National Cancer Institute

INTRODUCTION TO RADIATION PHYSICS AND DOSIMETRY

Steven L. Simon, Ph.D.
Radiation Epidemiology Branch
Division of Cancer Epidemiology and Genetics
National Cancer Institute

RADIATION EPIDEMIOLOGY & DOSIMETRY COURSE

SPRING 2011

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
National Institutes of Health

GOALS OF THIS LECTURE:

To assist you in gaining an understanding of the fundamental concepts of physics underlying the theory of dosimetry for ionizing radiation.

Here are the topics that I hope you will gain an understanding of:

- Basic concepts of the nucleus and the nuclear particles involved in radioactive decay
- The meaning and the differences between radioactivity and radiation
- The processes that lead to emission of radiation
- The processes that lead to absorption of radiation in tissue
- The approximate ranges of energies in which the various emission and absorption processes operate
- The basic definitions of ‘exposure’ and ‘absorbed dose’
- Which dose units to use and why.
- Sources of radiation exposure in normal life.
- Sources of information about dosimetry that might assist you in epidemiologic studies.

Note: This presentation was prepared for training for Fellows in Radiation Epidemiology Branch of NCI

THE MOST BASIC CONCEPT IN THE STUDY DOSIMETRY IS WHAT ??

ENERGY

Energy…what's that?

Beyond the basic definition, ENERGY is usually defined according to type.

Energy: The amount of work a physical system can do.

Chemical energy: The potential for substances to undergo transformation or to transform other substances.

Kinetic energy: the form of energy as a consequence of the motion of an object.

Potential energy: the form of energy that is due to the position of an object.

Binding energy: the energy required to disassemble a whole into separate parts, e.g., the binding energy of electrons, nuclear particles, or even molecules.

Nuclear energy: energy that is the consequence of decomposition of an atomic nucleus.

<u>WORK</u>: The amount of energy transferred by a force.

<u>FORCE</u>: An influence that may cause a body to accelerate. It may be experienced as a lift, a push, or a pull.

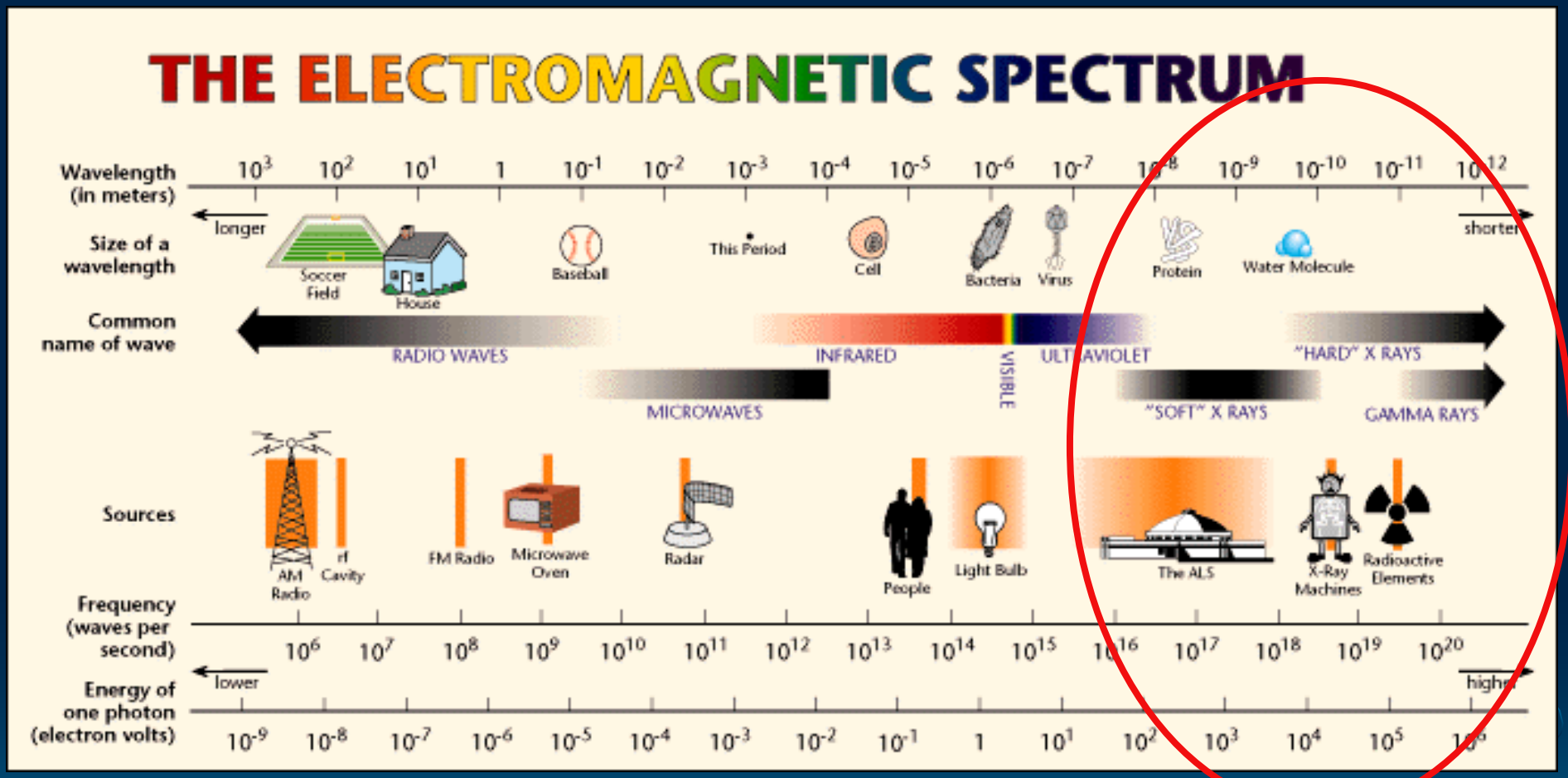
Force is mathematically defined as the rate of change of the momentum of the body (F= mass * acceleration)

