Elements of Nuclear Physics and Chemistry

MEDIH-502

Teacher: N. Pauly

Course organization

- Theory:
  - 3 ECTS (85% of the final note)
  - Slides available on http://metronu.ulb.ac.be/pauly_cours.html
- Exercises:
  - 1 ECTS
- Laboratories:
  - 1 ECTS
  - Organization: M. Ciccarelli (Maureen.Ciccarelli@ulb.be)
  - 15% of final note → Laboratory reports

References:

- K.S. Krane : Introductory Nuclear Physics (Wiley, 1988)
- K. Heyde : Basic Ideas and Concepts in Nuclear Physics (Institute of Physics, 1994)
- S.S.M. Wong : Introductory Nuclear Physics (Wiley, 1998)
- B.H. Bransden and C.J. Joachain, Physics of Atoms and Molecules (Prentice Hall, 2003)
- B.R. Judd, Operator Techniques in Atomic Spectroscopy (Princeton Landmarks in Physics, 1998)
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- R.D. Cowan, The Theory of Atomic Structure and Spectra (Los Alamos Series in Basic and Applied Sciences, 1981)

Contents

Chapter I:
Introduction

Summary

1. Definition

2. Brief history

3. Radiations in medicine

Definition

- Nuclear physics = study of atomic nuclei →
  - Theoretical model of atomic nucleus
  - Interaction of particles with nucleus
  - Mechanisms of nuclear reactions

- Applications:
  - Medicine
  - Energy production (fission, fusion)
  - Military applications
  - Food-processing (sterilization of food by irradiation)
  - Astrophysics
  - Dating (^{14}C)
  - …

Brief history (1)

1895: Discovery of X-rays by Röntgen

1896: Discovery of radioactivity from uranium by Becquerel

1897: Discovery of the electron by Thomson

1898: Pierre and Marie Curie → other materials are radioactive
→ discovery of Ra and Po

1899: Discovery of α and β rays by Rutherford

1900: Discovery of γ rays by Villard

1903: Discovery of the law of radioactive decay by Rutherford and Soddy

1905: $E = mc^2$ by Einstein

1908: Discovery of the nucleus by Rutherford

1909: α is a helium nucleus and β is an electron (Rutherford)

Brief history (2)

1912: X rays and γ rays are electromagnetic waves (von Laue)

1913: Discovery of the notion of isotope (Soddy and Richards)

1923: Use of radioactive tracers in biology by von Hevesy

1928: Theory of decay based on tunnel effect by Gamow

1929: Invention of the cyclotron by Lawrence and Livingston

1930: Pauli predicts the existence of the neutrino / Dirac predicts antimatter

1932: Discovery of neutron by Chadwick / Discovery of positron by Andersen

1934: Fermi theory for β decay

1936: Strong force occurs through meson exchange (Yukawa)

1936: Lawrence treats leukemia with ^{32}P

Brief history (3)

1938: Hahn, Strassman, Meitner and Frisch discover the fission

1939: Bethe discovers the nuclear fusion in stars

1942: First fission reactor (Fermi)

1945: First atomic bomb at Hiroshima

1948: Big Bang nucleosynthesis (Alpher, “Bethe”, Gamow)

1951: First nuclear reactor producing electricity (EBR-1, Idaho)

1952: First hydrogen bomb (Teller, Ulam) / Decision for creation of the CEAN (future SCK-CEN) in Belgium

1954: Protontherapy at Berkeley

1956: First reactor at critical state in Belgium (BR-1)

1961: First PET scan at Brookhaven

1964: Gell-Mann and Zweig propose the model of quarks

Brief history (4)

1964: Theory of Brout-Englert-Higgs boson

Mid-1970s: Standard model

1975: First nuclear reactor producing electricity in Belgium (Doel-1)

1979: Three Mile Island accident (INES 5)

1986: Tchernobyl accident (INES 7)

