

Accelerators for Medical and Industrial Applications

JUAS
Archamps, March 7th 2017

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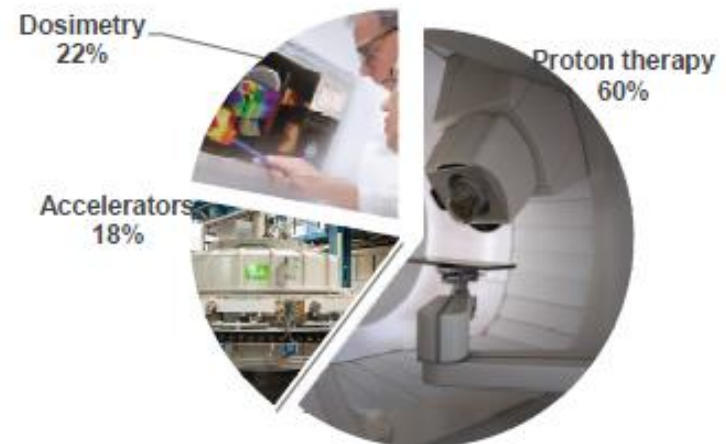


Organization of the lecture

- Intro: A few words about IBA
- Part 1: Radioisotopes for medical applications
 - a. Diagnosis and molecular imaging
 - b. Radioisotopes for cancer therapy
- Part 2: Cyclotrons magnetic design and beam dynamics
- Part 3: Particle therapy systems for cancer treatment
- Part 4: Industrial electron beam technology
- Part 5: The ProteusOne and S2C2 project (if sufficient time)

The IBA Group in 2016

- ❑ 1200 employees worldwide
- ❑ More than 300 systems (200 Cyclotrons) installed
- ❑ Not anymore just a cyclotron company, but a company focused on medical technology for the fight against cancer:
 - Cancer diagnostic: cyclotrons for molecular imaging
 - Cancer treatment: Particle therapy & dosimetry
- ❑ More than 400 patents in use
- ❑ Listed on Euronext Brussels
- ❑ <http://www.iba-worldwide.com>



IBA Today: Centering on the fight against cancer

Accelerators

Cyclotrons

- To produce Radioisotopes

E-beam / X-rays

- To irradiate / treat many industrial products



Particle Therapy

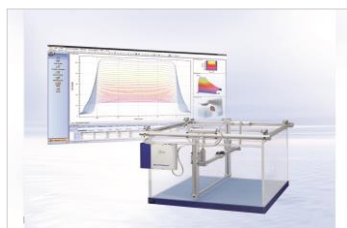
Proton Therapy is increasingly considered as the ultimate radiotherapy for cancer due to its superior dose distribution



Dosimetry

Dosimetry equipment to measure and calibrate radiation dose for

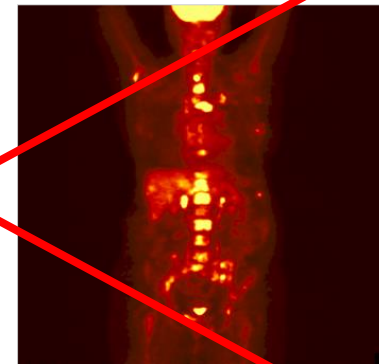
- Radiotherapy
- Radiodiagnostics



~~Pharmaceuticals~~

~~Radiopharmaceuticals~~

- Molecular Imaging
- Nuclear Medicine (diagnostics & therapy)



IBA recruits

- For the year 2017 IBA is hiring about 200 new engineers worldwide
- If interested go to the following website

www.ibarecruits.com

Part I-A: radio-isotopes for medical diagnosis

SPECT: Single Photon Emission Computed Tomography

PET: Positron Emission Tomography



How is imaging done with radio-tracers ?

