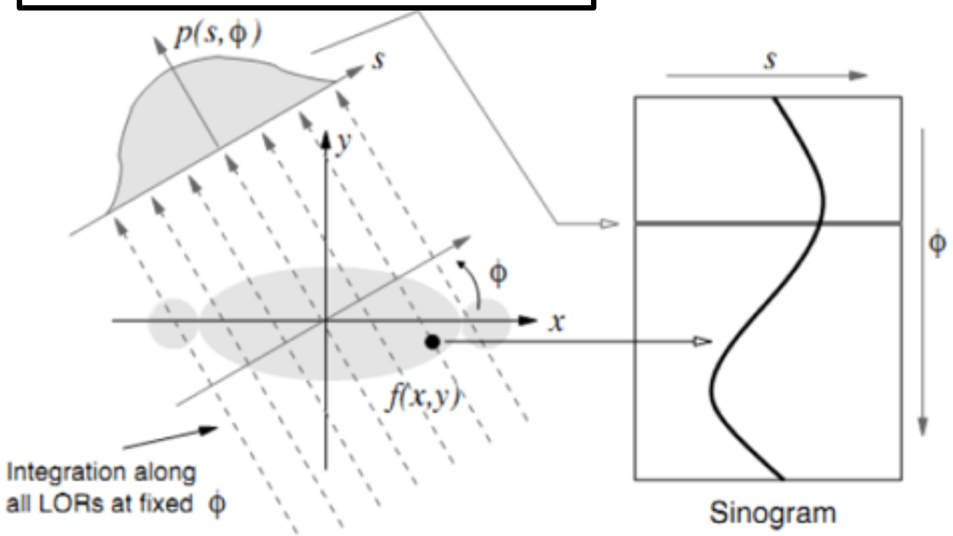


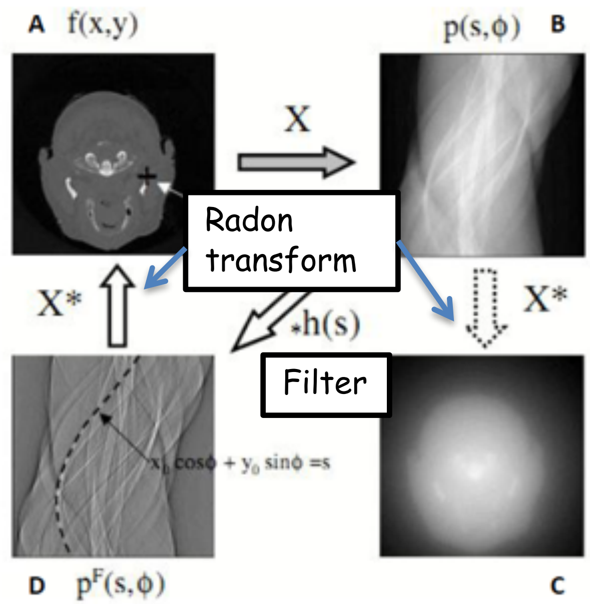
X-rays

Diagnostics: Tomography

- Generic mathematical tool from 1D → 2D
- CT with X-rays is most renown

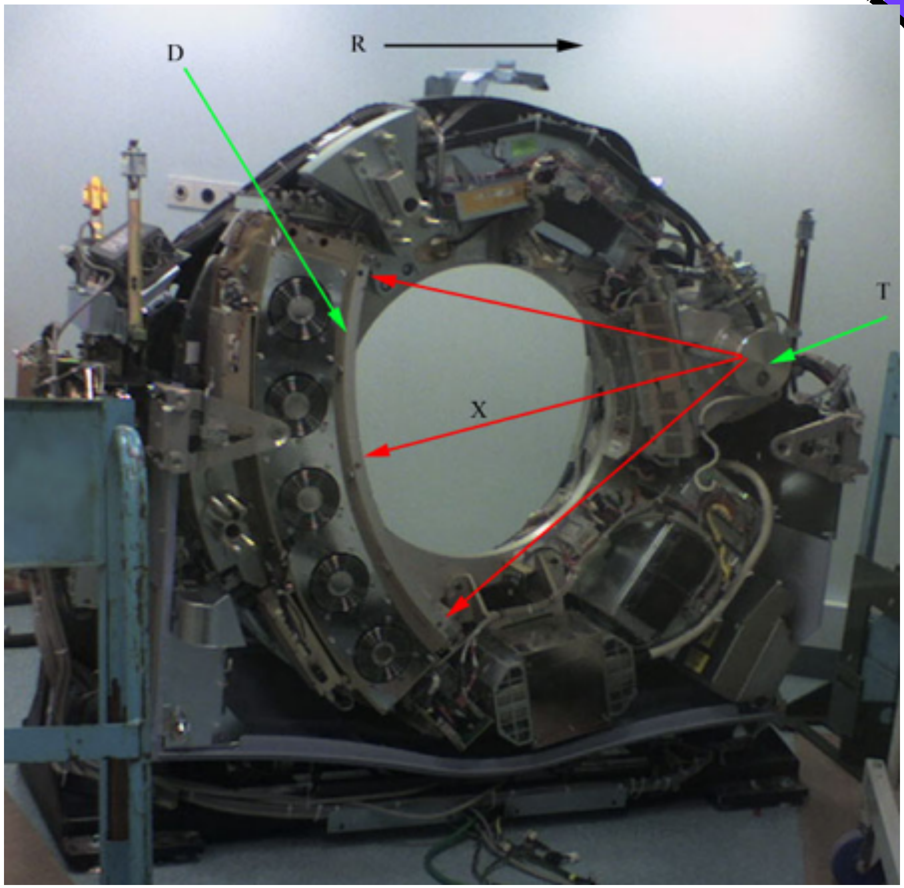
From image to sinogram





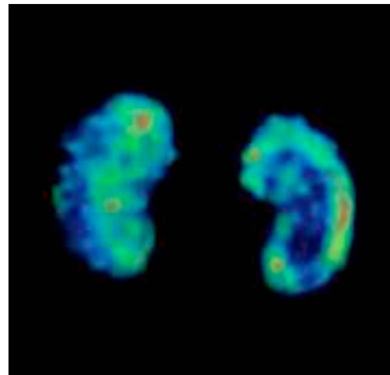
CT Scanner

- T= X-ray tube
- X= X-rays
- D= detector
- R=gantry rotation



Diagnostics: SPECT

Single Photon Emission Computerized Tomography

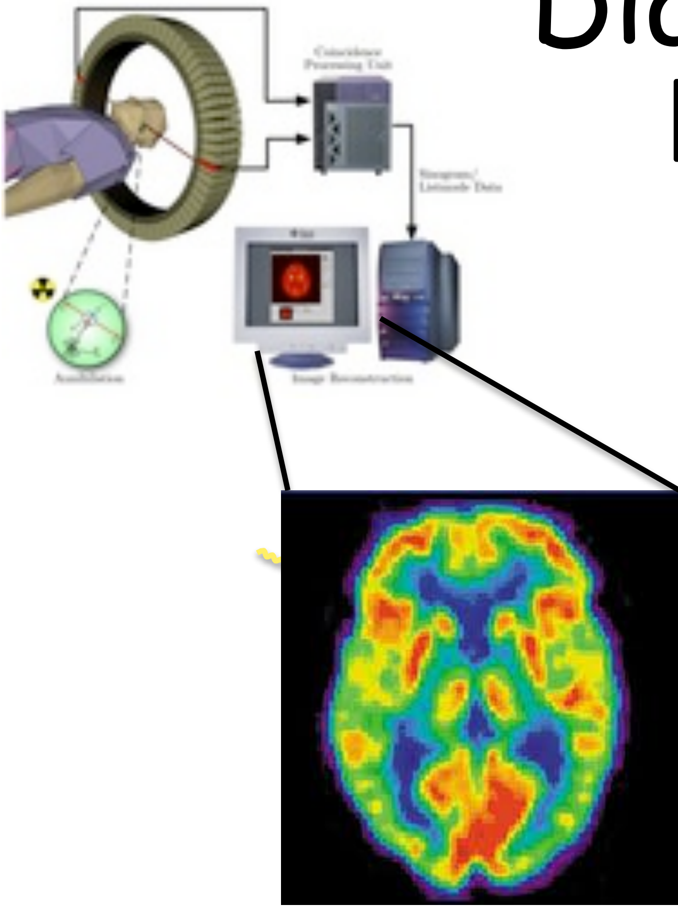


- Inject radionuclide (typically ^{99}Tc but also ^{131}I)
- Decays with single photon
- Detection ~50cm from source with anger camera

Gamma decays

Diagnostics: PET

Positron Emission Tomography



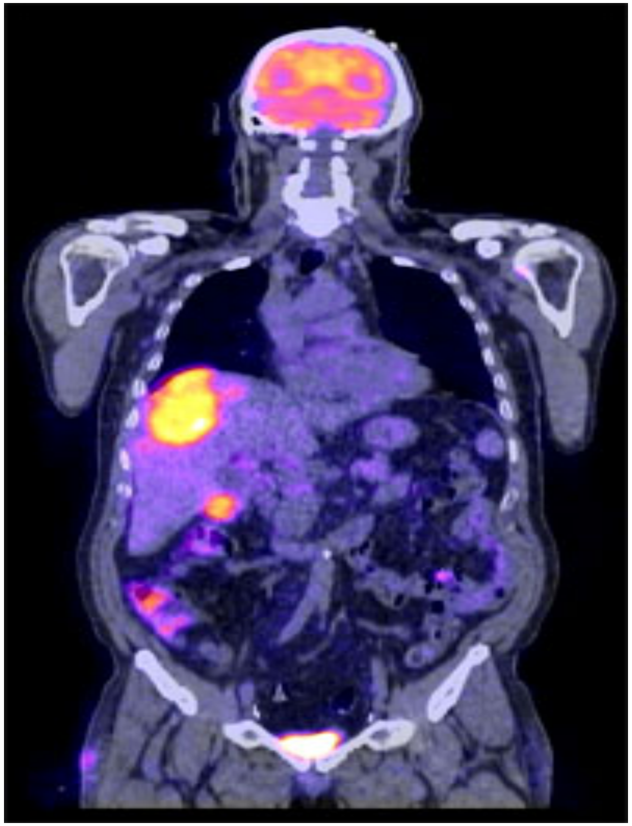
- Inject radionuclide (^{18}F in FDG, FET, 11C in methionine, choline)
- β+ decay
- Detect the two gammas in coincidence outside patient

Beta+ decays

PET: Uses

- Detect cancer.
- Determine whether a cancer has spread in the body.
- Assess the effectiveness of a treatment plan, such as cancer therapy.
- Determine if a cancer has returned after treatment.
- Determine blood flow to the heart muscle.
- Determine the effects of a heart attack, or myocardial infarction, on areas of the heart.
- Identify areas of the heart muscle that would benefit from a procedure such as angioplasty or coronary artery bypass surgery (in combination with a myocardial perfusion scan).
- Evaluate brain abnormalities, such as tumors, memory disorders and seizures and other central nervous system disorders.
- To map normal human brain and heart function.

PET/CT FUSION



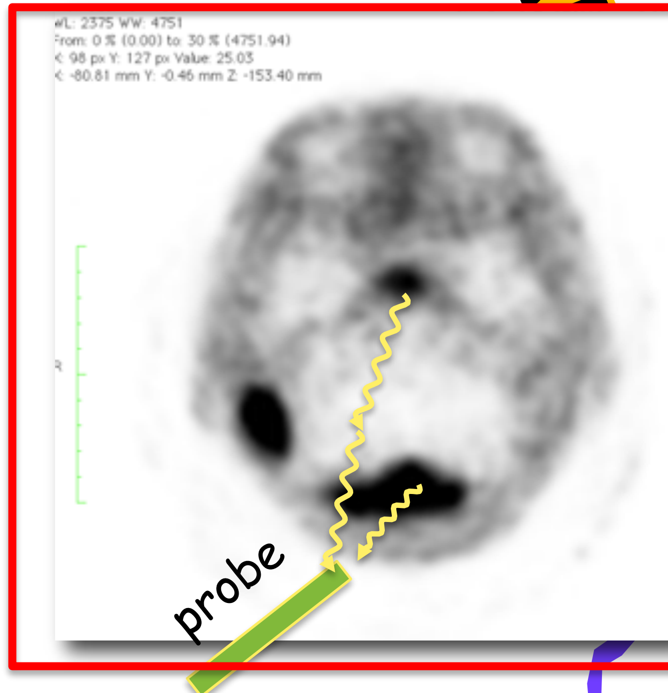
Radio-guided surgery

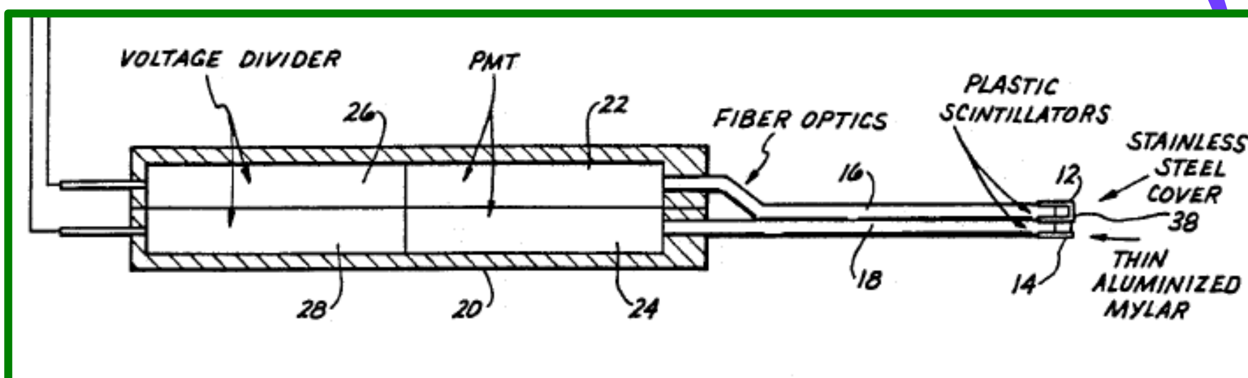
- Administer, before operation to patient (either systemically or locally) a drug which:
  - the tumor takes up significantly more than the healthy tissue.
  - is linked to a radio-nuclide that emits particles via nuclear decay
- Wait for the drug to diffuse to the margins of the tumor
- Start operation
  - Remove the bulk of the tumor
  - Verify with a probe that detects the emitted particles the presence of:
    - Residuals
    - Infected lymph nodes