2011: Fukushima accident (INES 7)

2013: Experimental evidence of BEH boson (CERN)

2019: First protontherapy center in Belgium

2025-2030 (?): First fusion reactor ITER

20??: MIRRHA in Belgium: First accelerator-driven system

Radiations in medicine

- Radiography
- Nuclear medicine
- Radiotherapy
- Sterilization

Radiography: Definitions (1)

- Radiology aims to establish an anatomical diagnosis of a patient
- Radiography = imaging technique using X-rays (generally) or γ-rays (more rarely) to view the internal form of an object → human body for applications in medicine
- A certain amount of the X-rays (or other radiation) is absorbed by the object depending on its density and structural composition
- Behind the object → detector (nowadays → digital detector)
- Production of flat two dimensional images → projectional radiography

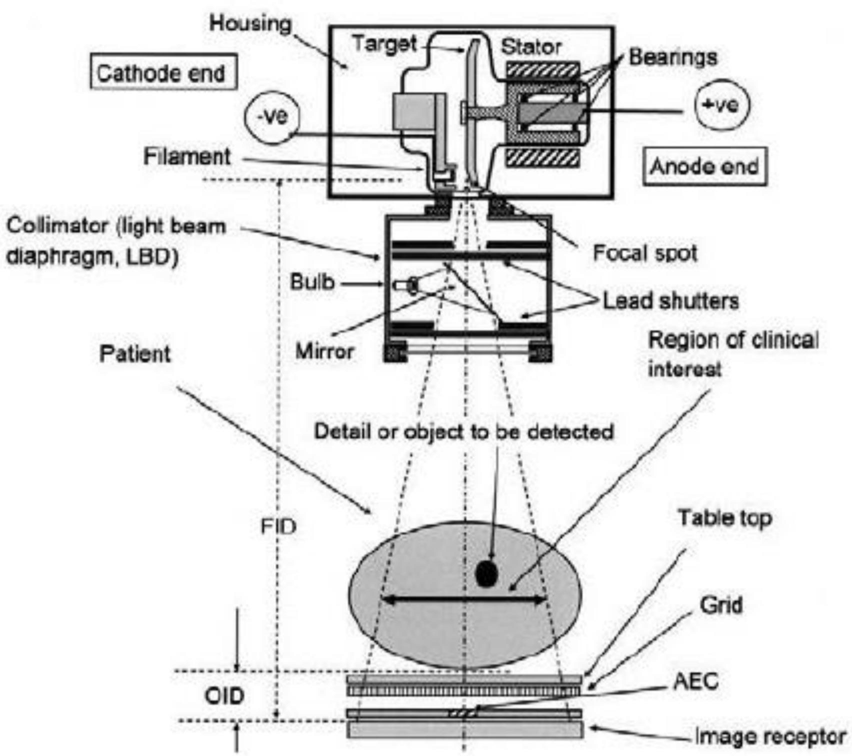
Radiography: Definitions (2)

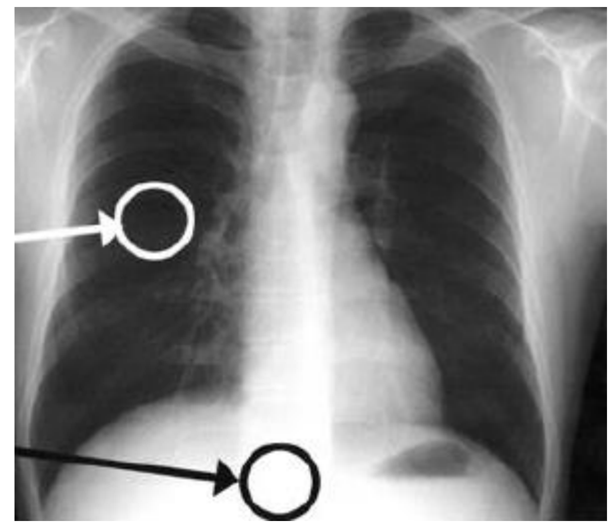
- If the X-ray source and its associated detectors rotate around the object which itself moves through the X-ray beam → computed tomography (CT scanning)