SPECT

PET

Single photon

2 photons of 511keV
(β^+ annihilation)

Radio-isotope

γ emitter

β^+ emitter

A camera (Gamma or PET) detects the photons emitted from the body and computes 3D distributions of the radio-activity

The use of Radio Isotopes for medical imaging

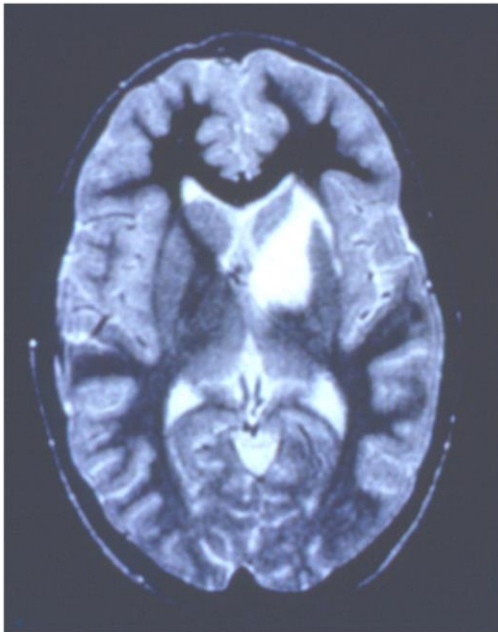
- ❑ Radio tracers can be used to label a specific bio-chemical molecule.

- ❑ They allow to see metabolism
 - X-ray (CT-) scan or MRI are better to see the anatomy (structure)

- ❑ Nuclear medicine (imaging of metabolism using molecules labeled with an appropriate radioisotope) is therefore not in competition, but in complement of imaging techniques such as X-ray, X-ray CT-scan or MRI.

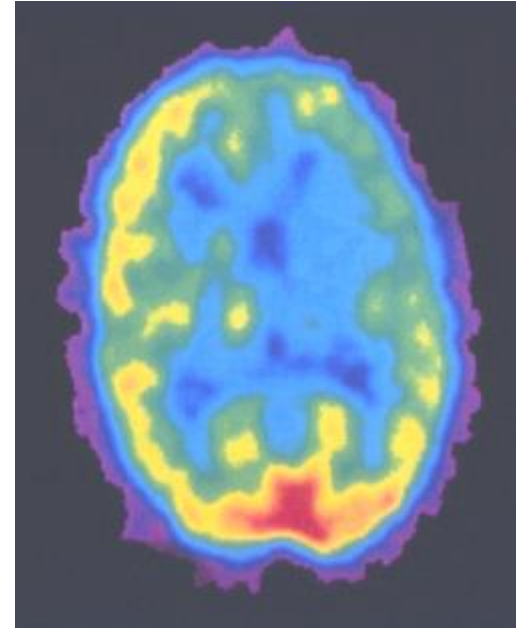
Metabolic versus anatomic imaging

MRI



Anatomic View
(Tissue-structure)

PET



Metabolic imaging
(Biological-function)

How is imaging done with radio-tracers ?

Single photon isotopes (SPECT)