Radioguided surgery

Three approaches

- Gamma: well established, e.g. sentinel lymph-node
- Beta+: based on the dual probe approach
- Beta-: future fronteer





Radio Isotope Production

- Hadronic collisions
  - $p + X \rightarrow Y + B$
  - $n + X \rightarrow Y + C$
  - ➔ Accelerators/reactors required

Physics Building Blocks of Diagnostics

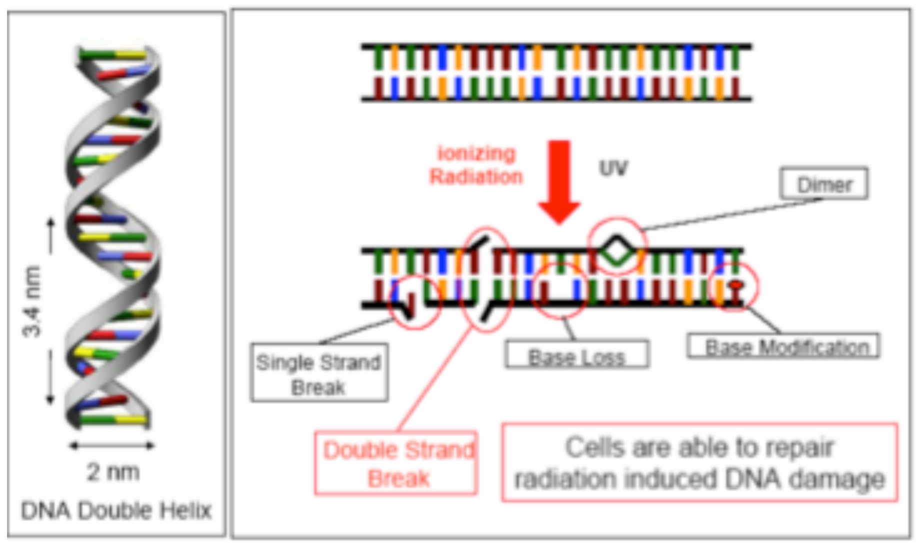
- Nuclear decays
- Production of radiation source:
  - X rays
  - Radio-nuclides → nuclear reactions/accelerators
- Dosimetry
- Detectors for photons and electrons

Radiotherapy

From conventional to Hadrotherapy

Radiotherapy

- Goal:
  - Deliver energy on tumor cells in order to break them in an irreparable way

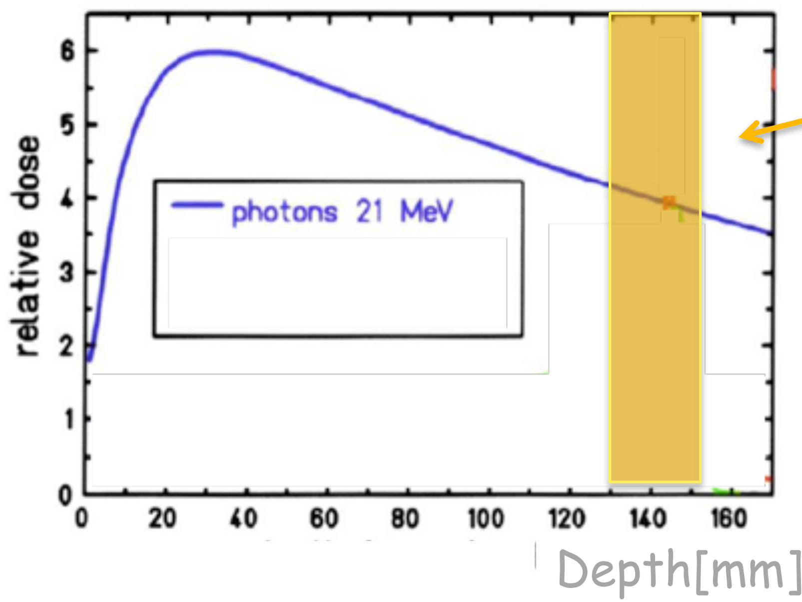


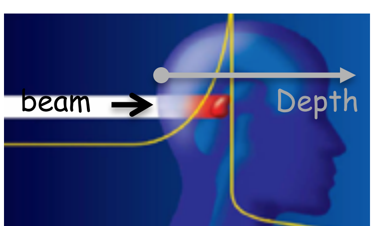
- Mean:
  - passage of particles through matter

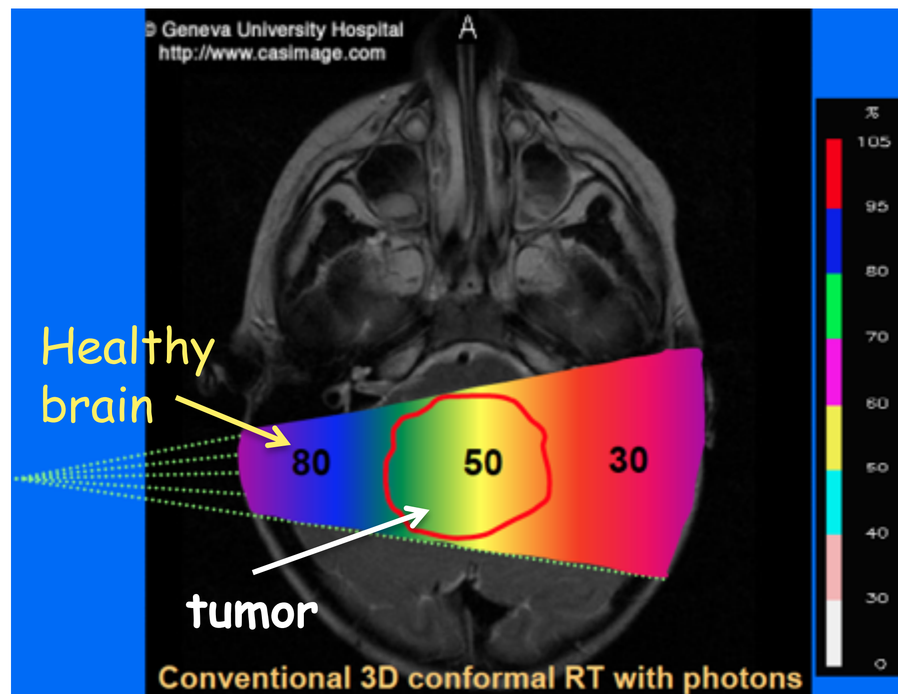
Conventional radiotherapy

Photon beams on patient

Large release of energy outside tumor

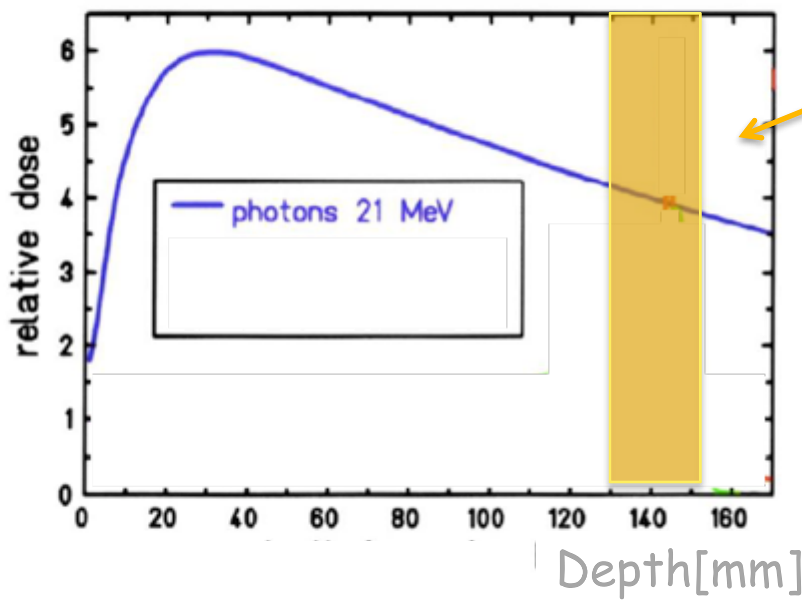


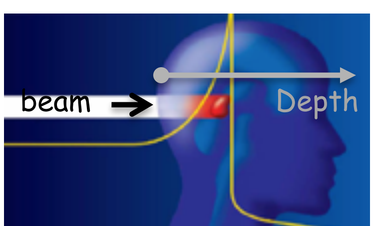




Conventional radiotherapy

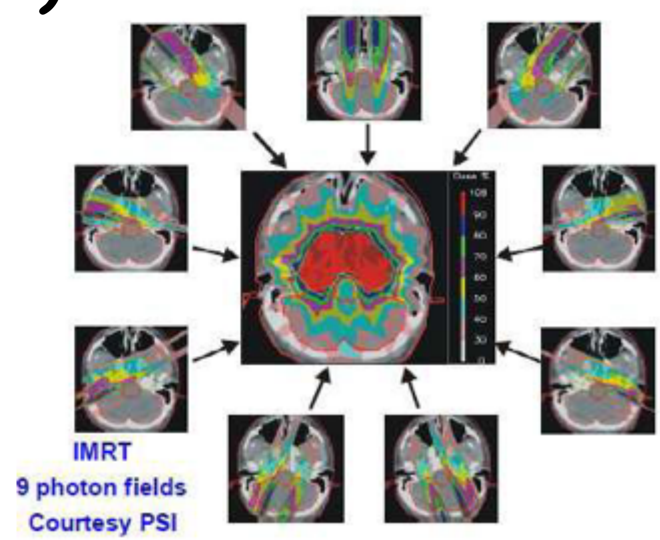
Photon beams on patient





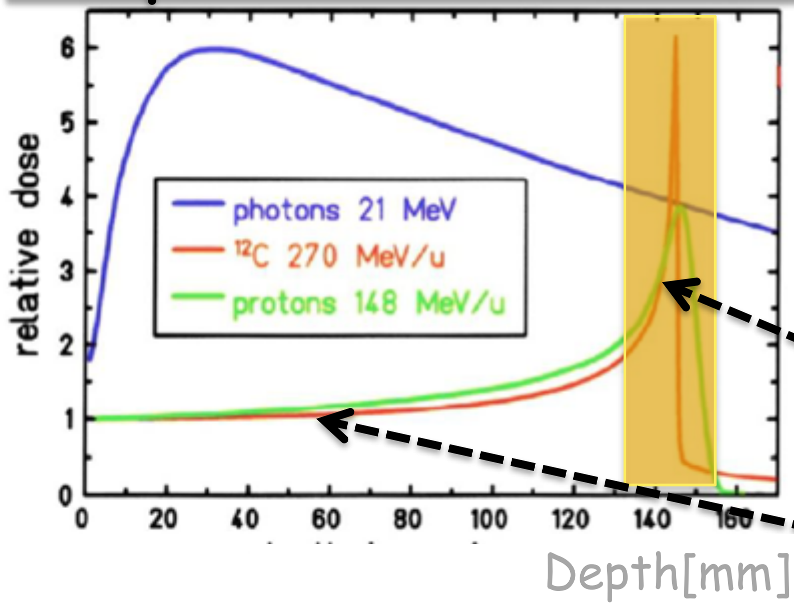
Large release of energy outside tumor

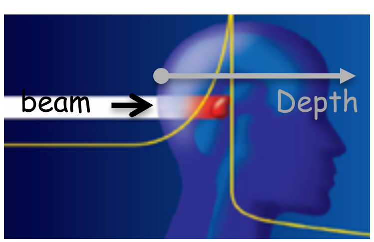
- Multiple beams each of smaller energy (IMRT)