- Other development → fluoroscopy = moving projection radiographs → performed to view movement (of tissue or of contrast agent) → real-time moving images

- Particular application of fluoroscopy → angiography = view of the cardiovascular system (use of a radio-opaque contrast agent)

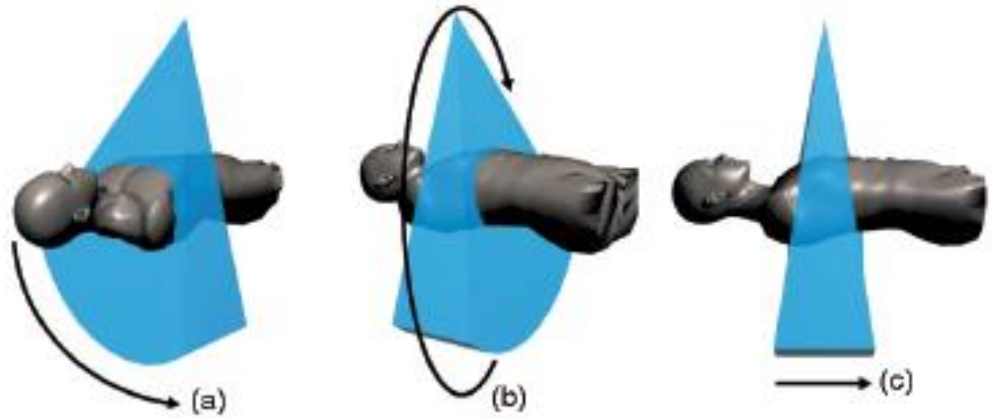
Projectional radiography





Images taken from: D.R. Dance, S. Christofides, A.D.A. Maidment, I.D. McLean, K.H. Ng (Eds), *Diagnostic Radiology Physics: A Handbook for Teachers and Students*, IAEA, Vienna, 2014

Computed tomography



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Radiography: History (1)

- 1895 → discovery of X-rays by Röntgen → production of X-rays in a Crookes tubes → high voltage between 2 electrodes → acceleration of electrons hitting glass or anode → production of X-rays
- Immediate X-rays medical use → picture of his wife hand on a photographic plate

- 1896 → first use of X-rays in clinical conditions → Hall-Edwards → radiography of a needle stuck in a hand
- 1913 → invention by William Coolidge of the Coolidge x-ray tube → heated filament as the source for electrons + high vacuum → more brilliant x-ray source

Radiography: History (2)

