Review of last week: Introduction to Nuclear Physics and Nuclear Decay

Nucleons (protons & neutrons) experience a very short range (~1 fm) strong attractive force that overcomes repulsive electrostatic force of protons to hold nucleus together. Nucleon mass =940 MeV/c^2 (1.7x10^{-27} kg) (e- mass = 0.5MeV/c^2 (9.1x10^{-31}kg)); nucleus ~ 10^{-14} m (atom~10^{-10} m)

Numbers of nucleons in nucleus

Z (*atomic number*) = number of protons in nucleus, determines element

N = number of neutrons in nucleus

A (*atomic mass number*) = *Z* + *N*

Excited & ground state nuclei with identical *Z*, *N*, and *A*

Nuclei with equal # are

Isotopes

Isotones

Isobars

Isomers

Stable nuclei have N > *Z* (more strong force to overcome larger electrostatic repulsion of more *p*) (except lowest *A* elements, where *Z* = *N*, up to O-16). Unstable nuclei exist on both sides of 'line of stability'

Alpha Decay: A>150 $\quad {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He^{+2} \qquad \alpha = {}^{4}_{2}He^{+2}$ mono-energetic, highly ionizing, no imaging appl.

Beta ± Decay: Isobaric $\quad {}^{A}_{Z}X \rightarrow {}^{A}_{Z\mp1}Y + \beta^{\pm} + \nu$ β± are electrons/positrons, energy shared by β & ν, β+→ PET

β+ decay competes with electron capture; ${}^{A}_{Z}X + e^{-} \rightarrow {}^{A}_{Z-1}Y + \nu$

Gamma Transition: Isomeric $\quad {}^{A[m]}_{Z}X^{[*]} \rightarrow {}^{A}_{Z}X + \gamma$ follows α, β decay, mono-energetic, competes with internal conversion, in which an orbital e- is ejected instead of the γ

Decay Equation: Random process (Poisson) $\quad N(t) = N_0 e^{-\lambda t} \qquad T_{1/2} = \frac{ln(2)}{\lambda} = \frac{0.693}{\lambda}$

Electron capture & internal conversion followed by characteristic x-rays (or Auger e-)