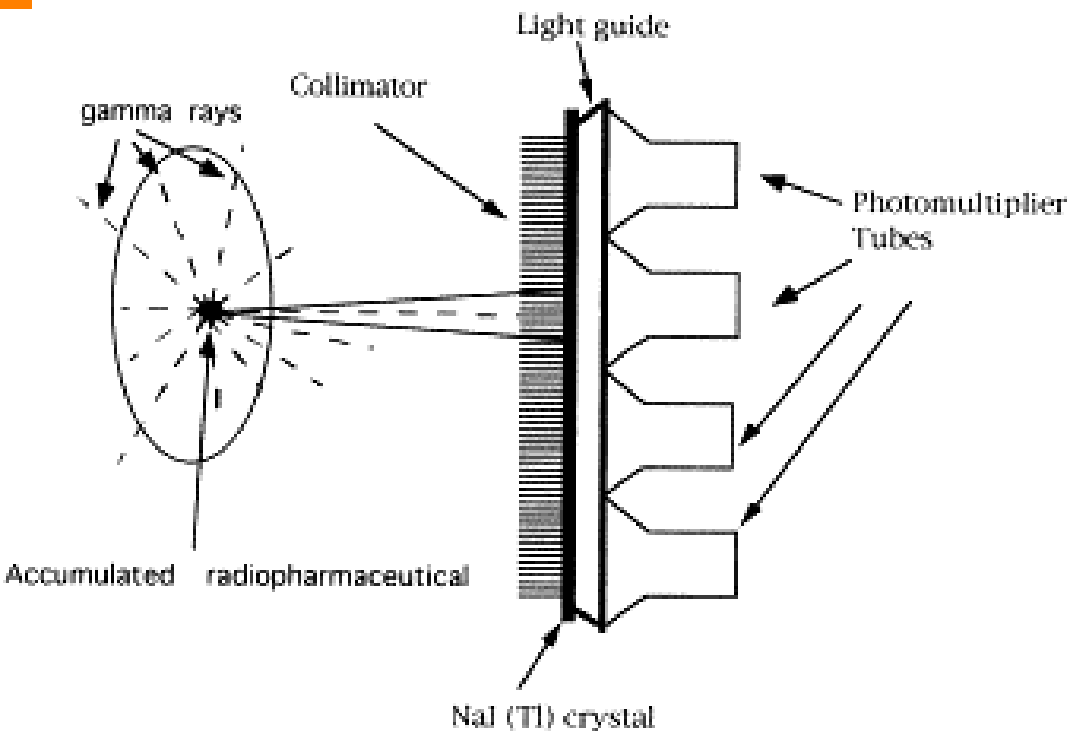
- The imaging of single photons emitters requires:
 - a collimator (causes a loss of efficiency !).
 - a position-sensitive detector (with good detection efficiency): the Gamma (or Anger) camera.

- The image obtained is a projection.
- Multiple (perpendicular) projections can be mathematically correlated to produce a 3D representation.
- SPECT (Single Photon Emission Computed Tomography).

The SPECT gamma camera (Anger camera)

Anger camera

The collimator prevents photons that are not approximately perpendicular to the collimator holes from interacting with the detector.



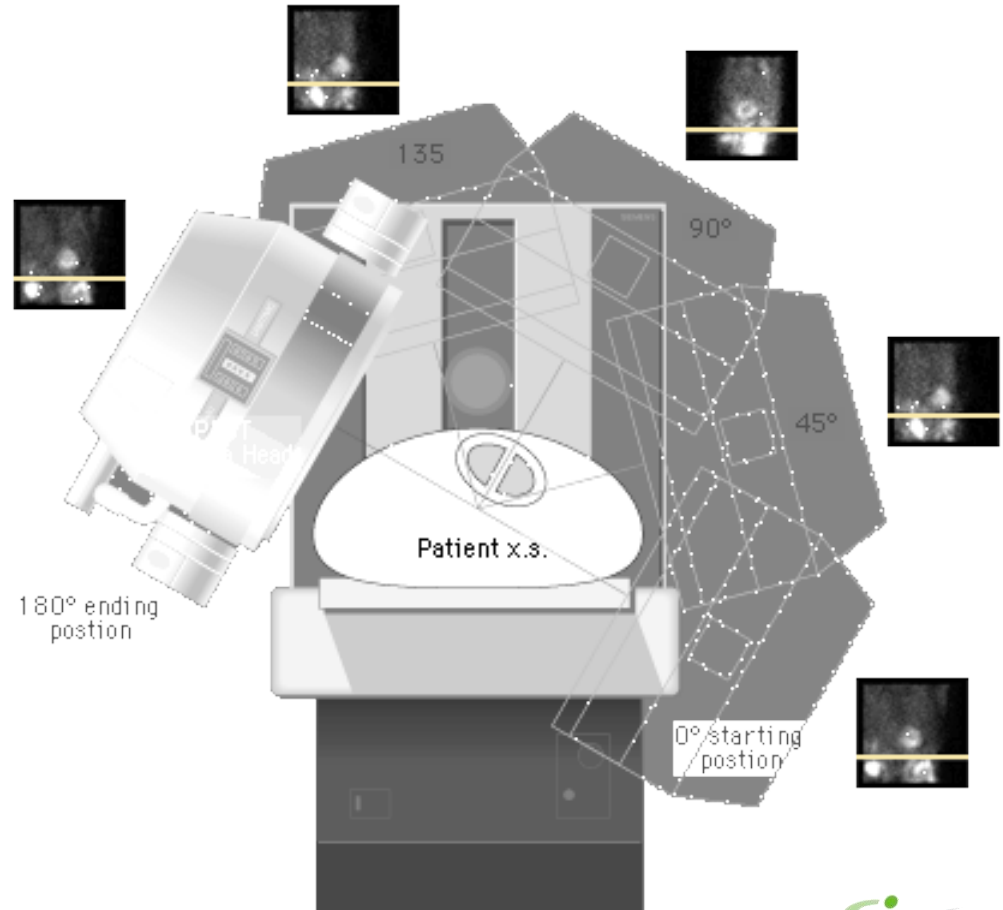
The field of view for the detector element behind each hole of the collimator is divergent, so that in a gamma camera, spatial resolution degrades as the distance to the object is increased. Collimators are usually made of lead.