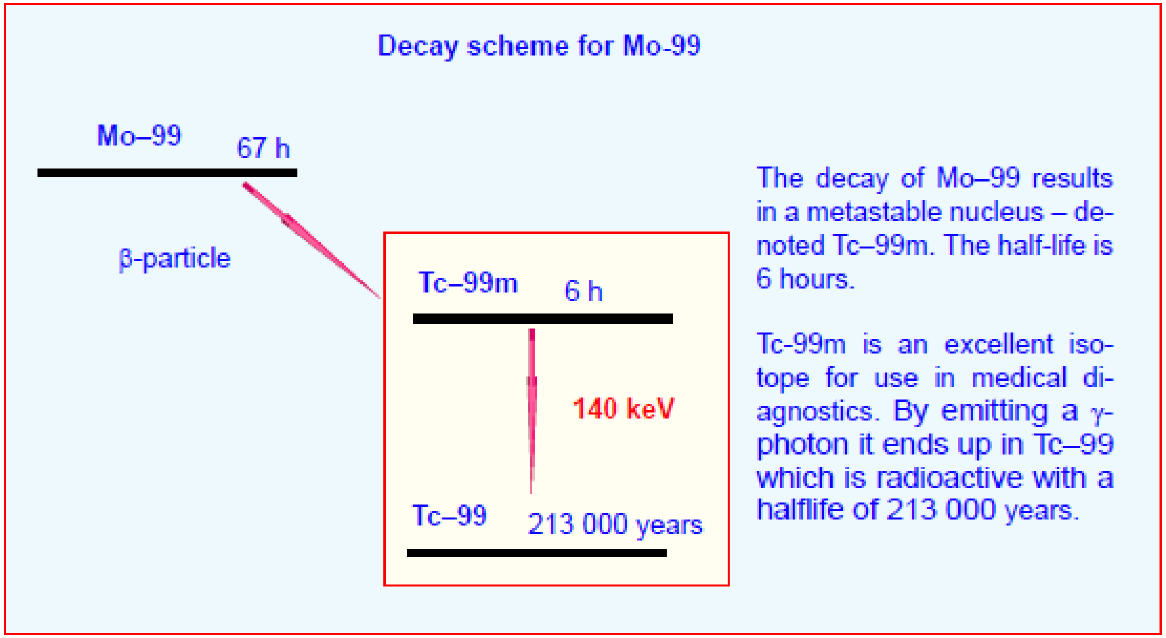
- 1917 → mathematical theory of X-ray computed tomography
- 1955 → X-rays image intensifier is developed → display of the X-rays movie using a TV camera and monitor → replacement of fluorescent system → opening way for angiography
- 1963 → Oldendorf develops the first CT apparatus
- 1970 → development of X-ray mammography
- 1972 → first commercially viable CT scanner (Hounsfield)
- 1978 → start of digital radiography
- 1984 → three-dimensional image processing using digital computers
- …

Nuclear medicine: Definitions

- Nuclear medicine aims to establish a functional diagnosis of a patient
- Use of radioactive isotopes for diagnostic purposes
- Use radioactive tracers which emit γ rays from within the body
- The isotopes are generally short-lived and linked to chemical compounds → specific physiological processes can be studied
- Due to short life → only artificial isotope can be used → necessitate cyclotron or neutron sources
- They can be given by injection, inhalation or orally
- Different techniques:
  - Scintigraphy: planar imaging using a gamma camera
  - Single-photon emission computed tomography (SPECT or SPET): tomographic imaging technique using gamma rays → provide true 3D information
  - Positron emission tomography (PET): detection of pairs of gamma rays emitted indirectly by a positron-emitting radioligand (most commonly fluorine-18)

Nuclear medicine: Tc–99m

- Isotope most often used for medical information = Tc–99m



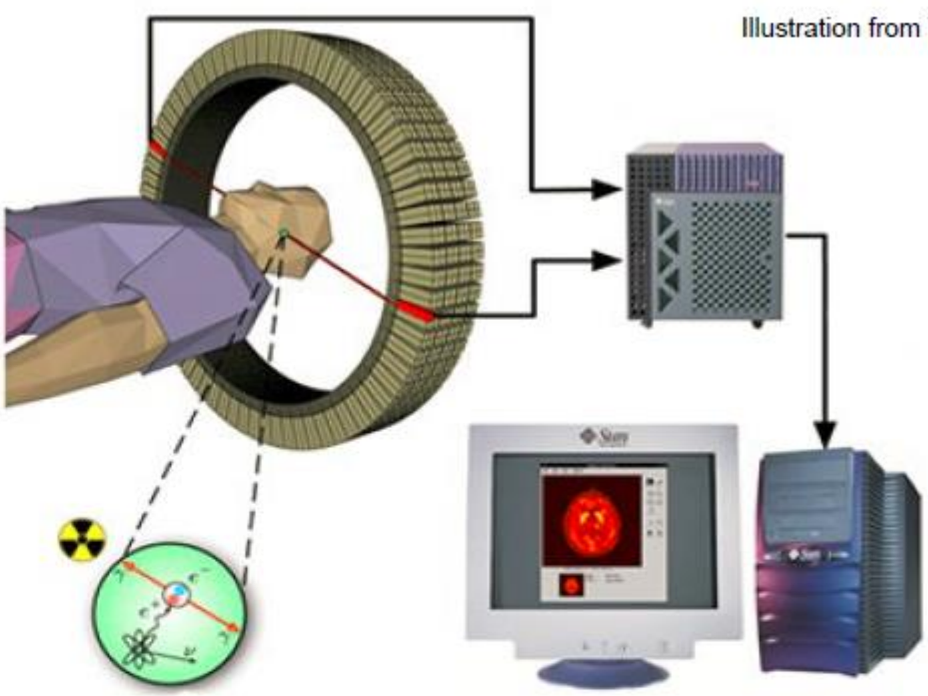
Courtesy of Arne Skretting, Norwegian Radium Hospital