Radionuclide Production

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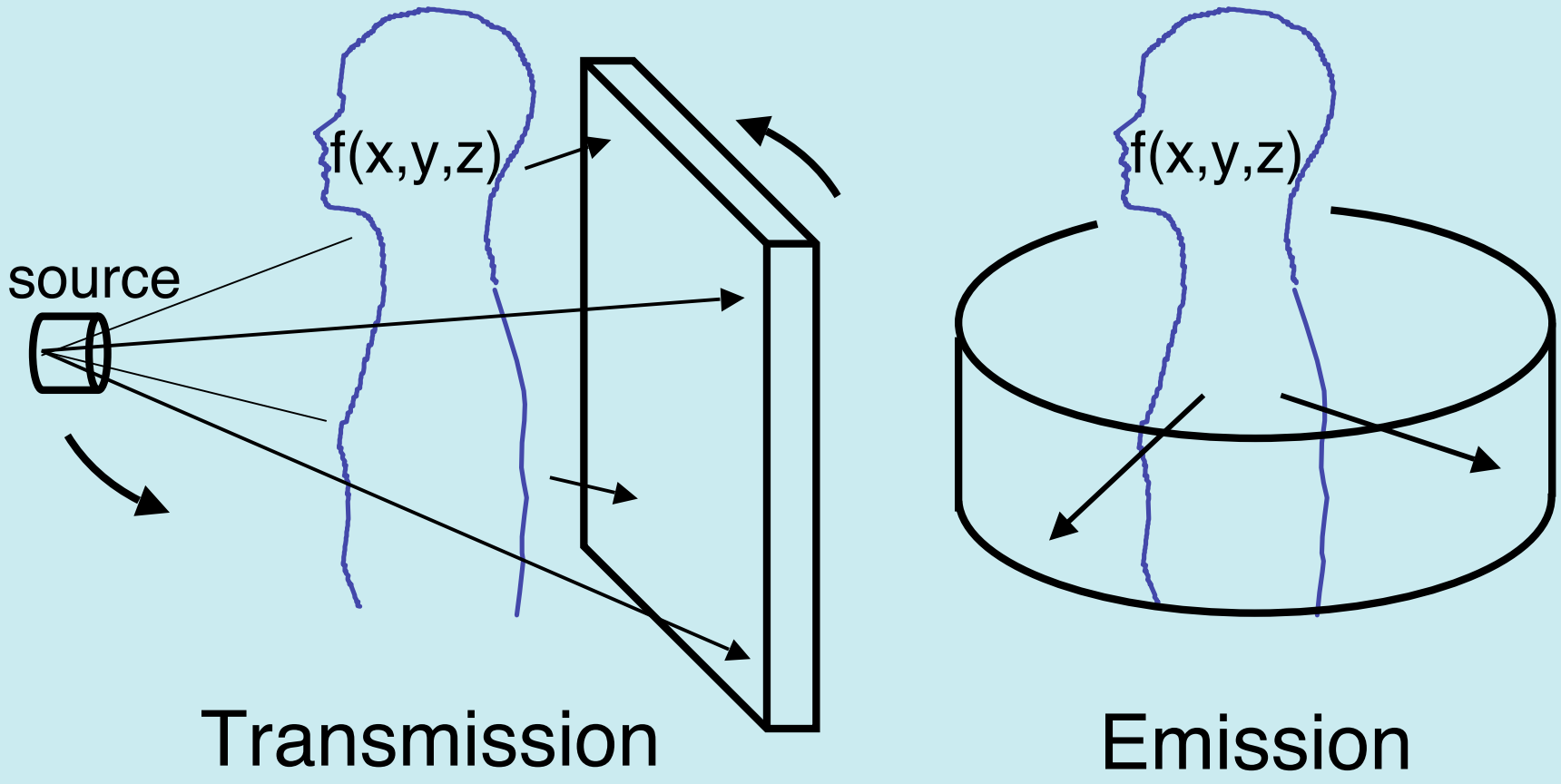
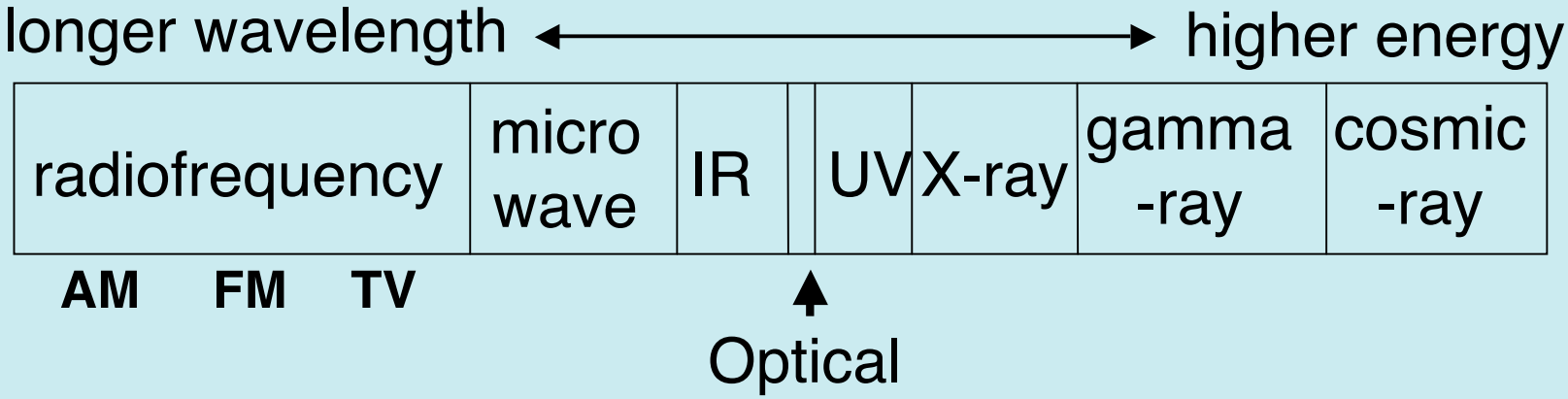
Emission versus Transmission Imaging