Only four fundamental forces are recognized in physics: (1) strong, (2) electromagnetic, (3) weak, and (4) gravitational (in order of decreasing strength). These forces account for why the nucleus of atoms stays together as well as explain radioactive decay.

Q: Why are we interested in understanding ENERGY (and consequently, WORK and FORCE in Radiation Epidemiology?

A quantitative description of the transfer of energy to biological materials (organisms, tissues, organs) is how radiation dose is defined. And radiation risk is defined to be a function of the dose.

Hence, the concepts of Energy and how Energy is transferred to produce radiation exposure provide the logical links between Physics, Radiation Dosimetry, and Radiation Epidemiology.



A reminder that we are discussing only ionizing radiation in this lecture…even though other types of radiation are of interest in epidemiology.

Radiation

Radiation, in our context, is energy in the form of high speed particles and electromagnetic waves. Radiation is further defined into ionizing and non-ionizing radiation.

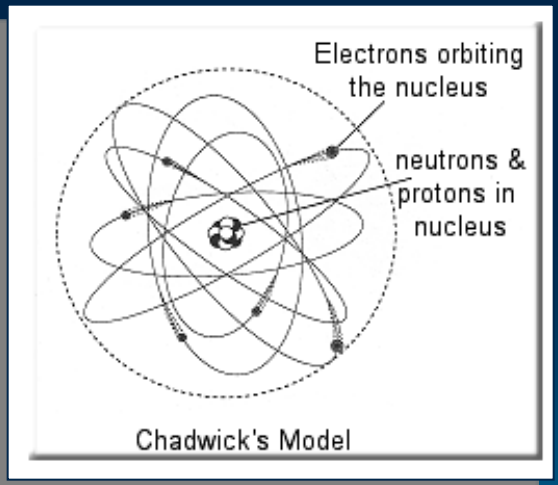
- ***Ionizing radiation*** is radiation with enough energy so that during an interaction with an atom, it can remove bound electrons, causing the atom to become charged or to become 'ionized'. Examples are X-rays and electrons.

- ***Non-ionizing radiation*** is radiation without enough energy to remove bound electrons from their orbits around atoms. Examples are microwaves and visible light.