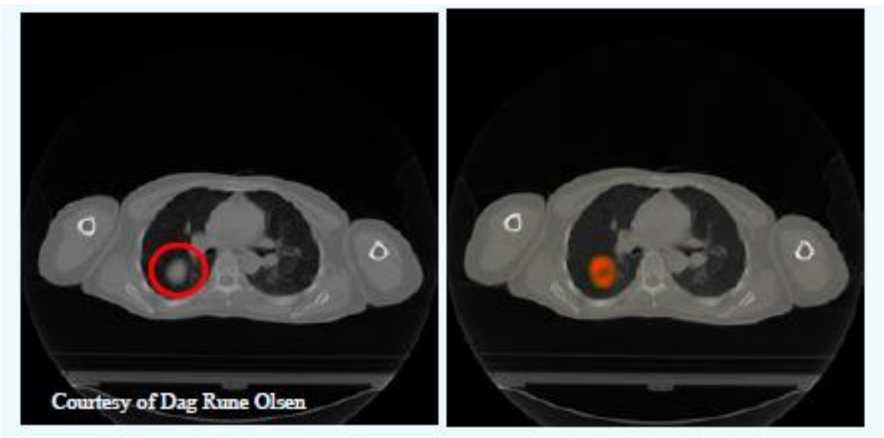
- Tc-99m is added to methylenediphosphonate → it is absorbed by the bone-forming cells (the osteoblasts) → it allows to study diseases of the skeleton (bone cancer,...)

Images taken from: T. Henriksen and Biophysics group at UiO, *Radiation and Health*, Oslo, 2013

Nuclear medicine: PET

- Application of the e^--e^+ annihilation → emission in opposite directions of 2 γ rays





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Radiotherapy: Definitions

- The purpose of radiotherapy is to perform a therapeutic treatment of a patient
- Radiotherapy or radiation therapy is a therapy method using ionizing radiation
- 4 different radiotherapy techniques:
  - External radiotherapy or teletherapy
  - Brachytherapy (in French: brachythérapie or curiethérapie)
  - Unsealed source radionuclide therapy (in French: radiothérapie vectorisée) → usually applied in department of nuclear medicine
  - Stereotactic radiation therapy (in French: radiochirurgie)

External radiotherapy: Definitions

- External radiotherapy = an external source of ionizing radiation is pointed at a particular part of the patient body
- External beam can be
  - Photons (X- or γ rays)
  - Electrons
  - Ions (protons or carbons)
  - Neutrons