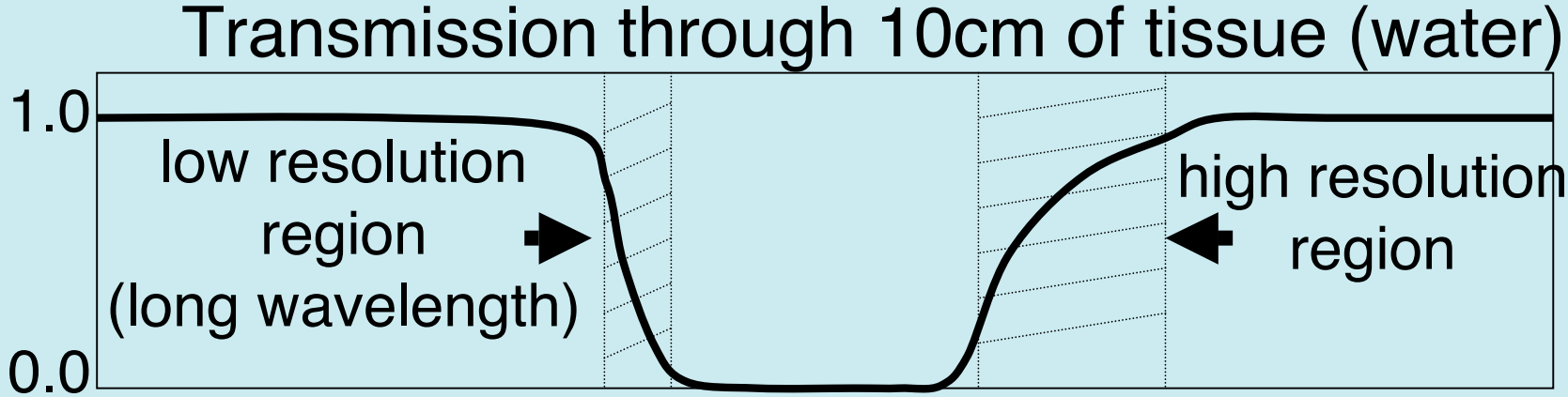
External versus internal radiation sources