Part I.
CONCEPTS OF NUCLEAR AND RADIATION PHYSICS

Nuclear Properties and Terminology

- The atom, for all practical purposes, consists of three basic particles, electrons, neutrons, and protons.
- The nucleus contains protons, which have positive charge, and neutrons, which have no charge.
- Both the proton and neutrons have masses approximately 1,836x that of orbital electrons which are generally described as surrounding the nucleus, either as discrete particles, are part of an electron 'cloud'.



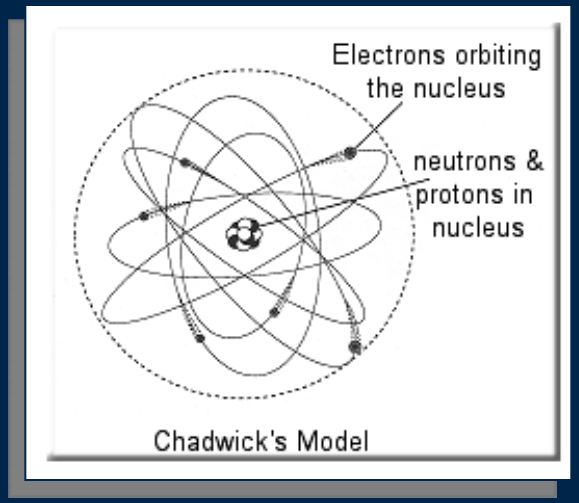
This model of the atom, though obviously simplistic, is sufficient for the purposes here.

Diameter of nucleus ~10^{-12} cm
Diameter of atom ~10^{-8} cm

Number of protons = Z, where Z is called the “atomic number”

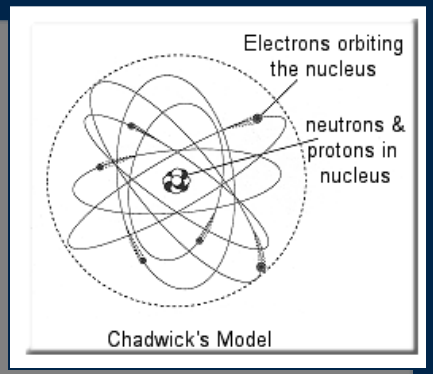
Number of neutrons = N

A = Z + N, where is the “atomic mass”



A nuclide is an atom of a particular atomic mass A

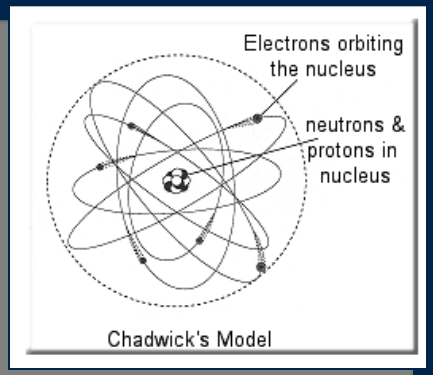
Nuclides are written as: $^{A}_{Z}X$ **(where X is the chemical symbol)**



- The nucleus contains about 99.75% of the mass of an atom.
- 1 mass unit or 'u' is equivalent to 1/12 a ^{12}C atom.
- The energy equivalent of that mass, determined as $E=mc^2$, is 1.49×10^{-10} Joules (J) or 931×10^6 eV (931 MeV).

Mass and energy equivalence of some nuclear particles

Particle	Mass units 'u'	m_oc^2 (MeV)
Electron	5.48597×10^{-4}	0.511007
Neutron	1.008665	939.551
Proton	1.007277	938.258
Alpha particle	4.001506	3727.323



The actual mass of an atomic nucleus is always a little smaller than the sum of the rest masses of all its nucleons (protons and neutrons).