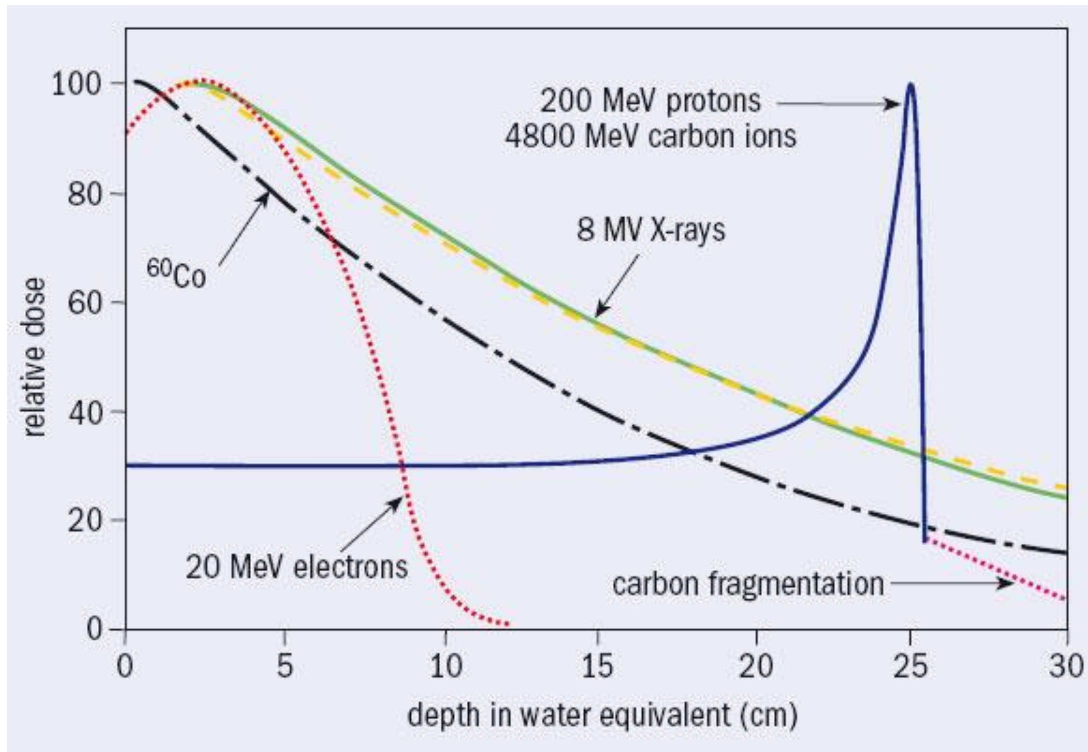


Image taken from: U. Amaldi, *Cern Courier*, 2006, https://cerncourier.com/particle-accelerators-take-up-the-fight-against-cancer/

External radiotherapy: Photons

- Photons used as therapeutic radiation are mainly generated using:
  - Superficial radiation therapy (SRT) machines producing low energy X-rays (20 - 150 keV) for skin treatments
  - Orthovoltage X-ray machines producing « deep X-rays » (DXR) in the range 200–500 keV → treatment of tissue to a depth of 4–6 cm
  - Linear accelerators (linac) producing MeV X-rays (4 MeV–25 MeV)
  - Cobalt units → radiation from Co-60 → 1.17 and 1.33 MeV γ rays

Linear accelerator

Images taken from: T. Henriksen and Biophysics group at UiO, *Radiation and Health*, Oslo, 2013