Physics of Transmission Imaging

The Electromagnetic Spectrum



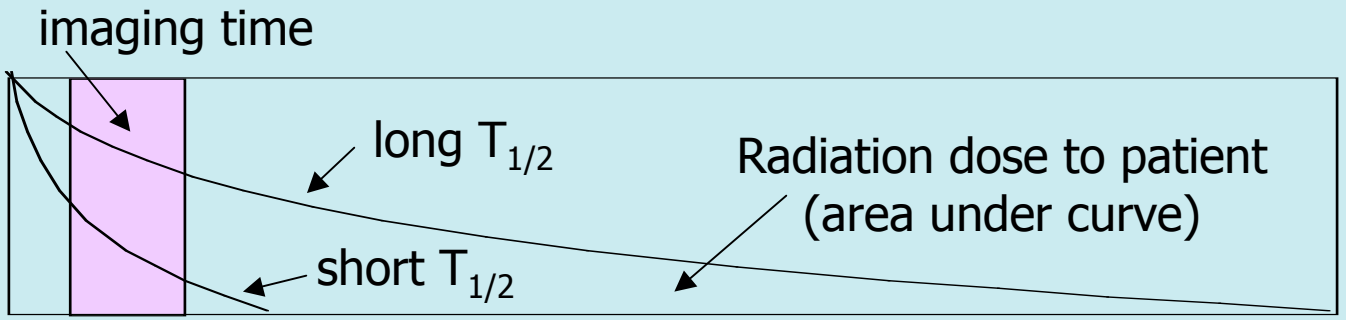


Injection of a Radiotracer

Short lived isotopes

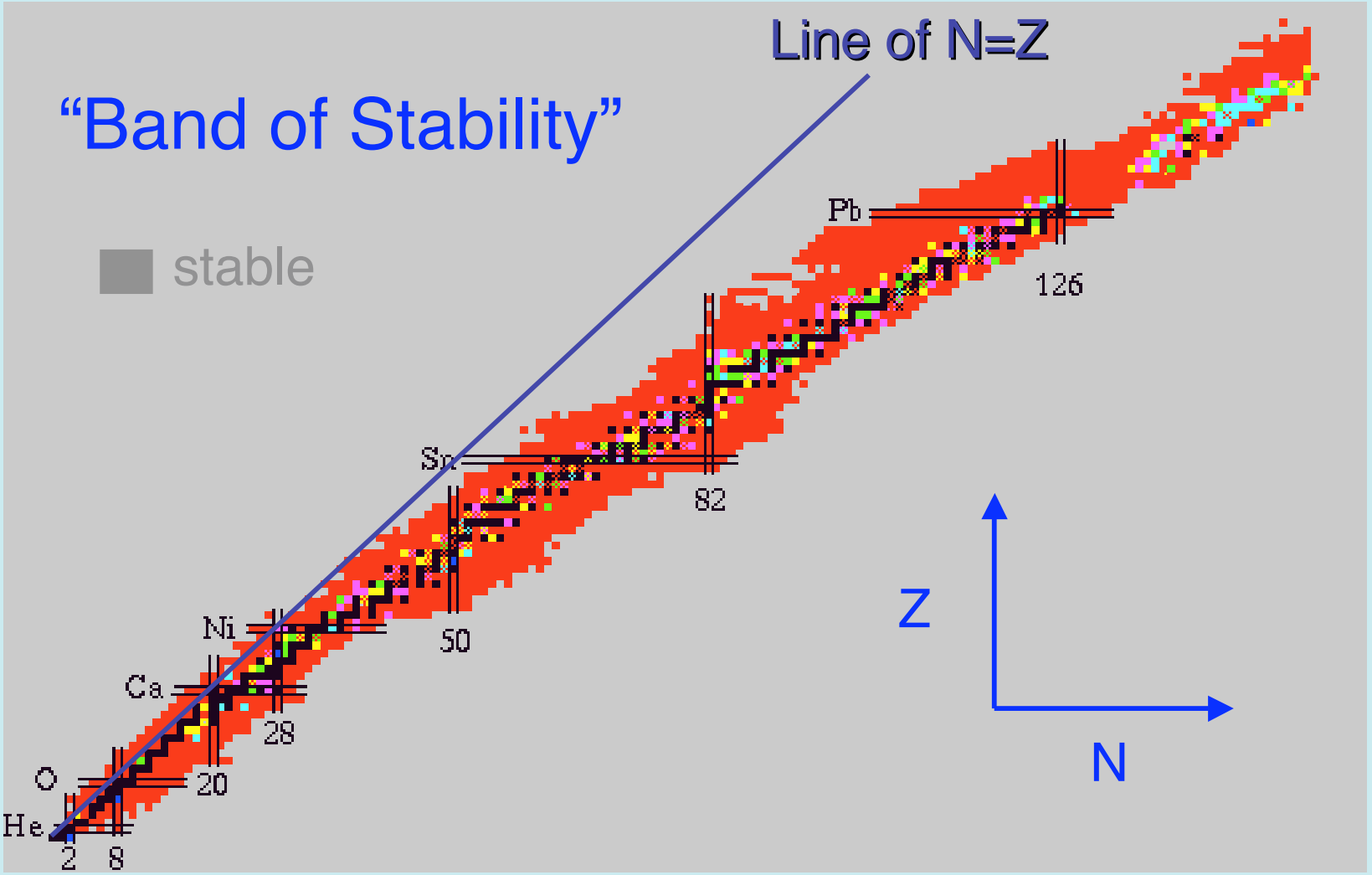
- We would like to use short-lived isotopes to minimize partient radiation dose
- Unlike an X-ray device. we can't turn it off
- Recall that radition decays with an exponentially, characterized by a 'half-life' $T_{1/2}$

$$A(t) = A(0)e^{-t(\ln(2)/T_{1/2})}$$



- Naturaly-occuring isotopes are long-lived, naturally
- So if we want a short-lived isotope we must produce it

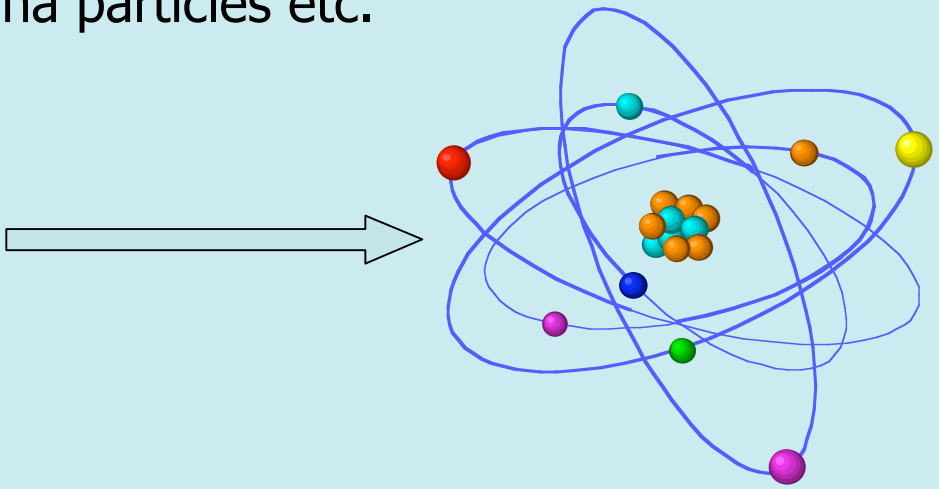
Making unstable isotopse



We have to change the ratio of neutrons (N) to protons (Z) to get outside the band of stability

Nulcear bombardment

Hit nucleus of stable atoms with sub-nuclear particles: neutrons, protons, alpha particles etc.