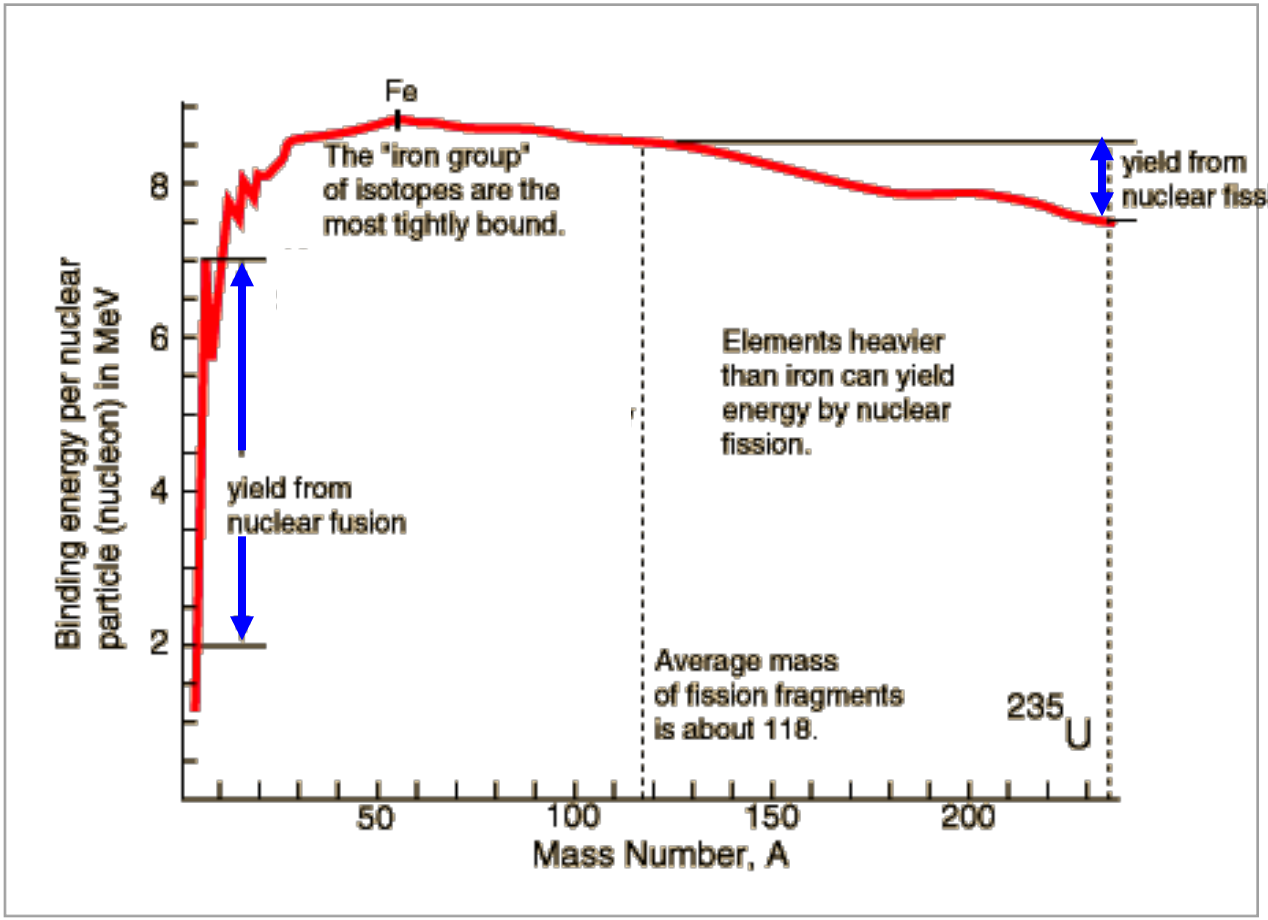
The reason is that some of the mass of the nucleons is changed into energy to form the nucleus (and overcome the electrostatic repulsion among like charges).