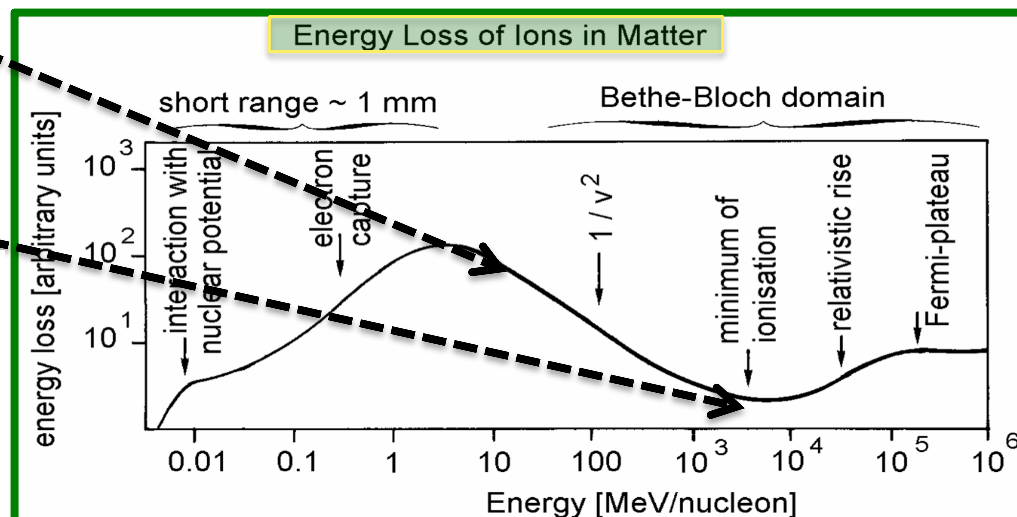
Hadrontherapy

Proton/ion beams on patient



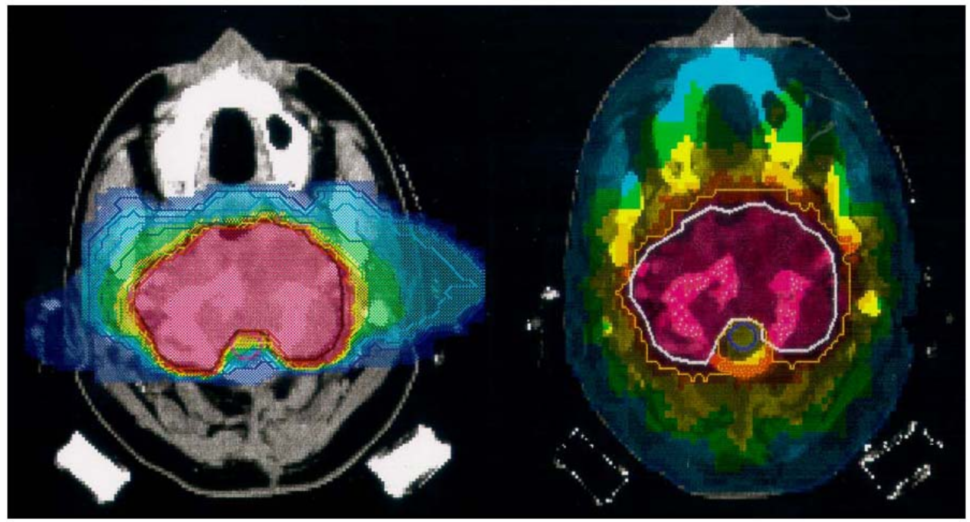


Concentrate release of energy inside tumor due to release of energy in ionization.



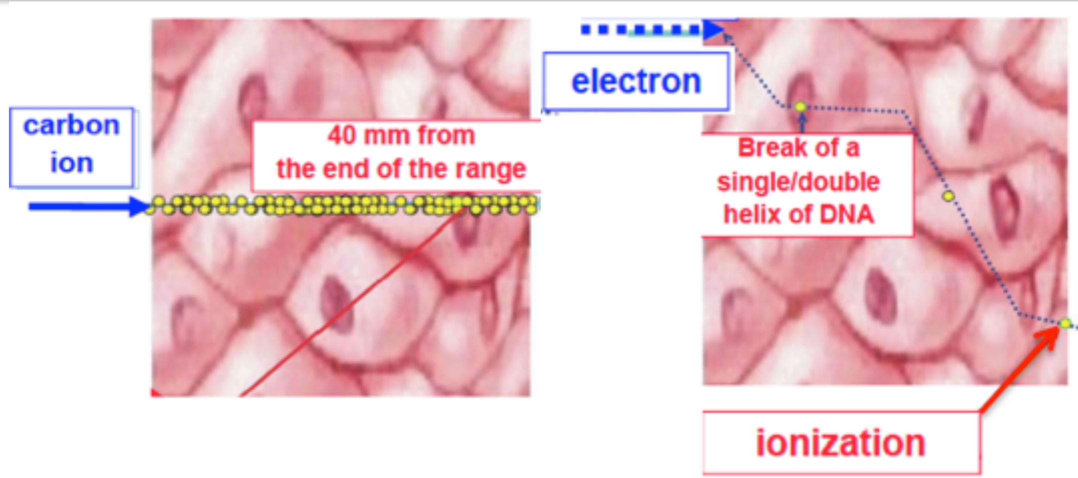
Comparison ^{12}C vs IMRT

Better confinement of energy release



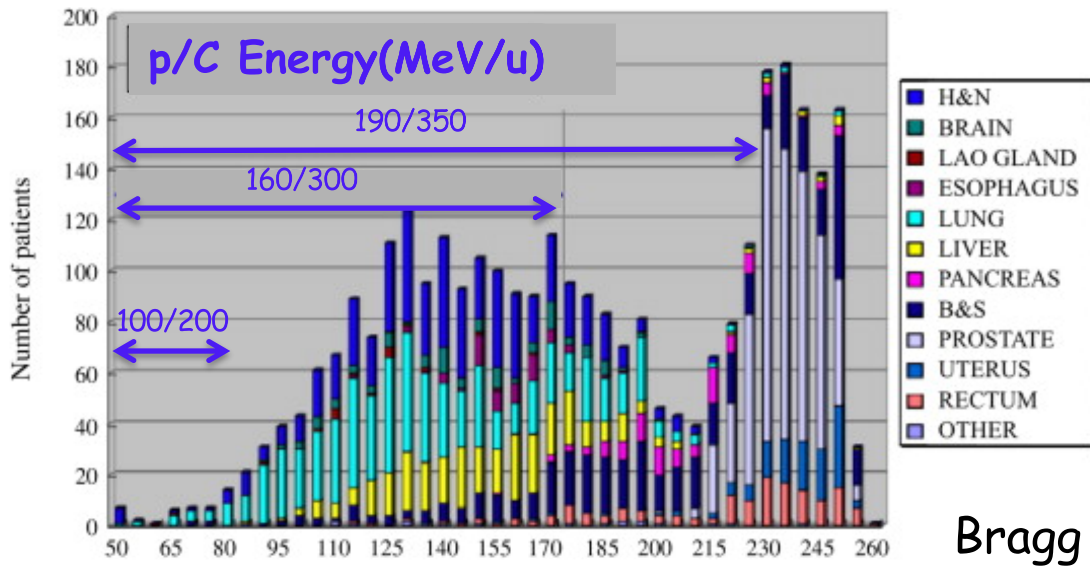
C-12, 2 fields IMRT, 9 fields

More effectiveness in killing cells



Accelerators

Required proton/Carbon energy



Bragg Peak depth (mm)

Proton Kinetic Energy between 100-250 MeV
Carbon Kinetic Energy between 200-400 MeV/u

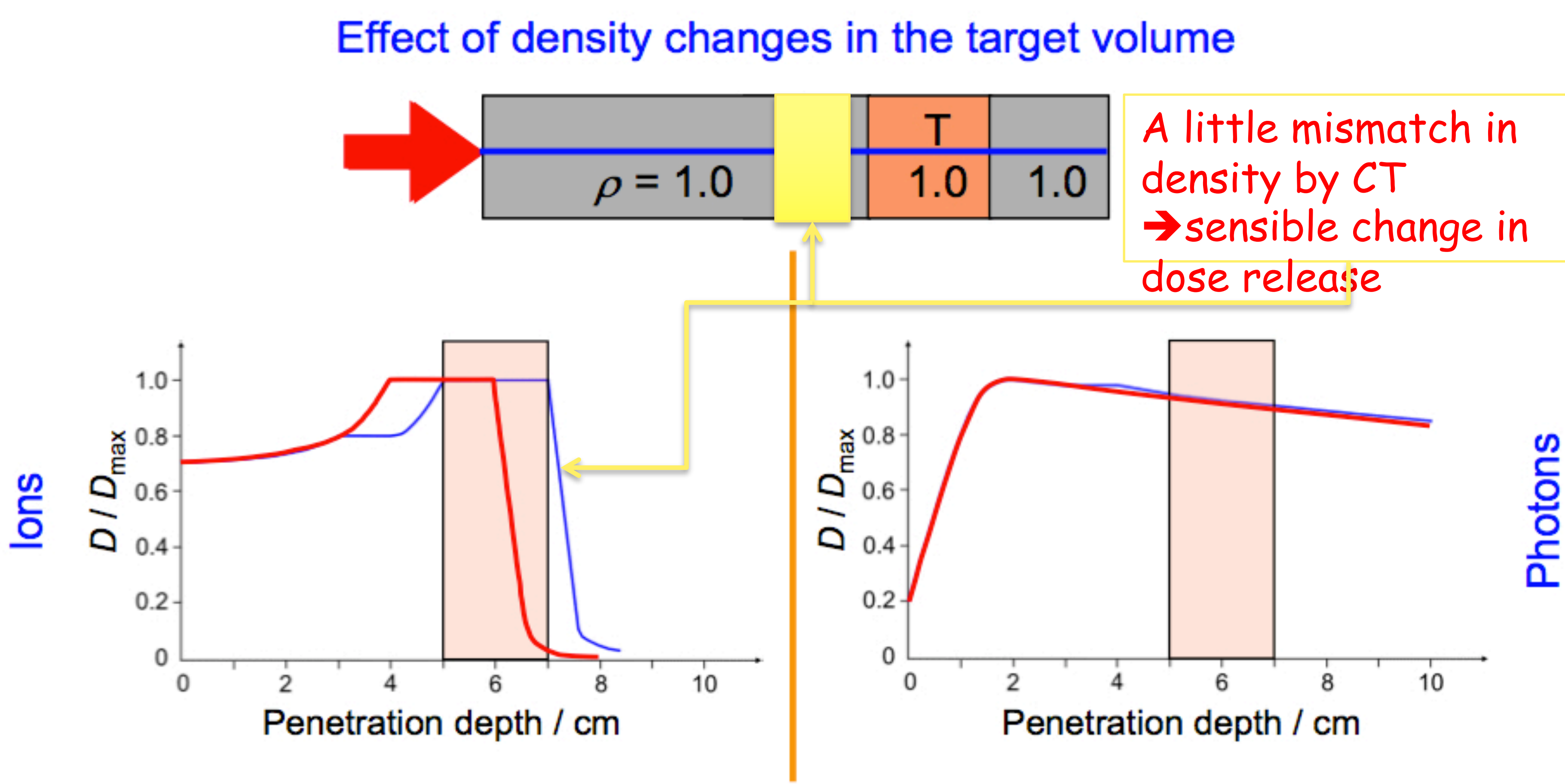
Present of hadrotherapy

HT: accelerators

- Cyclotrons: past, mostly for low energy applications (e.g. ocular tumors)→ today up to 250 MeV/u
- Syncrotrons: present → cover also carbon-therapy
- Future applications: CYCLINACS, proton LINACS, …

HT:Monitoring the dose

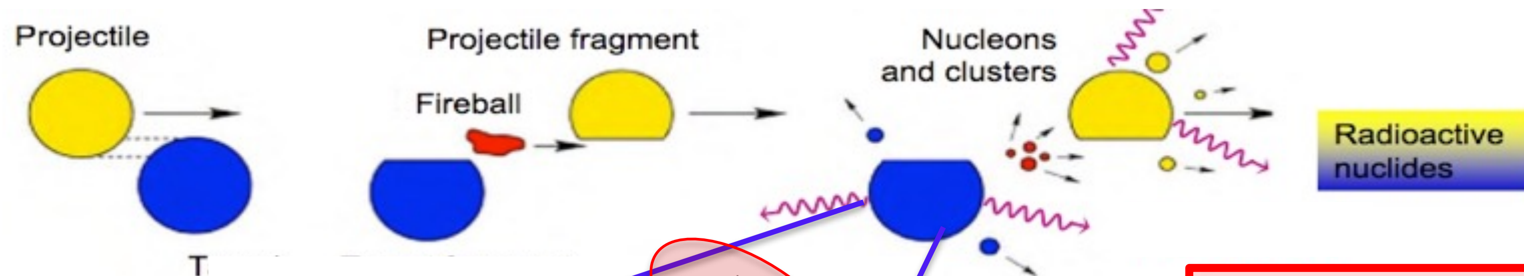
- Why is so crucial to monitor the dose in hadrontherapy ? Is like firing with machine-gun or using a precision rifle..