There are two main methods of performing this bombardment

1. Inserting target in a nuclear reactor - fine for longer-lived isotopes as some time is needed for processing and shipment
2. Using a charged-particle accelerator called a 'cyclotron' - needed locally for short-lived isotopes ($T_{1/2}$ ~ 1 to 100 min). We have two here at UWMC
3. We can also use longer-lived isotopes from a nuclear reactor that decay to a short-lived radioisotope in a portable 'generator'

Common Radionuclides

TABLE 9.1. *Characteristics of common radionuclides*

Nuclide	Photons (keV)	Production mode	Decay mode	Half-life ($T_{1/2}$)
^{67}Ga	93, 185, 296, 388	Cyclotron	EC	78 hr
^{99m}Tc	140	Generator	IT	6 hr
^{111}In	173, 247	Cyclotron	EC	68 hr
^{123}I	159	Cyclotron	EC	13 hr
^{125}I	27, 36	Reactor	EC	60 d
^{131}I	364	Fission product	β	8 d
^{133}Xe	80	Fission product	β	5.3 d
^{201}Tl	70, 167	Cyclotron	EC	73 hr

β, beta decay; EC, electron capture; IT, isomeric transition.

Raphex Question

An ideal radiopharmaceutical would have all the following except:

a. Long half-life
b. No particulate emissions
c. Target specificity
d. 150 to 250 keV photons
e. Rapid biological distribution

Raphex Question and Answer

An ideal radiopharmaceutical would have all the following except:

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a: The ideal radionuclide has a short half-life to reduce the radiation dose to the patient

Reactor Produced Isotopes

Most important reaction $^{235}U + n \rightarrow {}^{236}U^{*}$

which decays spontaneously via nuclear fission and a (hopefully) controlled chain reaction producing lots of protons, neutrons, alpha particles etc.

We can have different types of reactions to produce desired isotopes from stable target materials

1. (n,γ): $${}^{A}_{Z}X + n \rightarrow {}^{A+1}_{Z}X^{*} \rightarrow {}^{A+1}_{Z}X + \gamma$$
2. (n,p): $${}^{A}_{Z}X + n \rightarrow {}^{A}_{Z-1}Y + p$$

Notes

If the number of protons (Z) changes, then so does the element

Because neutrons are added, activated materials tend to lie above the line of stability, and thus to decay by electron emission

Even in high neutron fluxes, only small amounts are activated, say $1{:}10^{6}$-10^{9}

For (n,γ) production, which is most common, the element does not change, so it is difficult to get carrier-free product

Reactor Produced Isotopes

Some isotopes used in Nuclear Medicine

Table 7-1
Some Reactor-produced Radionuclides Used in Nuclear Medicine and Radiotracer Kinetics

Radionuclide	Decay Mode	Production Reaction	Natural Abundance of Target Isotope (%)	σ_c (b)*
^{14}C	β^-	$^{14}N(n,p)^{14}C$	99.6	1.81
^{24}Na	(β^-,γ)	$^{23}Na(n,\gamma)^{24}Na$	100	0.53
^{32}P	β^-	$^{31}P(n,\gamma)^{32}P$	100	0.19
		$^{32}S(n,p)^{32}P$	95.0	—
^{35}S	β^-	$^{35}Cl(n,p)^{35}S$	75.5	—
^{42}K	(β^-,γ)	$^{41}K(n,\gamma)^{42}K$	6.8	1.2
^{51}Cr	(EC,γ)	$^{50}Cr(n,\gamma)^{51}Cr$	4.3	17
^{59}Fe	(β^-,γ)	$^{58}Fe(n,\gamma)^{59}Fe$	0.3	1.1
^{75}Se	(EC,γ)	$^{74}Se(n,\gamma)^{75}Se$	0.9	30
^{125}I	(EC,γ)	$^{124}Xe(n,\gamma)^{125}Xe \xrightarrow{EC} {}^{125}I$	0.1	110
^{131}I	(β^-,γ)	$^{130}Te(n,\gamma)^{131}Te \xrightarrow{\beta^-} {}^{131}I$	34.5	0.24

*Thermal neutron capture cross-section, in barns, for (n,γ) reactions (see Section D.1). Values from ref. 1.