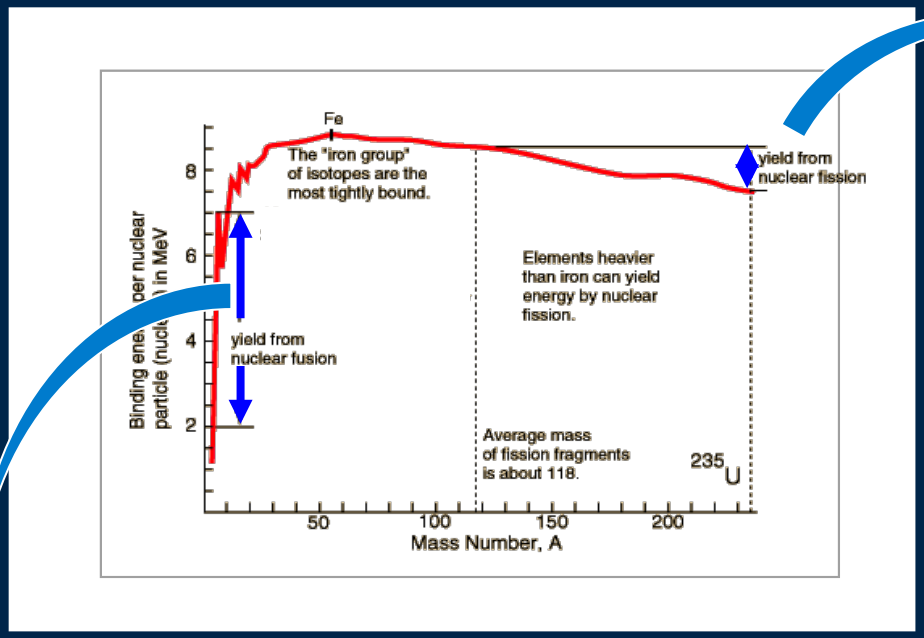
Using the $E=mc^2$ formulation, the **Binding Energy** can be written as difference in the sum of the rest masses of the individual nucleons and the rest mass of the assembled nucleus:

$$BE = [Zm_p + (A-Z)m_n - {}^{A}_{Z}m]\, c^2$$

The binding energy explains the source of the energy released by radioactive decay processes. **That energy is of great importance in dosimetry.**