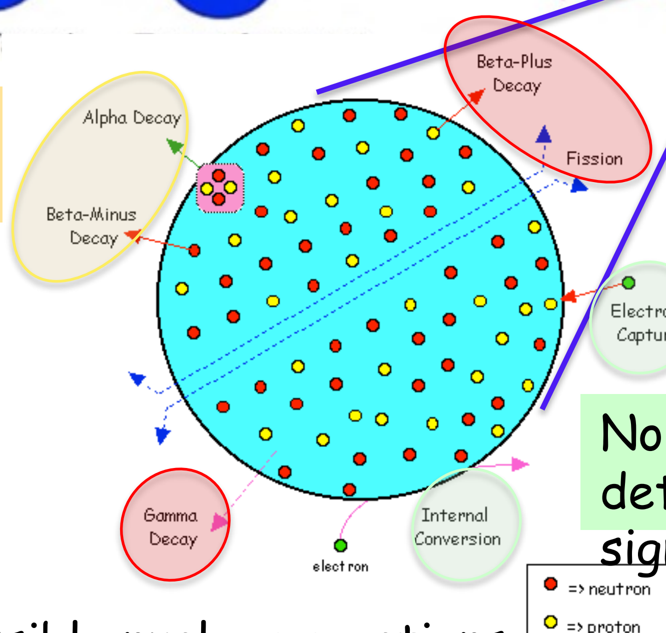
A little mismatch in density by CT ➔sensible change in dose release

Measuring the dose

Based on nuclear reactions between the projectile and the patient



Don't exit patient



Possible nuclear reactions

No detectable signal

Reactions of interest

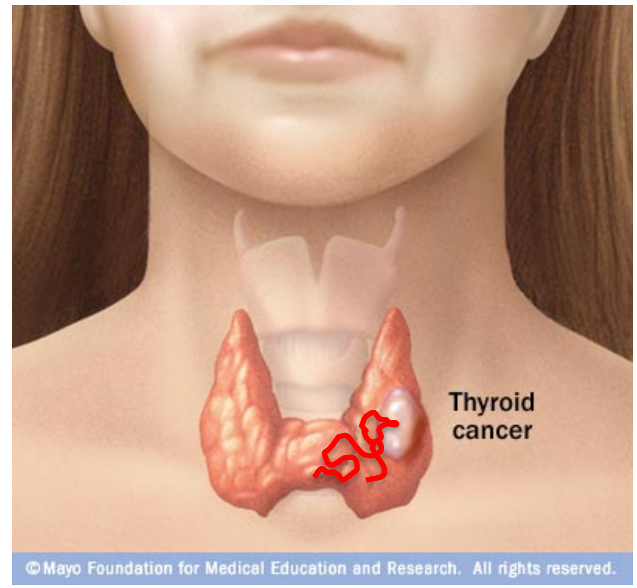
- β+ decays
- Prompt γ
- Charged products

Physics of Hadron Therapy

- Interaction between radiation and matter
  - Ionization
  - Bragg peak (how is it measured?)
- Particle accelerators
  - Cyclotrons, synchrotrons and LINACS
- Nuclear decays for dosimetry:
  - de-excitations, beta+ and fragmentation
- Detectors for photons, positrons and charged particles

radiomethabolic/Brachitherapy

- Inject/ position radionuclide (e.g. 131I)
- Beta- decays
- Electrons release energy in tumor locally



Beta- decays

Theragnostics

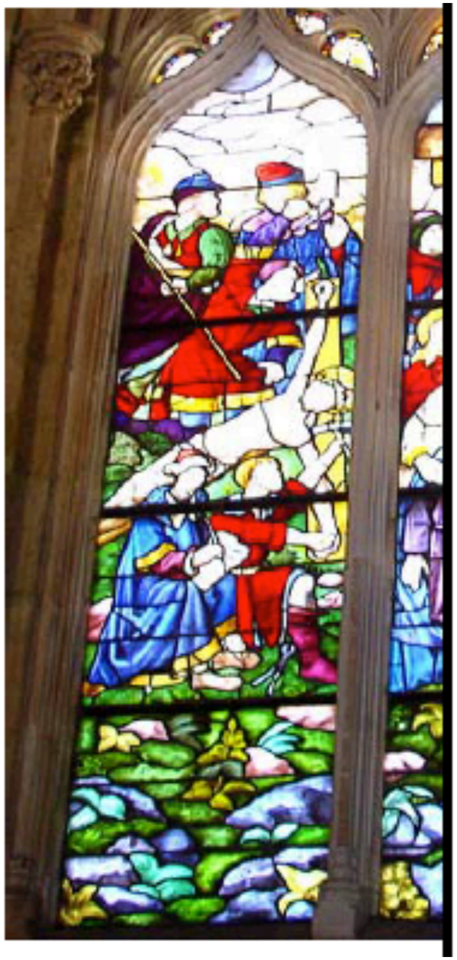
- Find radio-tracers that can couple imaging with therapeutics
  - Same drug → 177Lu
  - Similar drugs
    - 90Y
    - 68Ga

CULTURAL HERITAGE

Applications: jewelery

- Composition (gold, silver, copper, alloys…)
- Corrosion state
- Surface composition according with the surrounding environment where they were found
- Classification of the objects according the date/composition:
  - provenance (mines, workshops) identification,
  - counterfeits selection,
  - historical studies (manufacturing technologies, commercial, etc)

Applications: glasses

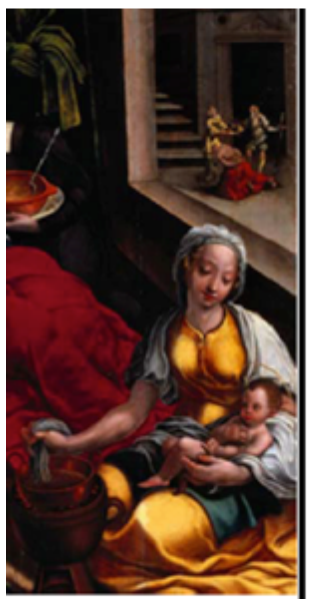


- Glass and pigments composition (Na, K, Fe, Cu, Pb…)
- Surface composition according with the surrounding environment (i.e. Humidity)
- Classification of the objects according the date/composition:
  - counterfeits selection,
  - historical studies

Applications

CERAMICS/SCULPTURES

- Pigments composition,
- Surface composition according with the manufacture techniques
- Classification of the objects according the date/composition:
  - restoration,
  - Conservation processes



- Surface composition for a better and adequate rehabilitation/restoration:
  - organic / inorganic materials
  - varnish composition / thickness
- Actual pigments composition
- Homogeneity
- Study the deterioration according with the pigments

PAINTINGS

CULTURAL HERITAGE

Neutron beams

- Neutron Beams
  - Elemental analysis
  - Tomography

Long Accelerators

- Ion Beams
  - Emissions: X and γ
  - Scattering: elastic and inelastic

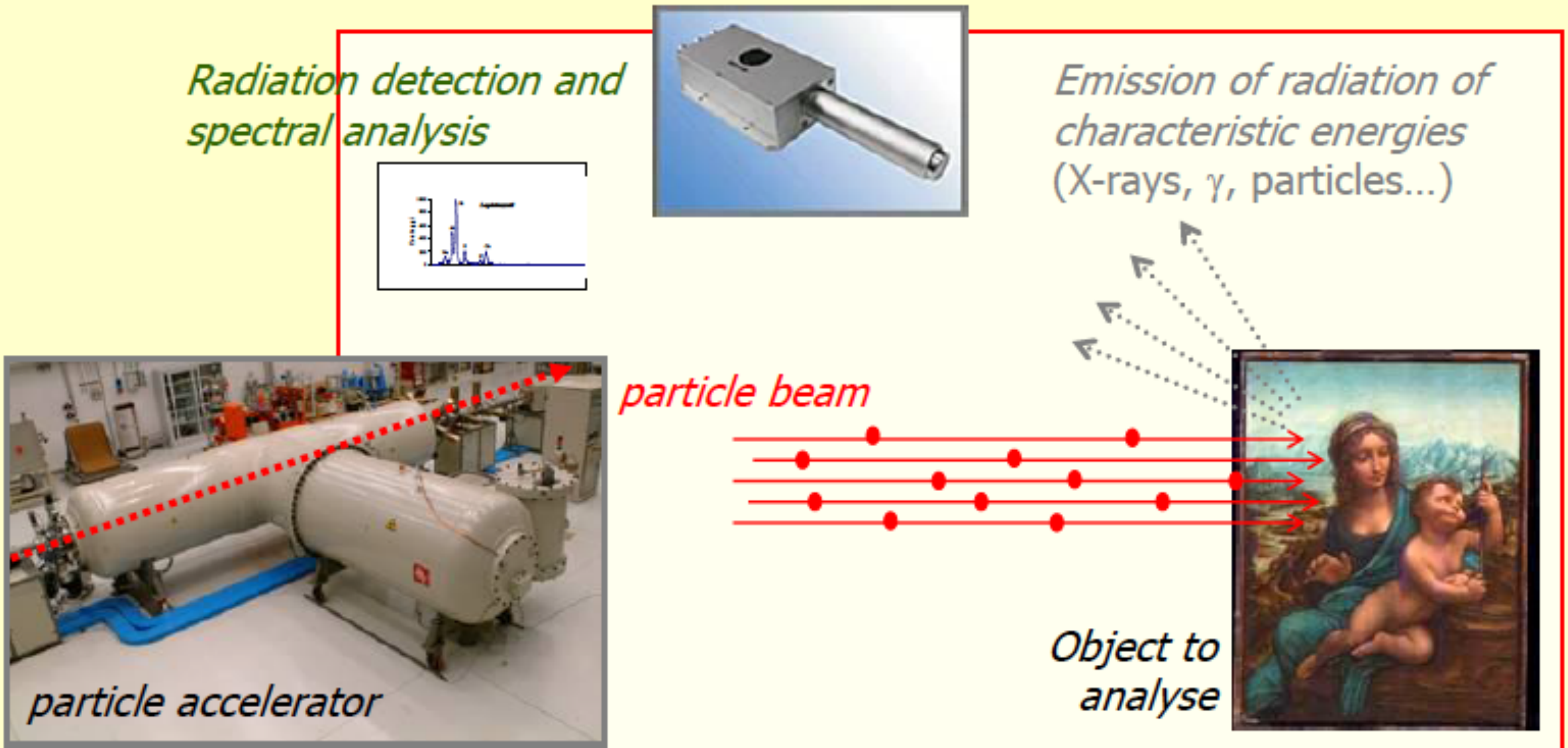
Portable Accelerators

- X ray Fluorescence
- ^{14}C dating

Internal Source

Ion Beam Analysis (IBA)

- Material composition analysis through beam particle bombardment
  - typically proton or alpha beams at some MeV energy