Cyclotron Production

Basically a linear accelerator rolled up into a spiral. Typically accelerate an H^- ion using alternating electric fields. The magnet is used to bend the path of the charged particle. The proton then hits the target

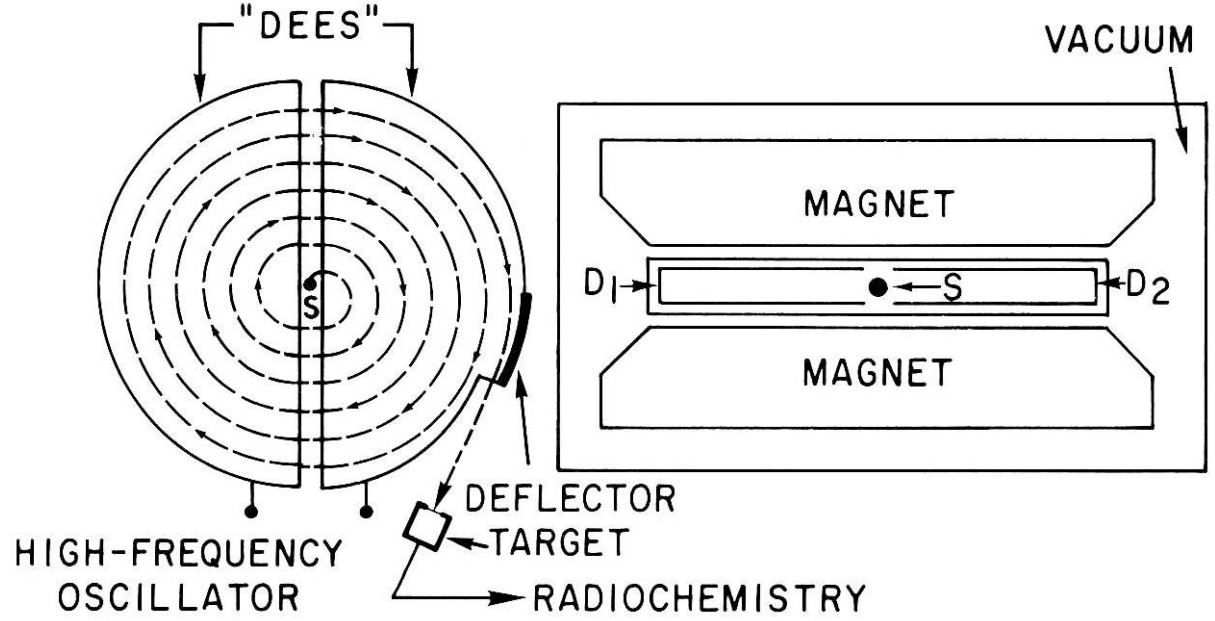

Fig. 7-2. Schematic representation of a cyclotron; top (left) and side (right) views. D_1 and D_2 are the ''dees'' to which the accelerating voltage is applied by a high-frequency oscillator. Target line may feed directly to a radiochemistry area.

Cyclotron Production

Notes

Since we are using proton bombardment we change the element and typically lie below the line of stability. Thus decay is typically by positron emission.

Cyclotrons can be located locally, thus allowing for short lived isotopes, reducing patient dose.

Cylcotrons, however, are very expensive to buy and operate. Often there are distrubution networks.

Cyclotron Produced Isotopes

By far the most common is ^{18}F in ^{18}F-FDG for PET oncology

Table 7-2
Some Cyclotron-produced Radionuclides Used in Nuclear Medicine

Product	Decay Mode	Common Production Reaction	Natural Abundance of Target Isotope (%)
^{11}C	β^+	$^{10}B(d,n)^{11}C$	19.7
		$^{11}B(p,n)^{11}C$	80.3
^{13}N	β^+	$^{12}C(d,n)^{13}N$	98.9
^{15}O	β^+	$^{14}N(d,n)^{15}O$	99.6
^{18}F	β^+,EC	$^{20}Ne(d,\alpha)^{18}F$	90.9
^{22}Na	β^+,EC	$^{23}Na(p,2n)^{22}Na$	100
^{43}K	(β^-,γ)	$^{40}Ar(\alpha,p)^{43}K$	99.6
^{67}Ga	(EC,γ)	$^{68}Zn(p,2n)^{67}Ga$	18.6
^{111}In	(EC,γ)	$^{109}Ag(\alpha,2n)^{111}In$	48.7
		$^{111}Cd(p,n)^{111}In$	12.8
^{123}I	(EC,γ)	$^{122}Te(d,n)^{123}I$	2.5
		$^{124}Te(p,3n)^{123}I$	4.6
^{201}Tl	(EC,γ)	$^{201}Hg(d,2n)^{201}Tl$	13.2

Generators

Alternative to reactors or cylotron is to use a 'mother' isotope that has a long half-life that decays to a short half-life 'daughter' that can be used for imaging.