Binding Energy for nucleons varies with mass number



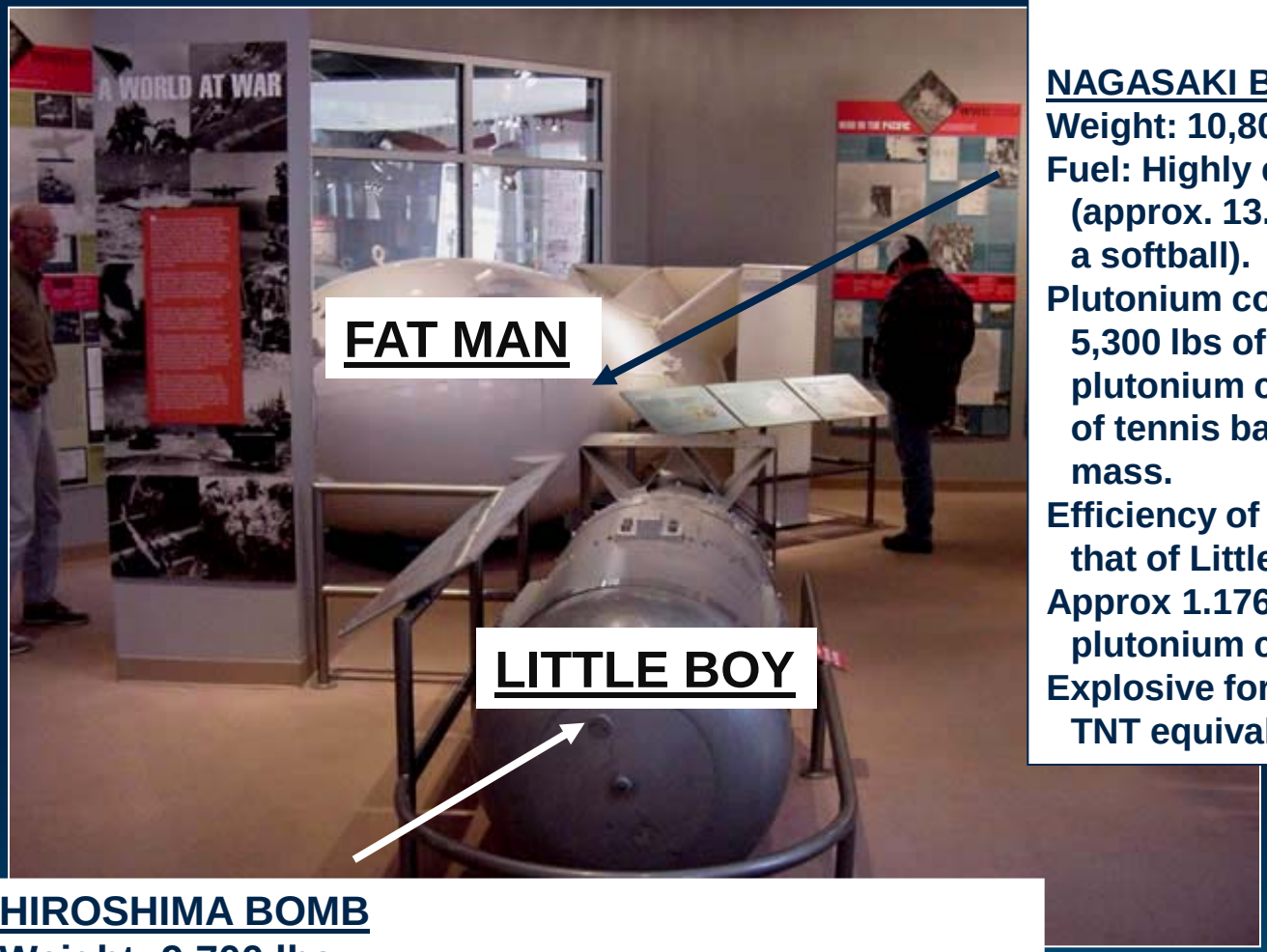

Fe
The "iron group" of isotopes are the most tightly bound.
yield from nuclear fission
Elements heavier than iron can yield energy by nuclear fission.
yield from nuclear fusion
Average mass of fission fragments is about 118.
235U
Binding energy per nuclear particle (nucleon) in MeV
8
6
4
2
50
100
150
200
Mass Number, A

Nuclear fission weapon

Nuclear fusion weapon

Nuclear fission power plant

Historical Sidebar on harnessing the Binding Energy



NAGASAKI BOMB

Weight: 10,800 lbs

Fuel: Highly enriched Pu-239 (approx. 13.6 lbs; approx. size of a softball).

Plutonium core surrounded by 5,300 lbs of high explosives; plutonium core reduced to size of tennis ball to form critical mass.

Efficiency of weapon: 10 times that of Little Boy.

Approx 1.176 Kilograms of plutonium converted to energy

Explosive force: ~21,400 tons of TNT equivalent.

HIROSHIMA BOMB

Weight: 9,700 lbs

Fuel: Highly enriched uranium (approx. 140 lbs); target - 85 lbs and projectile - 55 lbs

Efficiency of weapon: poor

Approx. 1.38% of the uranium fuel actually fissioned

Explosive force: ~16,000 tons of TNT equivalent.

Nuclear Decay Processes

- The process of spontaneous nuclear transformation occurs primarily because of instability in the neutron to proton ratio or because the atom is an excited state following a previous transformation.

- This transformation process towards a more stable condition is termed *nuclear disintegration or radionuclide decay*.

- Radioactivity refers to the property of unstable atoms to transform themselves and move to a more stable configuration.

- The nuclear transformation process releases energy via photons or emission of particles. The energy and/or particles released are loosely termed *radiation*. (!!!)

Summary of radiation types and selected characteristics

Radiation Type	Charge	Approximate energy range	Approximate range In air	Approximate range In water	Primary Source
	Energetic Particles				
Alpha (2n+2p)	+2	3 to 9 MeV	2 to 8 cm	20 μm to 100 μm	Some nuclei of high Z
Electron (beta, positron)	± 1	0 to 3 MeV	Up to 12 m	Up to a few mm	Nuclei with high or low n/p ratio
Neutron	0	0 to 10 MeV	Up to 100 m	Up to 1 m	Nuclear reactions
	Electromagnetic Radiation				
X ray	None	A few eV to several MeV	A few mm to 10 m	Up to a few cm	Orbital electron transitions and *Bremsstrah-ung*
Gamma ray	None	~10 keV to 10 MeV	A few cm to 100 m	From a few mm to several cm	Nuclear transitions

We will briefly discuss each process that leads to the emission of radiation …

Alpha decay

All nuclei heavier than lead (Pb) are unstable; most decay by alpha emission.