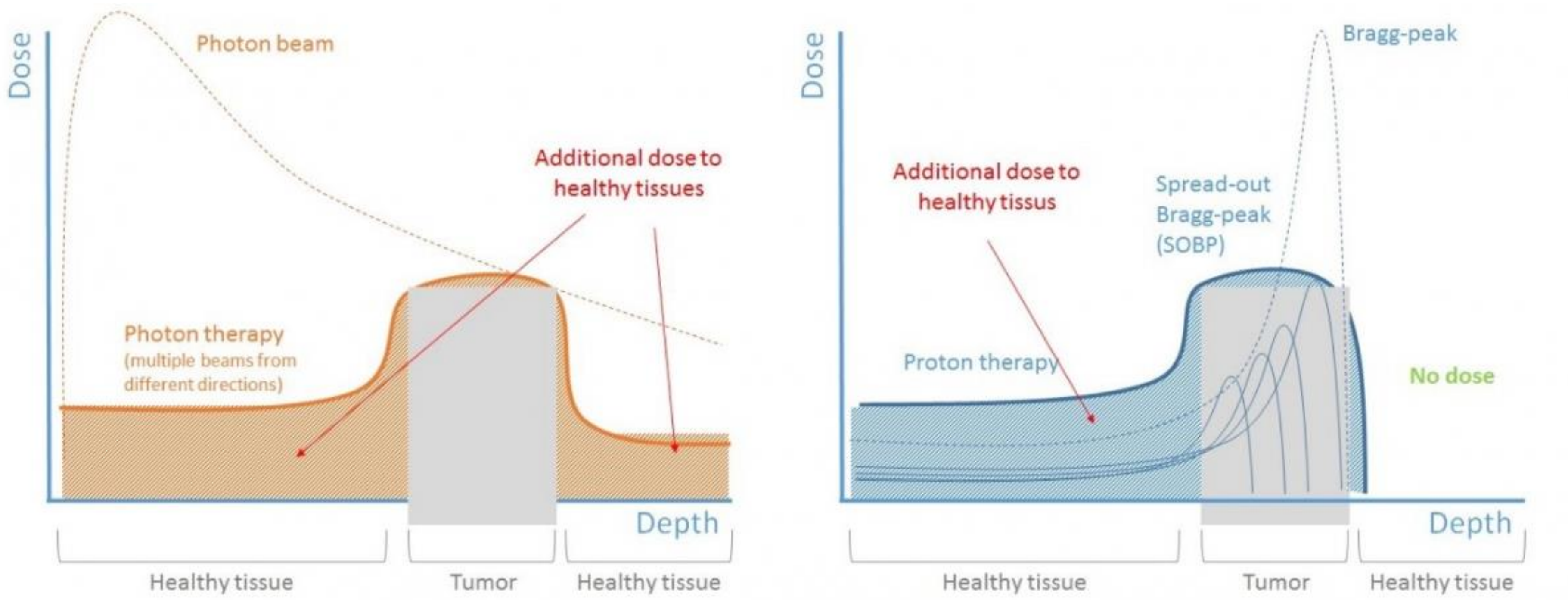
External radiotherapy: Electrons

- Electron beams have usually nominal energies in the range 4–20 MeV → depth of 1–5 cm (in water-equivalent tissue)
- Electron have finite range → afterwards dose falls off rapidly → electrons spare deeper healthy tissue
- Electron beam is produced by a linear accelerator
- Particular case: IntraOperative Electron Radiation Therapy (IOERT)
- In IOERT → application of electron radiation directly to the residual tumor during surgery (one single-treatment) → example: treatment of breast cancer at Bordet with Mobetron®

External radiotherapy: Protons (1)

- Use of protons → protontherapy, proton therapy, or proton radiotherapy
- Advantages of proton therapy → proton is a charged particle → the dose is deposited over a narrow range of depth → minimal entry exit or scattered radiation dose → less damage to healthy tissue and dose escalation on the tumor
- Proton therapy is especially used for the treatment of children cancers, for cases in which dose escalation is needed (ocular tumors,…) or to reduce unwanted side effects by lessening the dose to normal tissue (prostate cancer,…)
- Use of cyclotrons to produce beam of protons → typically 230 MeV → smaller energies are obtained after deceleration into a degrader (up to 70 MeV)

External radiotherapy: Protons (2)



External radiotherapy: Neutrons

- Boron neutron capture therapy (BNCT) → 2 steps →
    1. the patient is injected with a tumor-localizing drug containing a non-radioactive isotope characterized by a high probability to capture thermal neutrons → boron-10 (^{10}B)
    2. the patient is irradiated by neutrons → the neutrons are captured by the ^{10}B → emission of high-energy alpha particles → kill tumor cells