Typical dimensions: holes 3mm, walls 1mm, depth 40mm.

The SPECT gamma camera



Projections from different angles are taken by rotating the camera around the patient

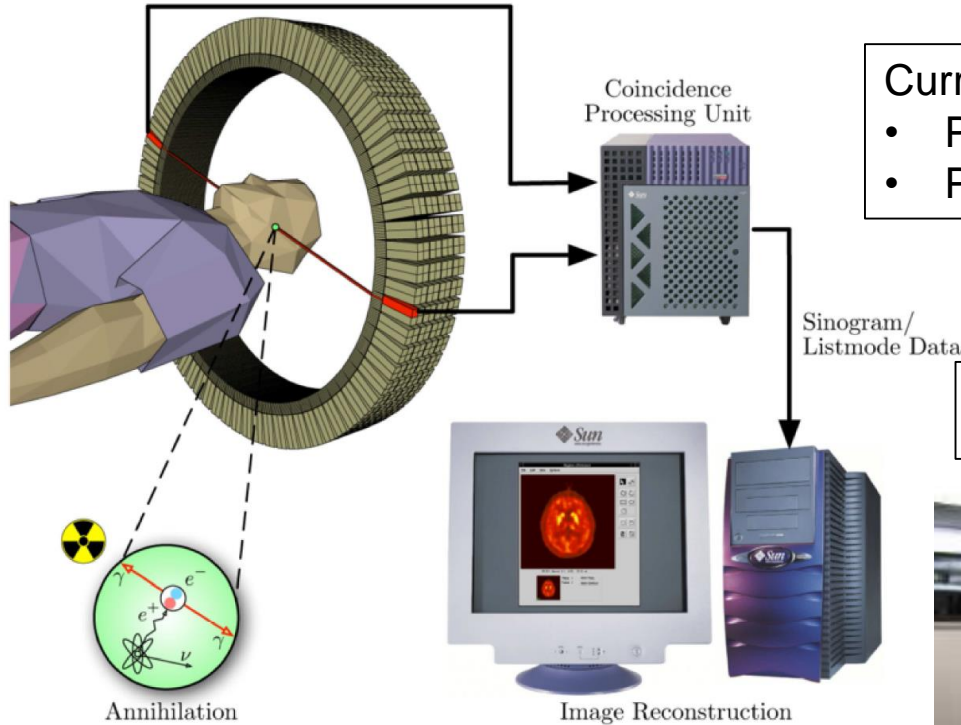


How is imaging done with radio-tracers ?