IBA SETUP

Lower energies wrt medical applications

Proton Induced X-ray emission

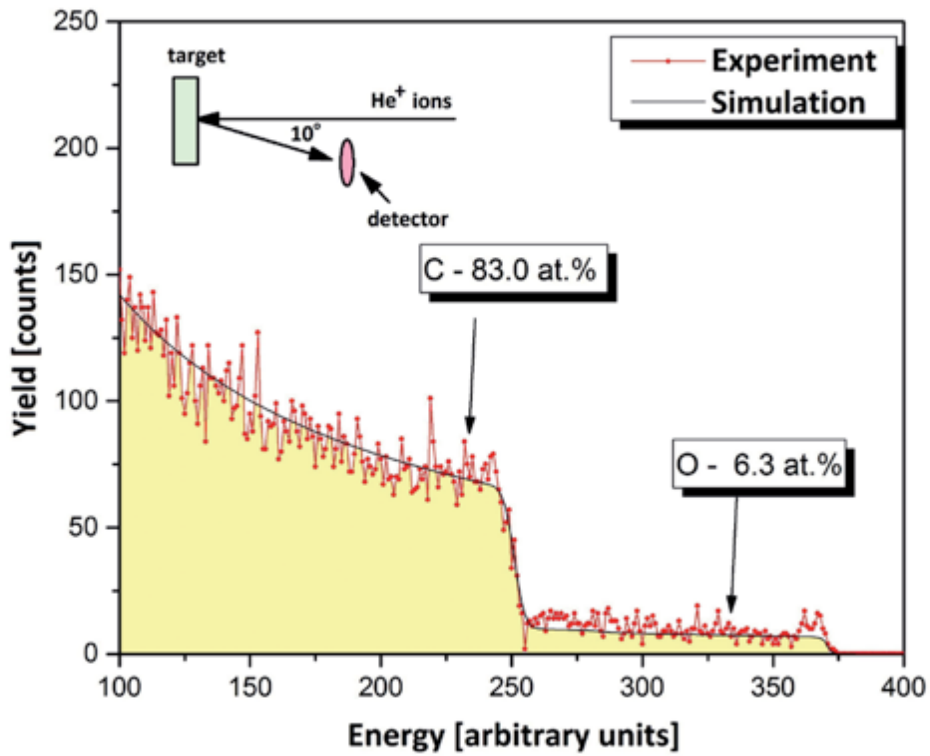
Depth profiling of atomic composition

Works for Z>=14

↓

Use gamma emission (PIGE) for lighter elements

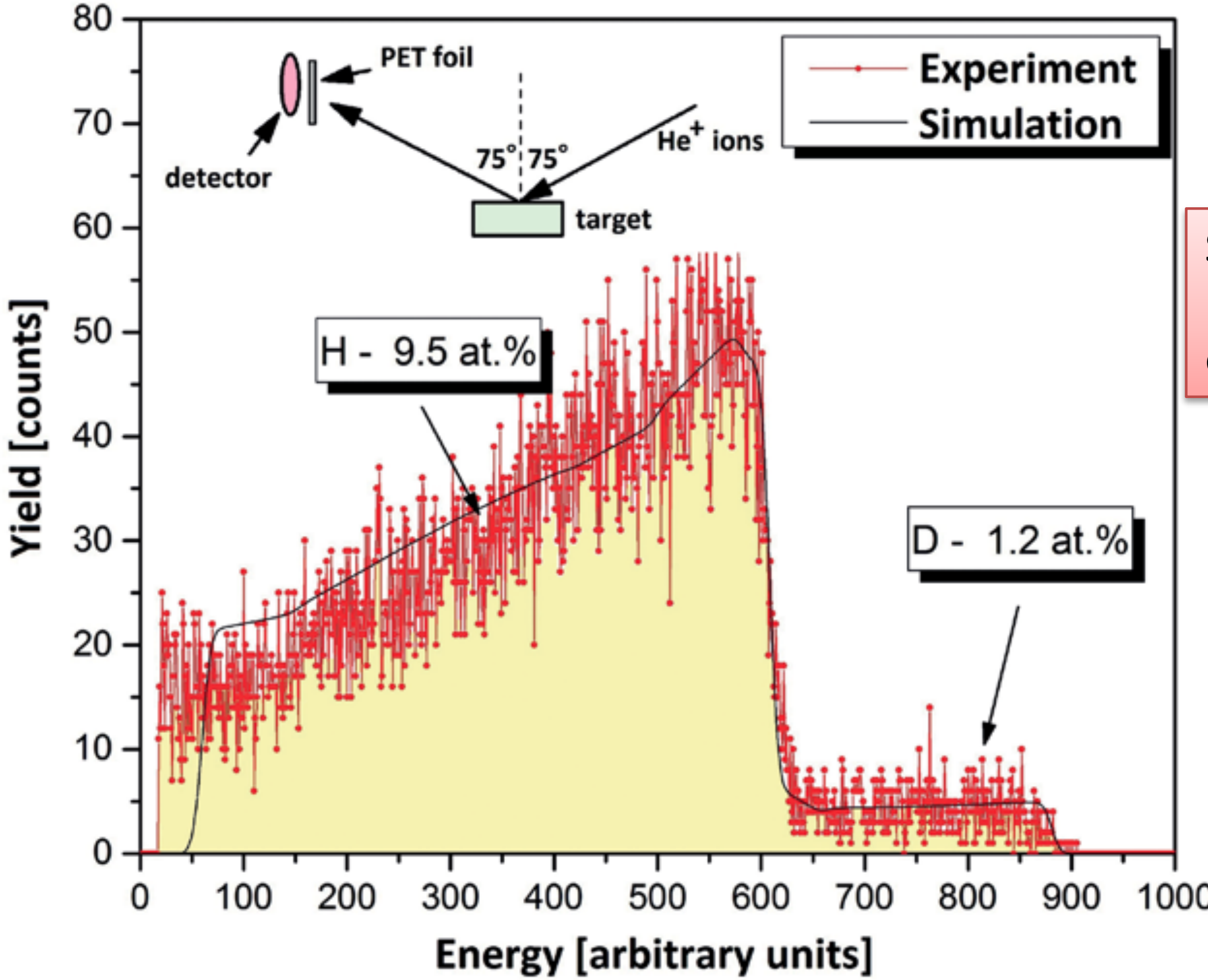
Rutherford Backscattering Spectroscopy



Used for thin films

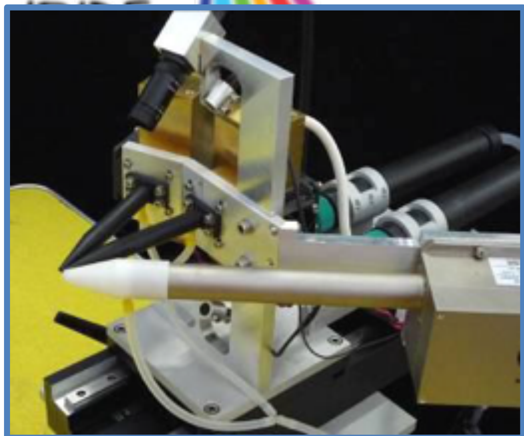
Heavier Nuclei preferred

Elastic Recoil Detection Analysis (ERDA)



Suited for light elements

X-Ray Fluorescence (XRF)

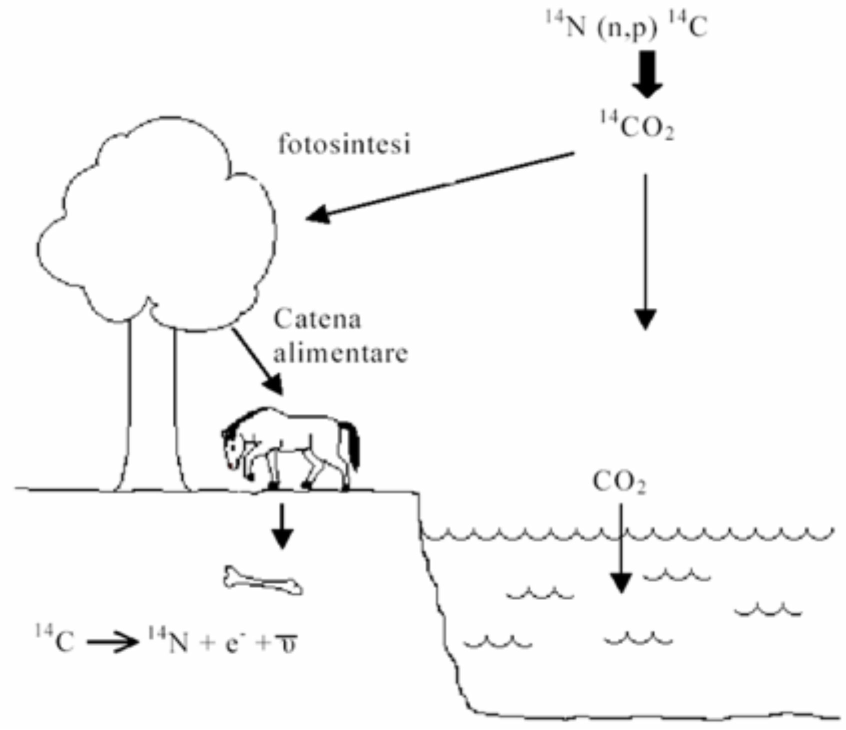


Use X-Rays instead of protons for atomic excitation

Portable apparatus

Not for light elements

^{14}C dating



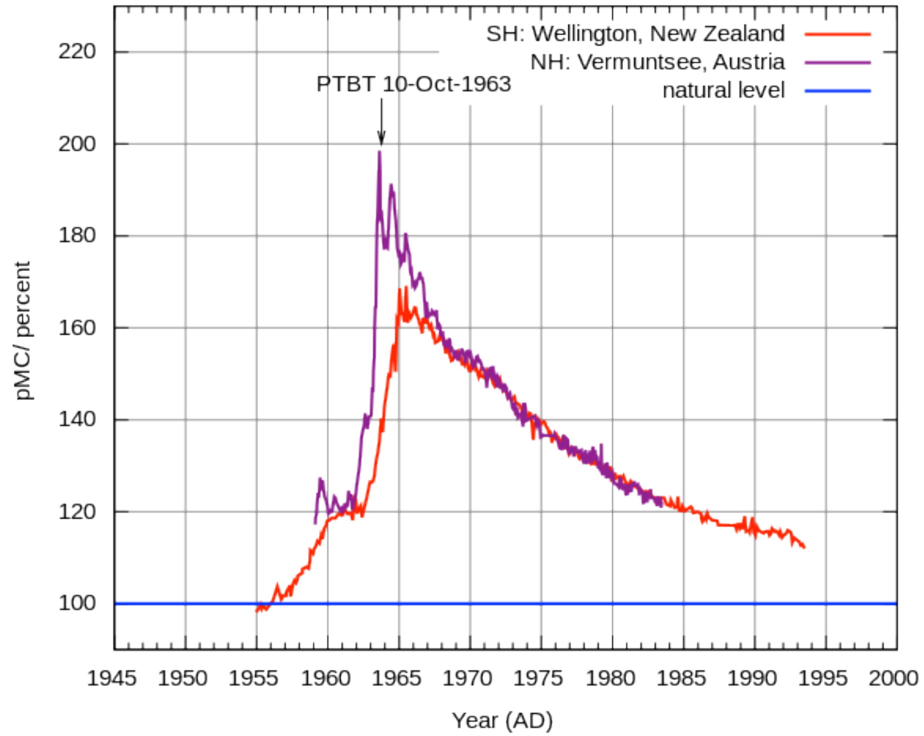
Concept: until a living organism is in equilibrium with ambient, ^{14}C rate is fixed (~10^{-12}).

Then it decays with τ~8000yr.

Archeological applications

14C in Nuclear Age

Enhancement of 14C rate due to nuclear weapons

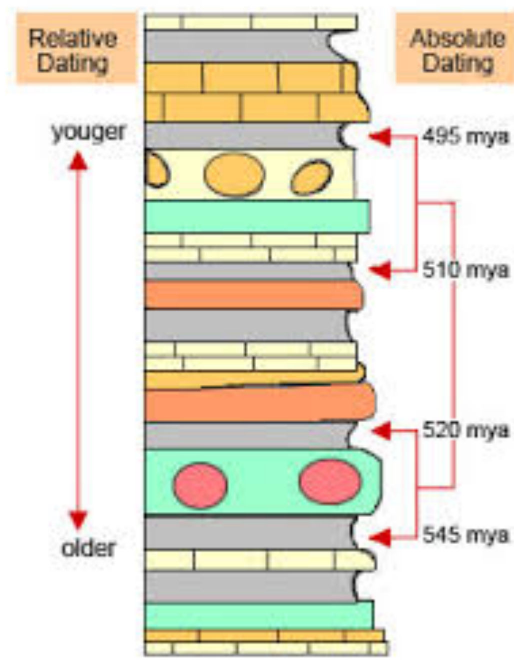


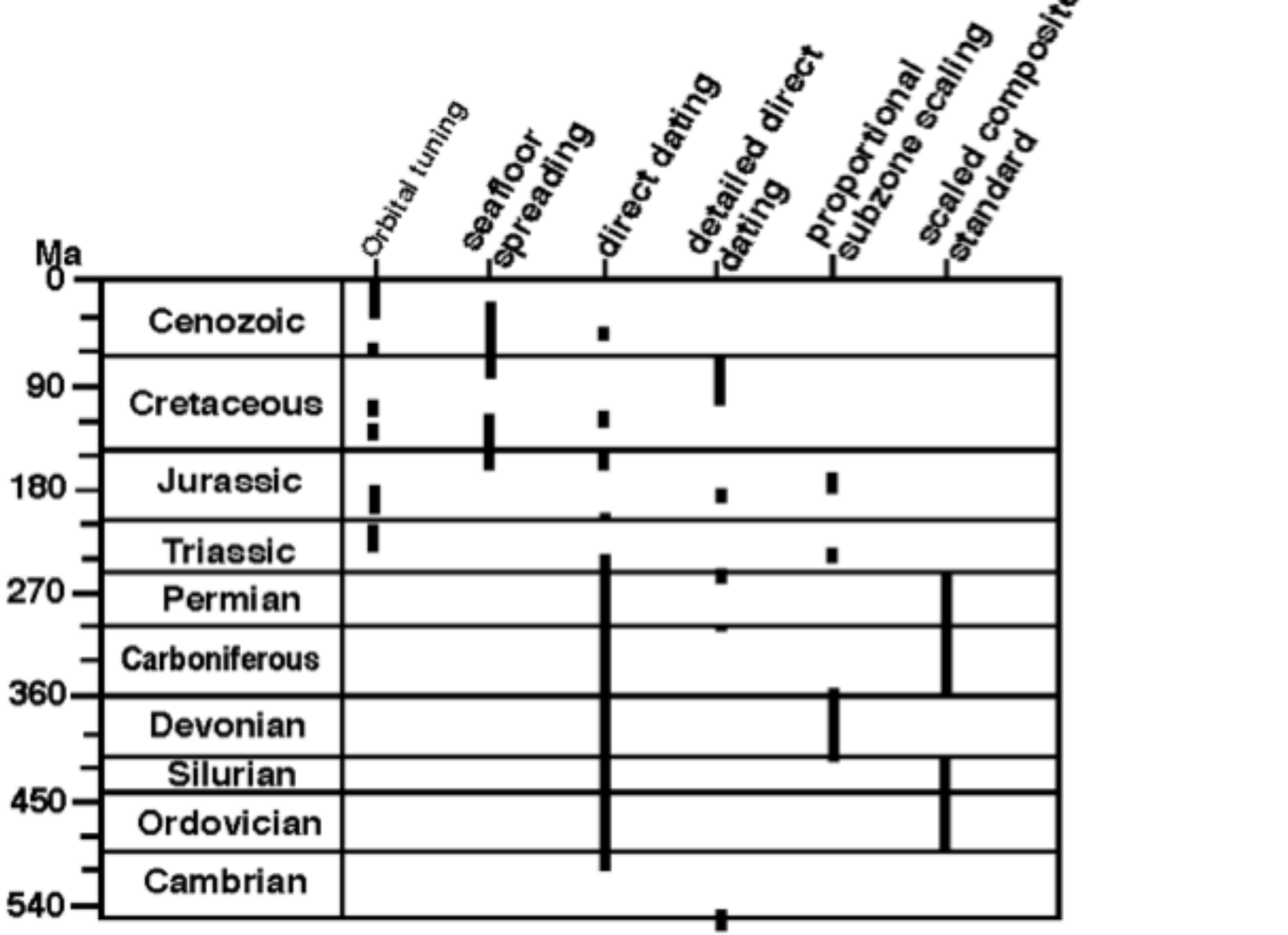
IDENTIFICATION OF MODERN ARTIFACTS

Applications to Geology

Geochronology is the science of determining the age of rocks, fossils, and sediments

Chronostratigraphy is the branch of stratigraphy that studies the age of rock strata in relation to time