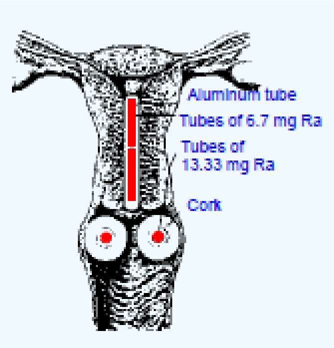
$$ {}^{10}_{5}B + {}^{1}_{0}n \rightarrow \begin{cases} {}^{7}_{3}Li + {}^{4}_{2}\alpha & Q = 2.792 \text{ MeV (fundamental - 6\%)} \\ {}^{7}_{3}Li^{*} + {}^{4}_{2}\alpha & Q = 2.310 \text{ MeV (excited - 94\%)} \end{cases} $$

- Treatment of locally invasive as brain tumors
- Need of nuclear reactor or neutron source accelerator
- Developments in USA, Japan, Finland, Sweden, (Belgium?),…

Brachytherapy

- Brachytherapy (« brachios » is a Greek word meaning short-distance) → form of radiotherapy where a sealed radiation source is placed inside the area requiring treatment (on the skin or inside the body)
- Treatment of cervical, prostate, breast and skin cancer
- First → use of Ra-226
- Now → Ra is stopped due to problems of safety for the people around the patient → other isotopes are used: Co–60, Ir–192,…

Isotope	Radiation	Half life $T_{1/2}$
Ra-226	Average 0.83 MeV	1620 years
Co-60	1.17 and 1.31 MeV	5.26 years
Cs-137	0.66 MeV	30 years
Au-198	0.42 MeV	2.7 days
Ir-192	0.38 MeV	73.8 days
I-125	28 keV EC. γ + x-rays	60 days
Pd-103	21 keV EC. x-rays	17 days
Cs-131	29 keV EC. x-rays	9.7 days



Images taken from: T. Henriksen and Biophysics group at UiO, *Radiation and Health*, Oslo, 2013

Unsealed source radionuclide therapy

- Unsealed source radionuclide therapy (RNT) or molecular radiotherapy → use of radioactive substances (radiopharmaceuticals) to treat diseases (cancer) → they are introduced into the body (commonly injection or ingestion) → they migrate to specific locations (depending on their properties)

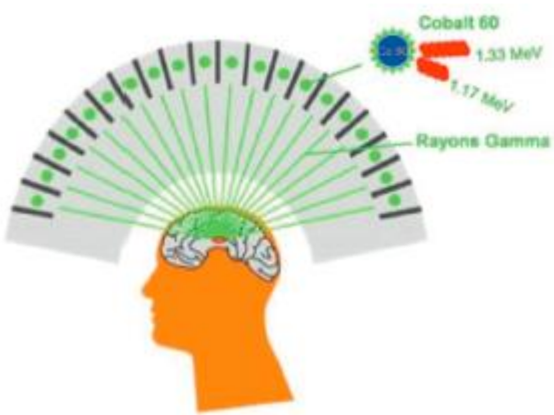
- Example: thyroid cancer → injection of I-131

Stereotactic radiation therapy

- Stereotactic radiation therapy (also stereotaxic radiation therapy) → use of special equipment to position the patient and precisely deliver radiation to the tumor
- Treatment of brain tumors (principally)
- Delivery of high doses of radiation with sub-millimeter accuracy
- Example: Gamma Knife at Erasme

Image taken from: N. Massager, *Rev. Med. Brux.*, 2012; 33 : 367-70

Erasme Gamma Knife



Sterilization

- Sterilization with ionizing radiation inactivates microorganisms very efficiently
- Method for sterilizing single-use medical devices such as syringes and surgical gloves
- More than 160 gamma irradiation plants around the world to sterilize medical devices
- Around 12 million m^3 of medical devices are sterilized by radiation annually

Source: https://www.iaea.org/