Positron emitting radio-isotopes (PET)

- ❑ The emitted positron travels a few millimeters, then meets an electron and annihilates, emitting two anti-parallel photons of 511keV.
- ❑ These two photons can be detected in **coincidence** by a ring of detectors surrounding the region of interest.
- ❑ One knows then that the origin of the photons is on the line connecting the two detectors => no collimator needed
- ❑ Several detections allow to locate the source.
- ❑ By mathematical reconstruction, a 3D representation of the activity can be obtained.
- ❑ PET (Positron Emission Tomography).

The PET scanner



Currently available are

- PET scanners integrated with CT: PET-CT
- PET scanners integrated with MRI: PET-MRI

PET scanner in a hospital



- Coincidents events are grouped into projected images (sinograms) and sorted by the angle of view
- Analogous to the projections obtained with Computed Tomography (CT) scanners
- 3D image re-construction is similar

How to select a good single-photon radio-tracer?

1. The energy of the emitted photon

- Low enough to keep a good detector efficiency
- Low enough in order to achieve good collimation
- High enough to cross the body tissue
- $100 \text{ keV} \leq E \leq 300 \text{ keV}$ is generally the optimum

2. The half-life:

- Short enough to minimize the patient's exposure
- Long enough to allow distribution to the hospitals
- Practically $10\text{h} \leq T_{1/2} \leq 100\text{h}$ is roughly best
- Generators are great too !

^{99}Mo (66 hours) = $^{99}\text{Tc}_m$ (6 hours)

^{81}Rb (4.6 hours) \Rightarrow ^{81}Kr (13sec)

How to select a good single-photon radio-tracer

3. The chemistry

- The radio-tracer should bind easily to organic bio-molecules of interest
- Essential bio-chemical behavior of the molecule should remain intact after labeling
 - Halogens (Fluor, Iodine), Technetium \Rightarrow good;
 - Noble metals (Gold) \Rightarrow difficult

“Traditional” nuclear medicine

- Technetium 99m, the most commonly used radio-isotopes in nuclear medicine is produced in reactors.
 - 90% of diagnostic studies in hospitals is done with ^{99m}Tc !
- But a number of other, very important nuclear medicine radio-isotopes are produced with cyclotrons of higher energy.
 - ^{201}Tl (Cardiac studies).
 - ^{123}I (Thyroid, Various examinations).
- For these longer life isotopes, international distribution is possible.
- Large, very powerful cyclotrons are owned by radiopharmaceutical companies.

Nuclear reactions for Radio-Isotopes production

Radioisotope	Half-life	Reaction	Energy (MeV)
^{201}Tl	73.1 h	$^{203}\text{Tl} (p,3n) \Rightarrow ^{201}\text{Pb} \Rightarrow ^{201}\text{Tl}$	17~28
^{67}Ga	78.3 h	$^{68}\text{Zn} (p,2n) \Rightarrow ^{67}\text{Ga}$	12~28
^{111}In	67.4 h	$^{112}\text{Cd} (p,2n) \Rightarrow ^{111}\text{In}$	12~28
^{123}I	13.2 h	$^{124}\text{Te} (p,2n) \Rightarrow ^{123}\text{I}$	20~25
		$^{124}\text{Xe} (p,2n) \Rightarrow ^{123}\text{Cs} \Rightarrow ^{123}\text{I}$	20~30
		$^{124}\text{Xe} (p,pn) \Rightarrow ^{123}\text{I}$	
		$^{127}\text{I} (p,5n) \Rightarrow ^{123}\text{Xe} \Rightarrow ^{123}\text{I}$	45~68