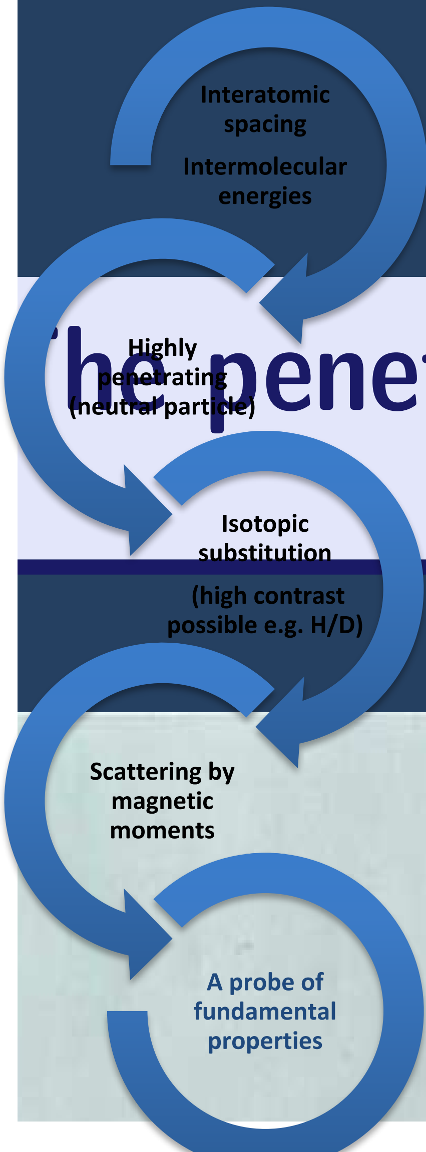




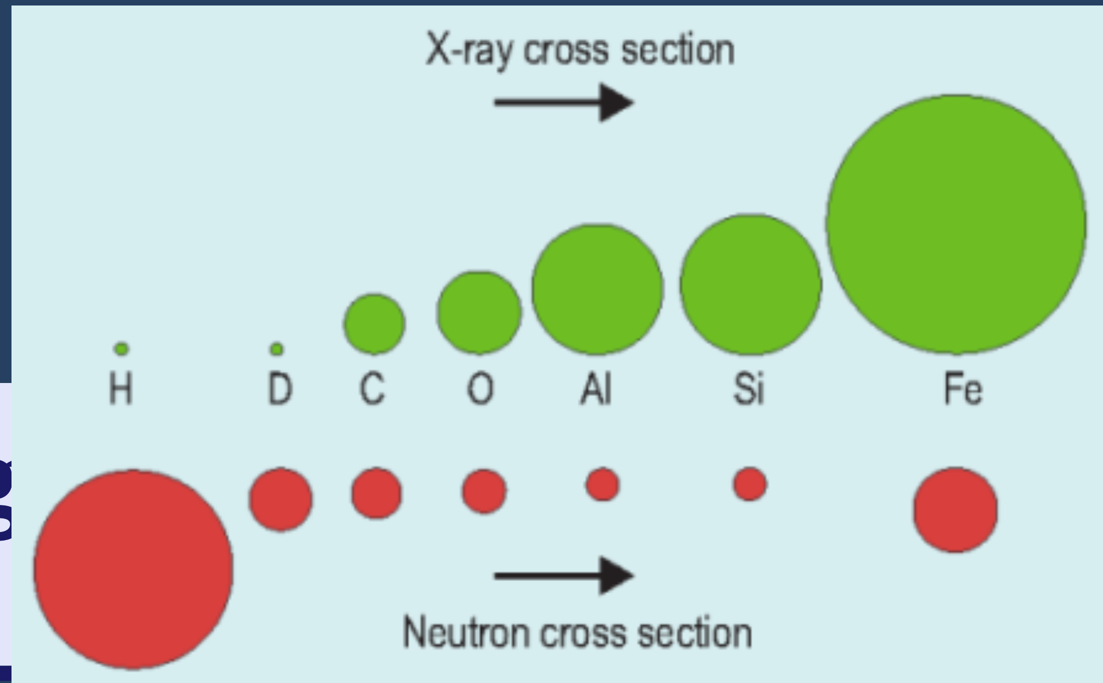
Methods used to construct the Geologic Time Scale 2004 (GTS2004) integrated different techniques depending on the quality of data available within different intervals.

NEUTRONS

Relevant Neutron Properties



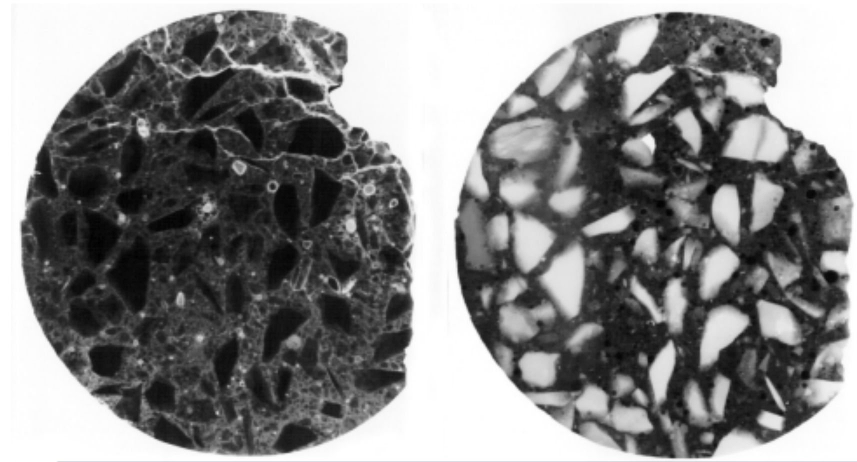
'he penetrating



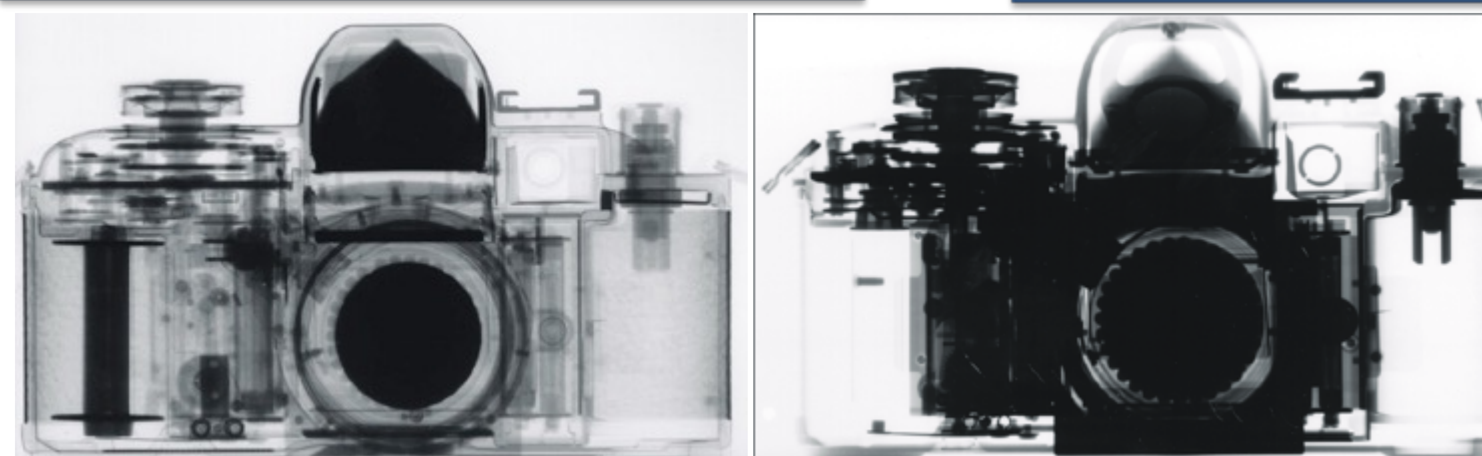
Neutron vs X-ray radiography

Neutron radiography provides a very efficient tool in the field of non-destructive testing as well as for many applications in fundamental research since are able to distinguish between different isotopes

X-ray radiography photography neutron radiography



X- ray radiography neutron radiography



neutron radiography X-ray radiography

neutrons penetrate the metallic enclosure; plastic components get able to be seen, whereas by X-rays the metal parts are visualized

Neutron tomography (NT)

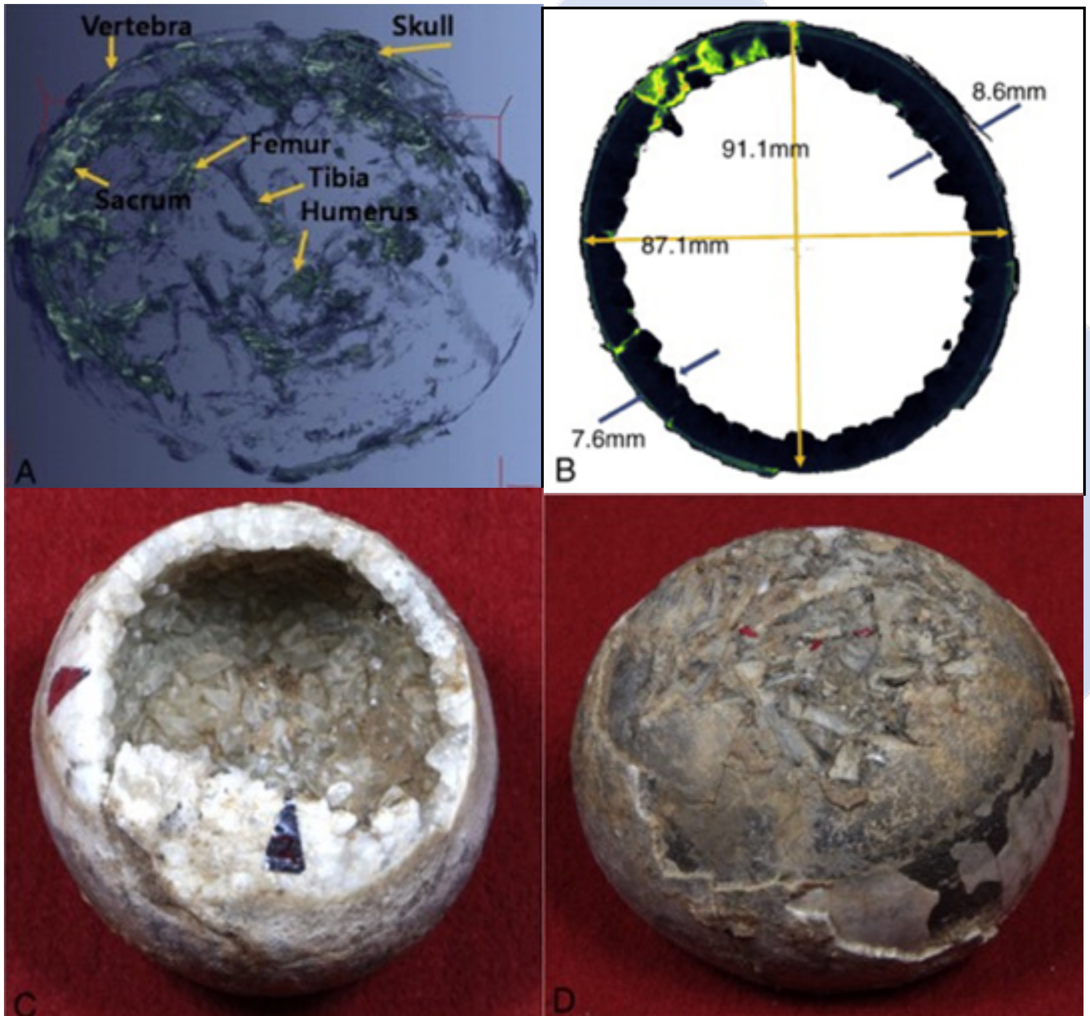
Imaging can lead to understanding of the evolution of life through 3D investigations of paleontological samples that are impenetrable by other non-destructive methods

neutron tomography of a titanosaur showing a fairly articulated and complete embryo

dimensions of egg with embryo

view of inside of the egg with calcite crystals

part of the embryo skeleton surface where the eggshell was naturally eroded



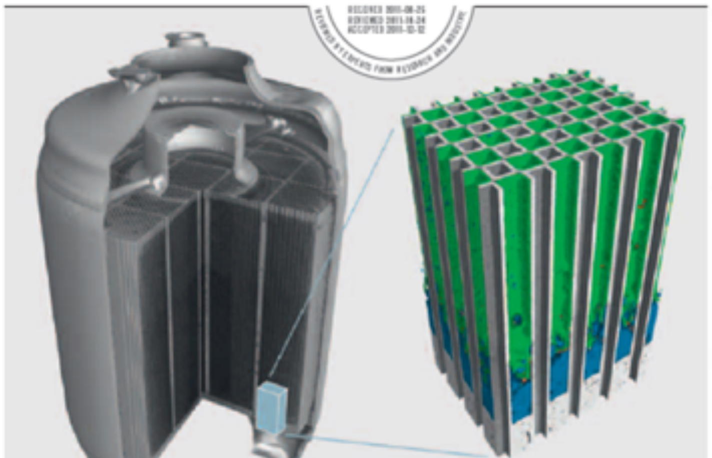
Titanosaur embryo in ovo, which is the first of its kind discovered and is hence valuable for destructive testing.