The mother isotope is produced in a nuclear reactor and then shipped in a 'generator'.

As needed, the daughter isotope is 'eluted' and combined into a radiopharmaceutical

Workhorse of general nuclear medicine

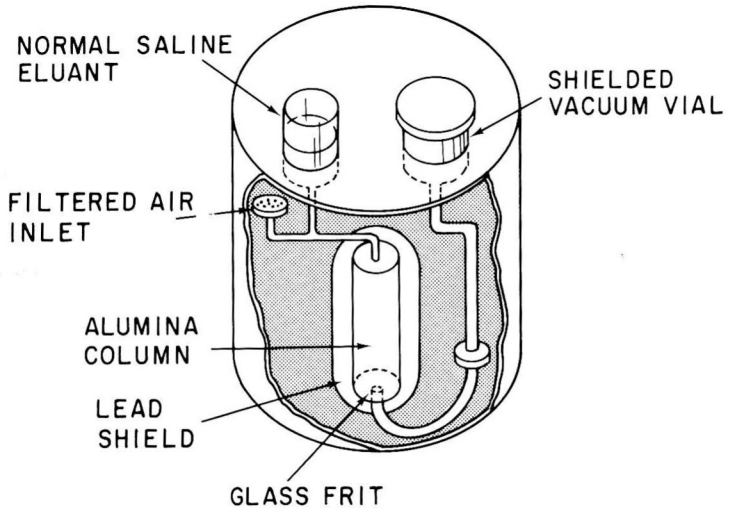

Fig. 7-5. Cross-sectional drawing of a ^{99}Mo-^{99m}Tc generator. (Courtesy of the Society of Nuclear Medicine and Thomas R. Gnau.)

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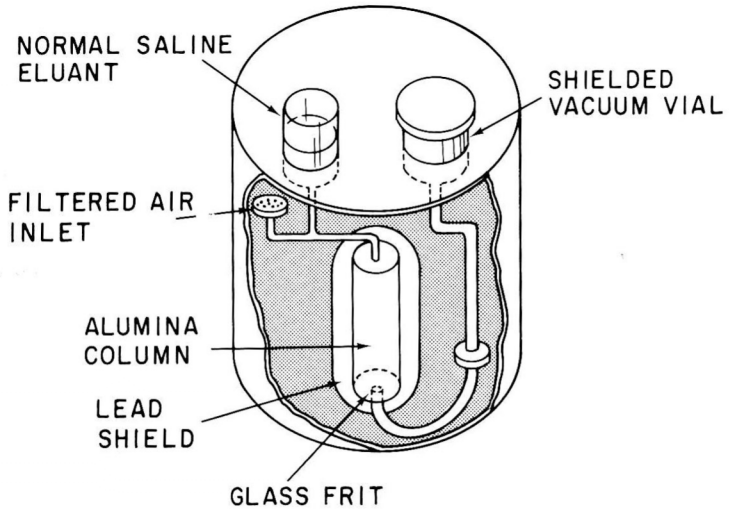

Fig. 7-5. Cross-sectional drawing of a ^{99}Mo-^{99m}Tc generator. (Courtesy of the Society of Nuclear Medicine and Thomas R. Gnau.)

Generator Radionuclides

- ^{99m}Tc (daughter isotopes) generators are by far the most common
- The mother isotope in ^{99}Mo, which is reactor produced.
- The generators typically replaced monthly

Table 7-3
Some Radionuclide Generators Used in Nuclear Medicine

Daughter†	Decay Mode	$T_{1/2}$	Parent	$T_{1/2}$
^{68}Ga	β^+,EC	68 min	^{68}Ge	275 days
^{82}Rb	β^+,EC	1.3 min	^{82}Sr	25 days
^{87m}Sr	IT	2.8 hours	^{87}Y	80 hours
^{99m}Tc	IT	6 hours	^{99}Mo	66 hours
^{113m}In	IT	100 min	^{113}Sn	120 days

†Generator product.