A 30 MeV cyclotron can often do the job

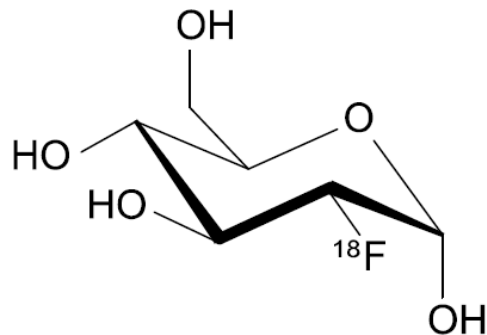
Common positron emitting radioisotopes for PET

Radioisotope	Half-life (min)	Positron energy (MeV)	Reaction	Energy (MeV)
^{11}C	20.4	1.0	$^{14}\text{N} (p,\alpha) \Rightarrow ^{11}\text{C}$	5 \Rightarrow 16
^{13}N	9.96	1.2	$^{16}\text{O} (p,\alpha) \Rightarrow ^{13}\text{N}$ $^{12}\text{C} (d,n) \Rightarrow ^{13}\text{N}$	8 \Rightarrow 16 3 \Rightarrow 8
^{15}O	2.07	1.7	$^{15}\text{N} (p,n) \Rightarrow ^{15}\text{O}$ $^{14}\text{N} (d,n) \Rightarrow ^{15}\text{O}$	5 \Rightarrow 14 3 \Rightarrow 8
^{18}F	109.8	0.6	$^{18}\text{O} (p,n) \Rightarrow ^{18}\text{F}$	5 \Rightarrow 14