NT permits full 3D imaging that provides a proof that lithostrotian titanosaurs were reproducing at the Aptian-Albian Algui Ulaan Tsav in Mongolia

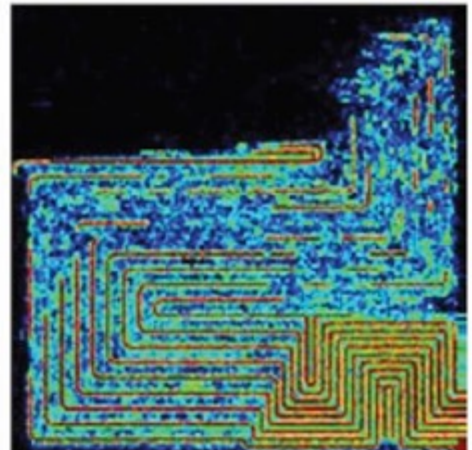
The contrast between fossilised material and the surrounding minerals, and thus the inner structure of fossils, at present can only be resolved by using the phase change of neutron waves

Neutron imaging: industrial applications

Alternative energy, environment, aerospace and automotive research in conjunction with commercial product development have developed into a central field of application for neutron imaging

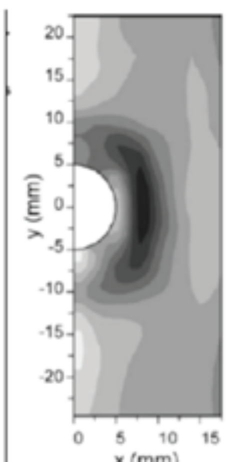


particulate filter

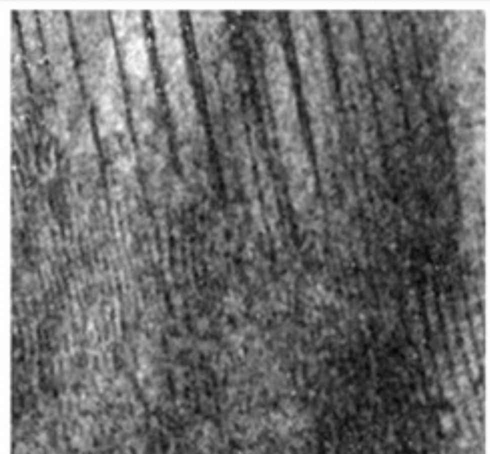


water in operating fuel cell

Increased chemical sensitivity, spatial resolution, and efficiency add capability in important fields of industrial research



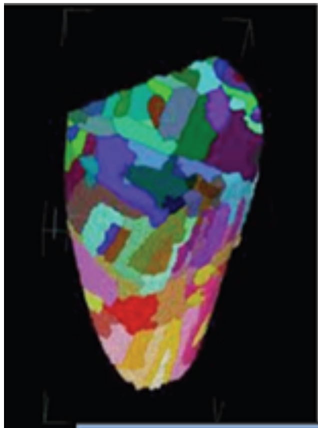
strain map in a rilled whole in steel



magnetic domains in trasformer steel

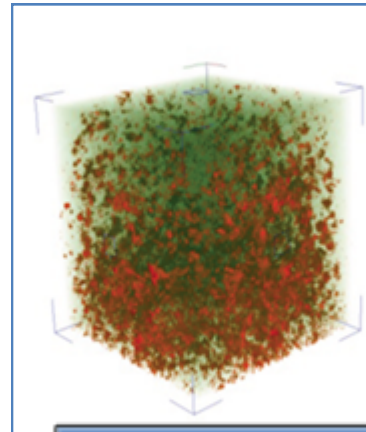
Neutron imaging: scientific applications

Neutron imaging is used to locate and visualize inhomogeneity on various length scales providing information about the structure and microstructure

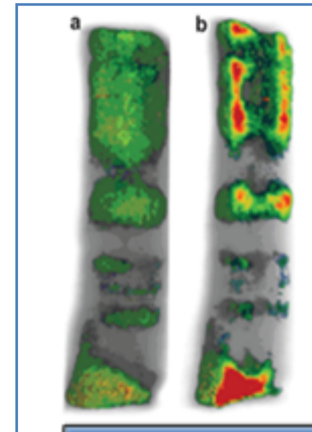


magnetic domains

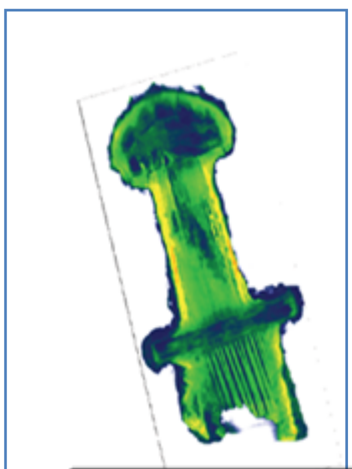
porosity distribution in casted Al specimen



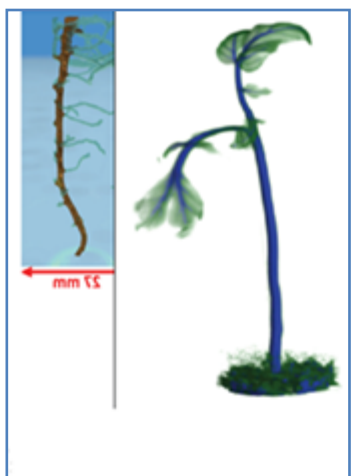
crystalline phase distribution in martensitic steel sample



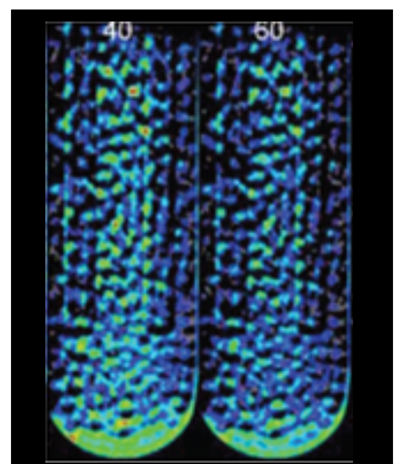
3D Curie temperature map in NiPd crystal



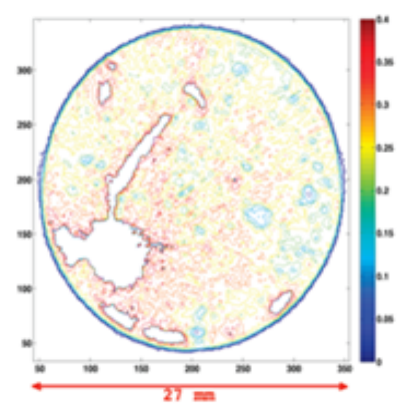
sword artifact



plant root and tomato seedling from water uptake studies



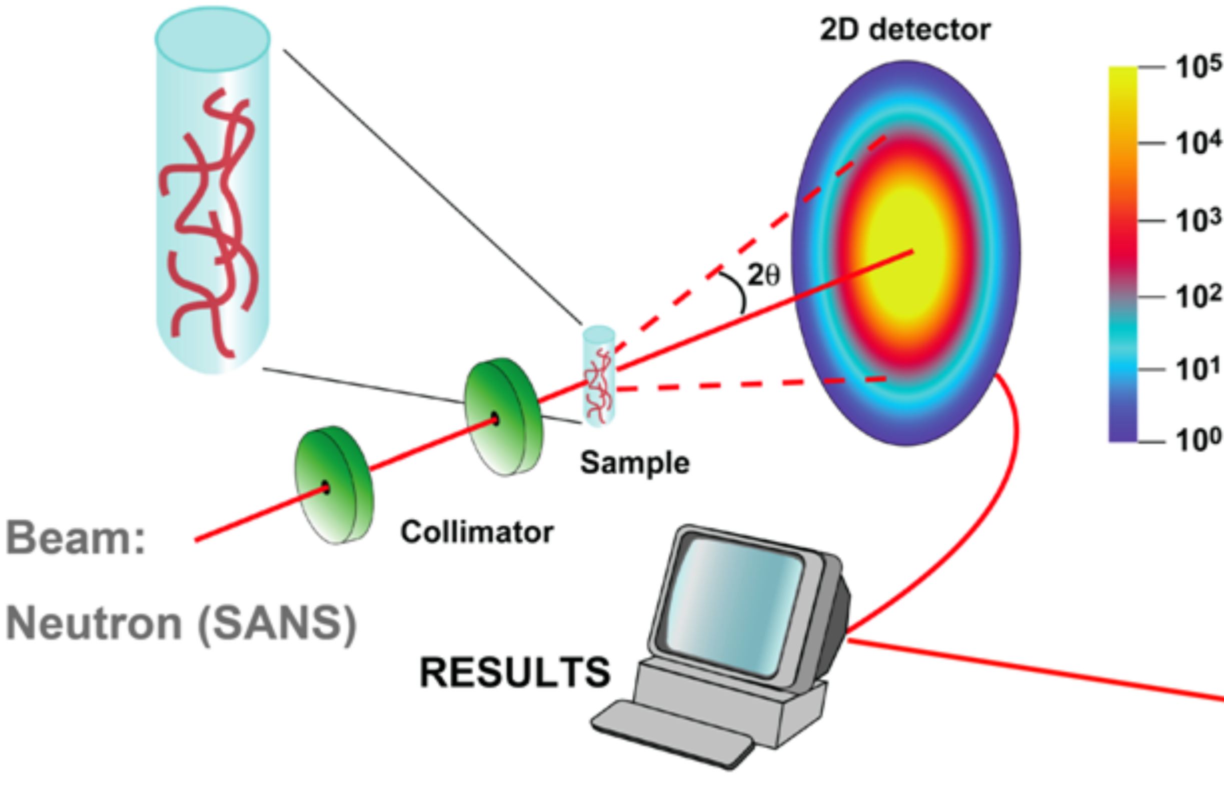
hydrogen storage investigations



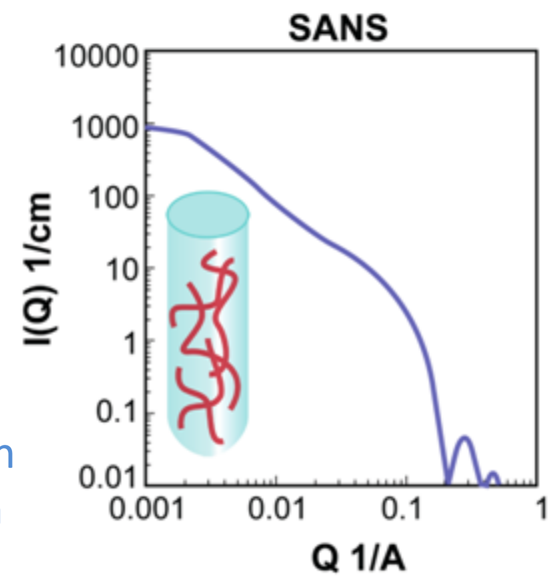
water distribution in soil around plant roots

Small Angle Neutron Scattering

SANS furnishes information on the shape, size and interactions of the scattering bodies (assemblies of scattering centres) in the sample



Typically measures structures at length scales from 10 Å to 1000-5000 Å



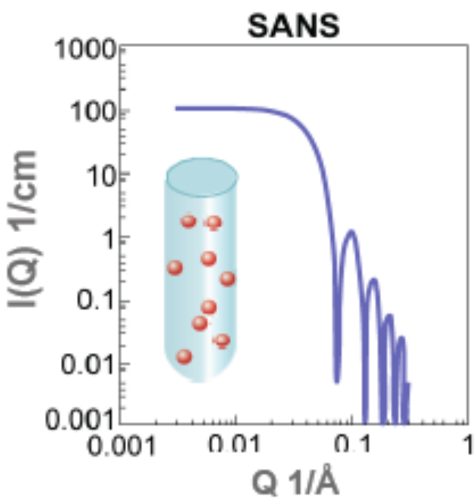
SANS is particularly useful within systems where the difference in scattering length (e.g. between hydrogen H and deuterium D) can be utilized to enhance domains of specific interest

Small Angle Neutron Scattering

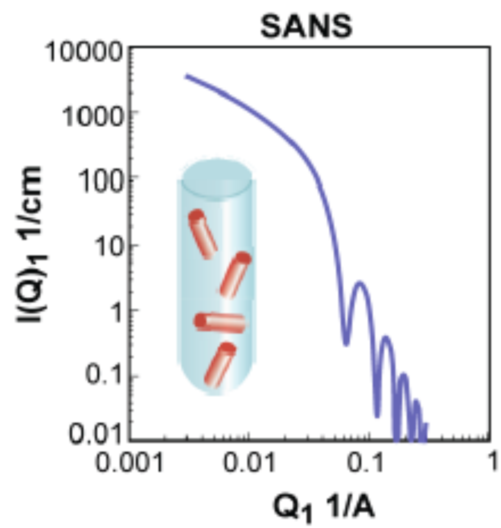
A sample of identical spheres with radius R dispersed in a solvent will scatter uniformly with an isotropic form factor. Analytic expressions exist for more complex topologies, such as concentric cylinders or hinged rods