Generator Activity Levels

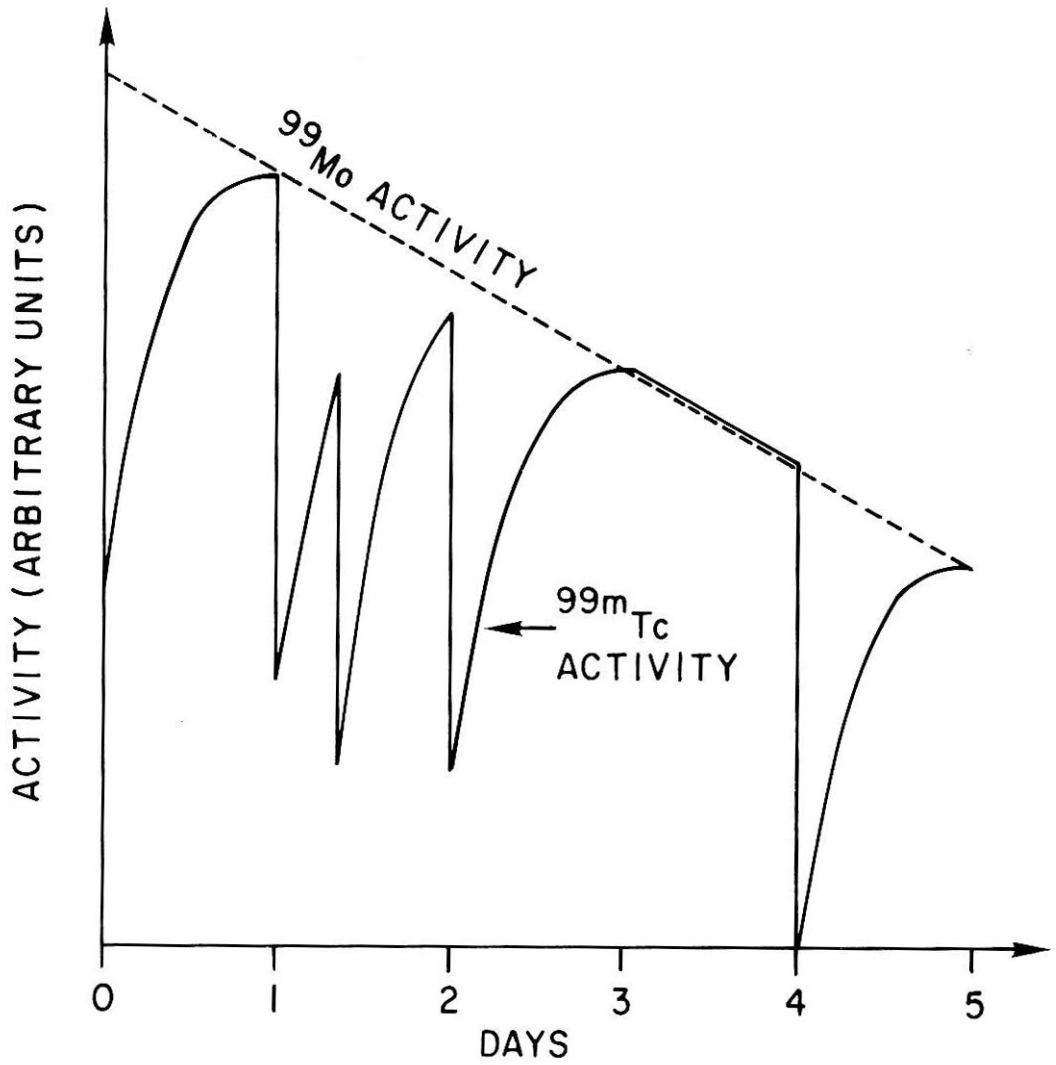

Fig. 7-6. Buildup and decay of ^{99m}Tc generator eluted on days 0, 1, 1.4, 2, and 4.

Raphex Question

99mTc generators cannot be:

a. Produced in a cyclotron

b. Used to dispense more than 1 Ci

c. Shipped by air

d. Purchased by licensed users

e. Used for more than 67 hours

Raphex Question and Answer

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a. Produced in a cyclotron

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a. ^{99}Mo can be produced in a reactor or from fission products, but it cannot be produced in a cyclotron (^{99}Mo is a beta emitter, requiring the addition of neutrons, not protons).