Cyclotrons 10-18 MeV

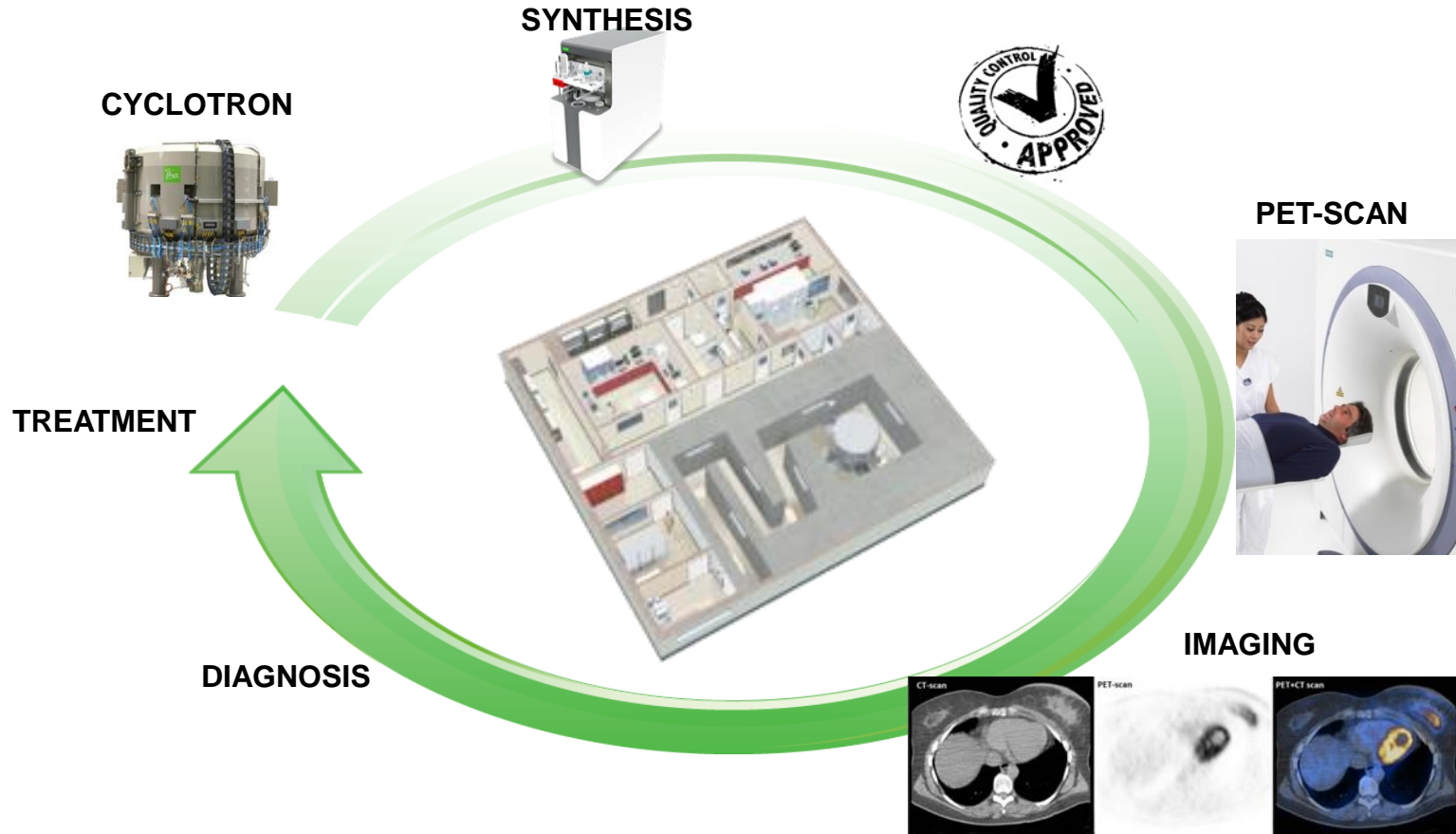
FDG = Fluoro-Deoxy-Glucose

- Most commonly made PET scan (90% of cases) is done with ^{18}F -FDG (Fluoro-Deoxy-Glucose)
- Metabolic activity by virtue of glucose uptake in tissue
- This tracer is mainly used to explore the possibility of cancer metastasis and the response to treatment



- In glucose one OH-group is replaced by a ^{18}F atom
- Both atoms have about the same size =>
- Bio-chemical behaviour almost not altered

Production and Application of PET radio-isotopes



Four different types of radiation therapy

1. External beam radiation therapy (teletherapy)
 - Radiation source is external (like proton therapy)
2. Brachy therapy:
 - Sealed radioactive sources placed precisely in the tumor
 - Can use temporary or permanent placement of radioactive sources
3. Systemic radiation therapy
 - Radioisotopes are given by infusion or by oral ingestion. Example: iodine => thyroid gland
4. BNCT: Boron Neutron Capture Therapy
 - mixture of 1 and 3.

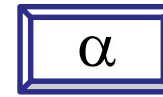
Radioisotopes

▣ Radiation types

In a radioisotope, the nucleus decays spontaneously, giving off particles and energy.



diagnosis



therapy

PET - $T_{1/2}$:

- F-18- 2h
- Ga-68- 1h
- Zr-89-3 d
- I-124-4 d
- O-15- 2min

SPECT- $T_{1/2}$:

- I-123-13d
- Tc-99m-6h
- Ga-67
- In-111
- Tl-201

- I-131
- Y-90
- Re-188
- Lu-177
- At-211*

Brachy therapy

- ❑ Dose is delivered by placing the radiation source directly inside the area requiring treatment
- ❑ Commonly used for cervical (uterus), prostate, breast and skin cancer
- ❑ Irradiation affects only a very localized area => healthy tissues are spared
- ❑ Much higher doses can be delivered. For comparison:
 - Proton therapy: about 40 Gray
 - Prostate brachytherapy: about 100 to 150 Gray
- ❑ Brachytherapy can often be completed in less time
 - Reduce the possibility of recovery of cancer cells between treatment intervals

Prostate brachytherapy with Pd-103 or I-125

Seeds placed with 3D precision verified with ultrasound probe
Seeds are not harmful and can stay in place after treatment