Different structures – Different scattering patterns

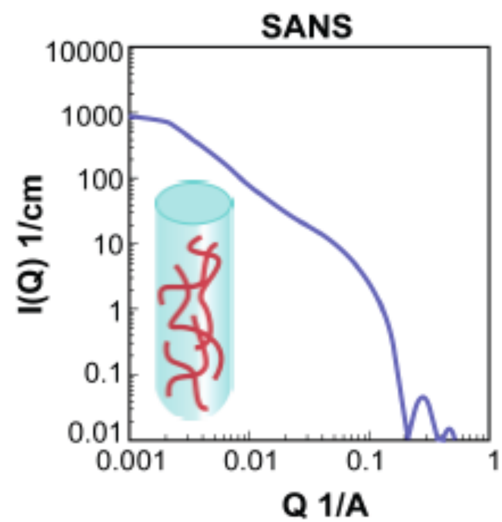
- **Spheres:**
  R = 60 Å



Rods: R = 60 Å
L = 1200 Å



Worms: R = 18 Å
L = 5000 Å,
Kuhn Length = 300 Å



$I(q) = \phi V (\Delta\rho)^2 P(q) S(q)$

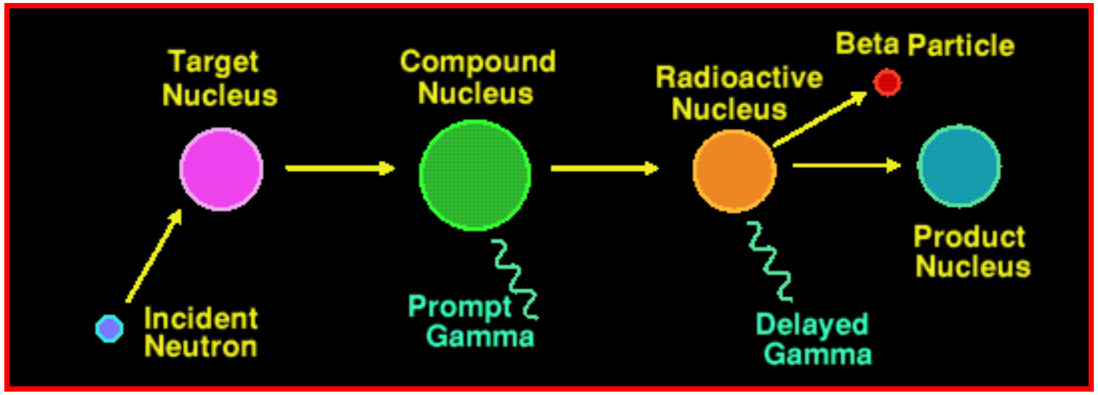
P(q): Particle form factor
S(q): Structure factor
ϕ: Concentration (vol/vol)
V: Volume of single particles ($Å^3$)
$\Delta\rho$: Excess scattering length density

NEUTRON ELEMENTAL ANALYSIS

- **Neutron Activation Analysis (NAA)**:

neutron is *captured* by the target, transmuting it into an unstable nucleus which then decays by fission or by the release of some particle or photon.

NAA, which uses low-energy thermal neutrons to transmute a wide range of nuclei into unstable isotopes, irradiation can take many hours while measurement of the decay energies and rates of the unstable transmuted isotopes can require days

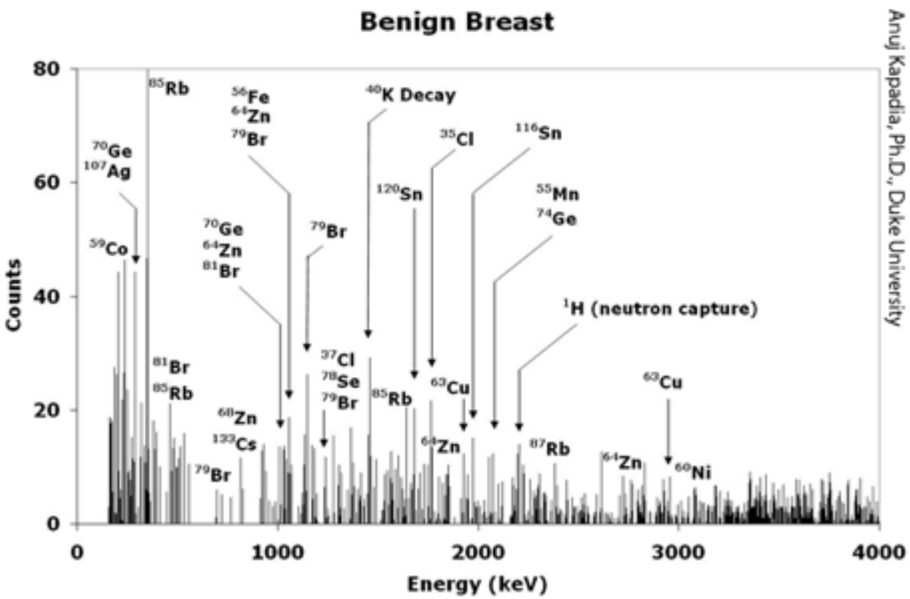


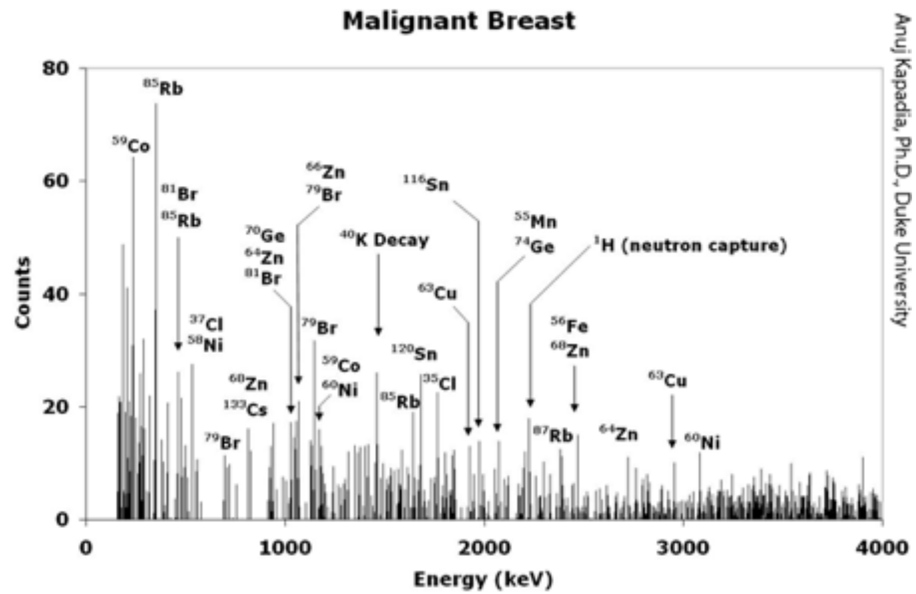
- **Neutron Stimulated Emission Computed Tomography (NSECT)**:

NSECT uses prompt gamma emission at higher neutron energies to provide many of the advantages and accuracy of NAA and allowing a rapid *in vivo* elemental analysis

NSECT MEDICAL APPLICATIONS

Several diseases in humans → Increased element concentration





Energy keV	Element Match	Counts Benign	Counts Malignant	Diff	p-val
219	^{79}Br	6	19	13	0.01
397	^{59}Co, ^{79}Br	16	2	-14	0.01
1028	^{81}Br	13	29	16	0.05
1128	^{39}K, ^{68}Zn	0	13	13	0.001
1306	^{56}Fe	10	0	-10	0.01
2299	^{27}Al	0	13	13	0.001
2469	^{37}Cl, ^{56}Fe, ^{66}Zn	5	15	10	0.05
3635	^{35}Cl	3	14	11	0.01

Chip Irradiation

Motivations

- One of the main reliability issues in state-of-the-art microelectronic chips is the occurrence of **Soft Errors** (SE) corrupting one or several bits on the chip and causing the chip malfunctioning. Such a failure may produce **severe problems in safety-critical systems**, such as the electronic systems on board of cars, airplanes, satellites, implanted medical apparatus, etc

Why neutrons?

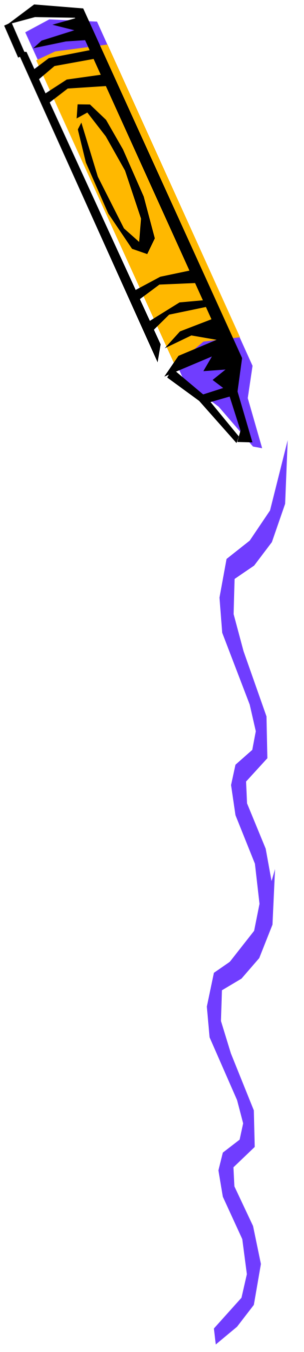
- A SE occurs when a **high-energy neutron**, produced by the primary cosmic rays interacting with the upper layers of the terrestrial atmosphere, strikes the **sensitive region** of a chip disrupting its correct operation.
- The **terrestrial neutron flux is weak** and the collection of experimental data may least several months: too long to quickly assess the **SE robustness** of new electronic devices and technologies

Who is affected?

- All makers of systems needing **high-reliability**
- Aerospace
  - Satellites
  - Civilian and military aircrafts
- Medical
  - Implanted electronic devices (pacemakers, defibrillators…)
  - Nuclear Industry
  - Instrumentation and control in proximity to reactors
  - Transport
  - Electronics in cars and trains
  - Signalling and traffic control networks
  - IT Networks

Industrial applications

ELECTRON BEAMS



Electron Beam Machining – Process

- Electron beam is generated in an electron beam gun.
- Electron beam gun provides high velocity electrons over a very small spot size.
- Electron Beam Machining is required to be carried out in vacuum.
- Otherwise the electrons would interact with the air molecules, thus they would loose their energy and cutting ability.
- Thus the work piece to be machined is located under the electron beam and is kept under vacuum.
- The high-energy focused electron beam is made to impinge on the work piece with a spot size of 10 – 100 μm.
- The kinetic energy of the high velocity electrons is converted to heat energy as the electrons strike the work material.

DRILLING

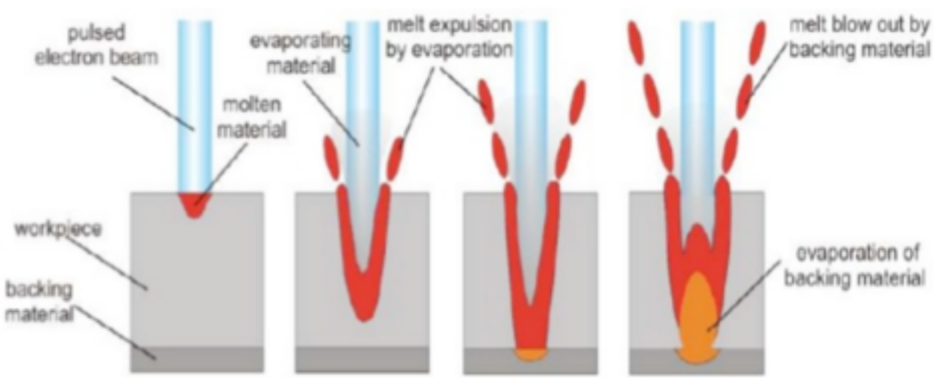
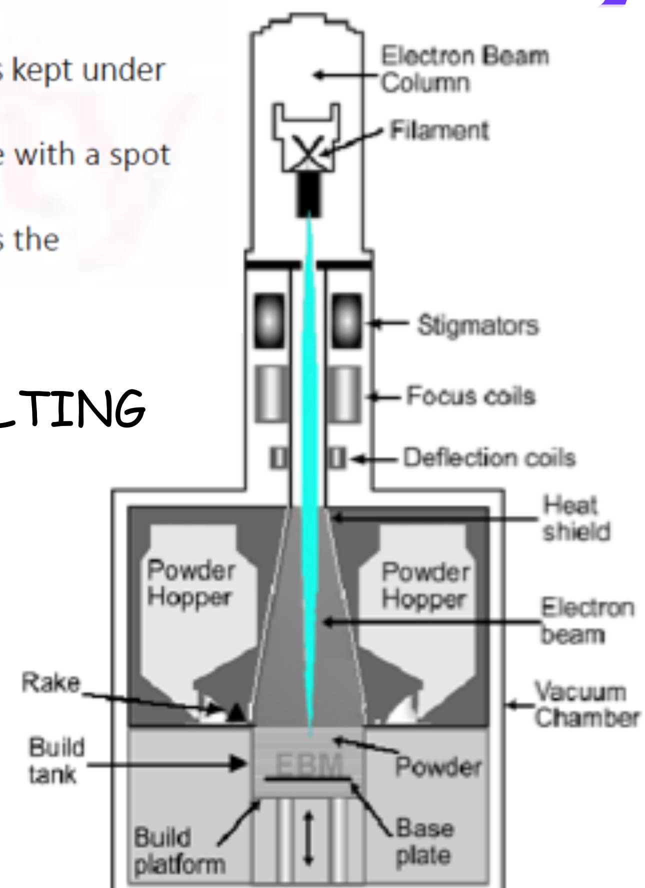


Fig:- Electron Beam Drilling Process[4]

MELTING



Electron Beam Machining