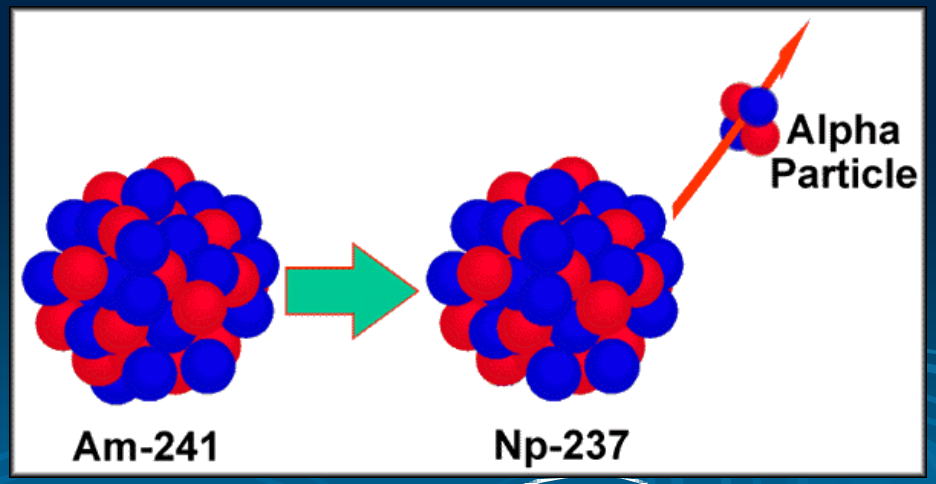
In alpha decay, 2p+2n leave the nucleus as a single 'alpha' (α) particle.

For example, natural uranium-238 decays by alpha emission:

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}\alpha$$

Energy released = Q_α = 4.268 MeV (KE of particle), $t_{1/2}$ = 4.51 $_{x\ 10}{}^{9}$ years

Another example is the decay of ^{241}Am, which itself is a product of the decay of ^{241}Pu:



Spontaneous fission

Some heavy nuclei can split (fission) into several smaller fragments plus neutrons.

Most nuclides that undergo spontaneous fission are more likely to decay by alpha decay.

For ^{238}U (>99.3% of all uranium), alpha decay is about 2 million times more probable than spontaneous fission, whereas in ^{256}Fm, 3% of the nuclei undergo alpha decay and 97% undergo spontaneous fission.

The fission fragments are generally radioactive and decay by a chain of β emissions toward stable nuclei. Example:

$$^{252}_{98}Cf \rightarrow {}^{140}_{54}Xe + {}^{108}_{44}Ru + 4\,{}^{1}_{0}n$$

Beta (β) decay

Beta decay involves a class of particles called ‘leptons’ which include electrons (e-), positrons (e+), neutrinos (ν), and anti-neutrinos ($\overline{\nu}$). Beta decay processes <u>conserve</u> lepton number as well as charge.

Beta (β) decay

Beta decay involves a class of particles called 'leptons' which include electrons (e-), positrons (e+), neutrinos (ν), and anti-neutrinos ($\bar{\nu}$). Beta decay processes <u>conserve</u> lepton number as well as charge.

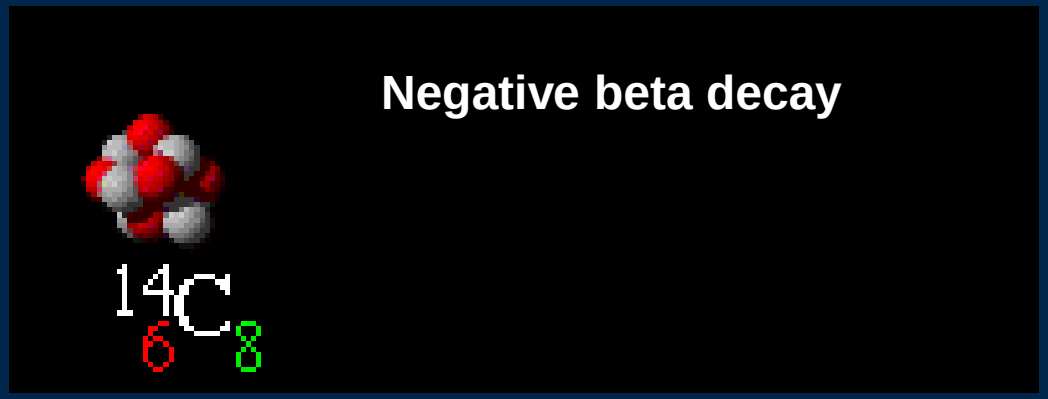
In β decay, there are 3 processes:

$n \rightarrow p + \beta^- + \bar{\nu}$ (β^- decay)

$p \rightarrow n + \beta^+ + \nu$ (β^+ decay)

$p + e^- \rightarrow n + \nu$ (electron capture or 'EC')

Negative beta decay: the decay of a neutron into a proton, which remains in the nucleus, and an electron, which is emitted as a beta particle

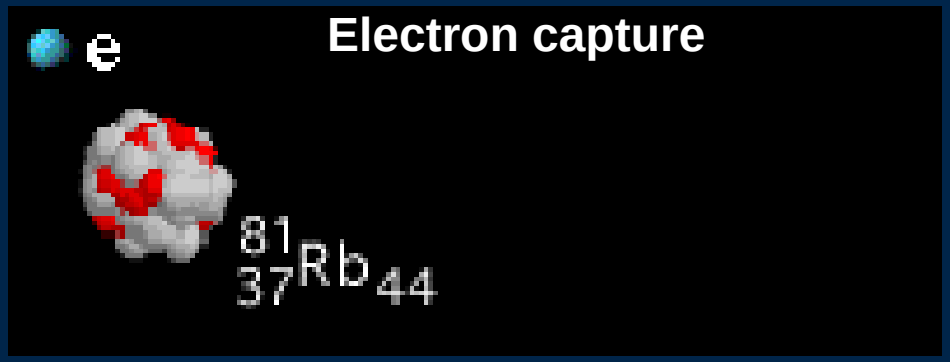


$$^{14}_{6}C_{8} \Rightarrow {}^{14}_{7}N_{7} + e + \bar{\nu}_e$$

Positive beta decay: the decay of a proton into a neutron, which remains in the nucleus, and a positive electron, which is emitted as a beta particle

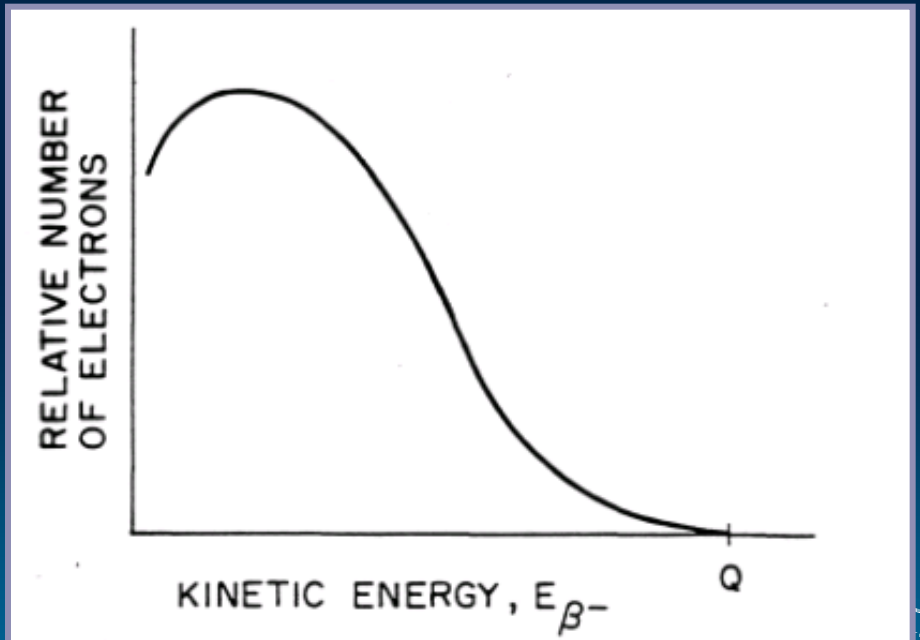
$$^{18}_{9}F_{9} \Rightarrow {}^{18}_{8}O_{10} + e^{+} + \nu_{e}$$

Electron capture: the capture of an electron by the nucleus, resulting in the loss of one proton and the creation of one neutron.



$$^{81}_{37}\mathrm{Rb}_{44} + \mathrm{e} \Rightarrow {}^{81}_{36}\mathrm{Kr}_{45} + \nu_{\mathrm{e}}$$

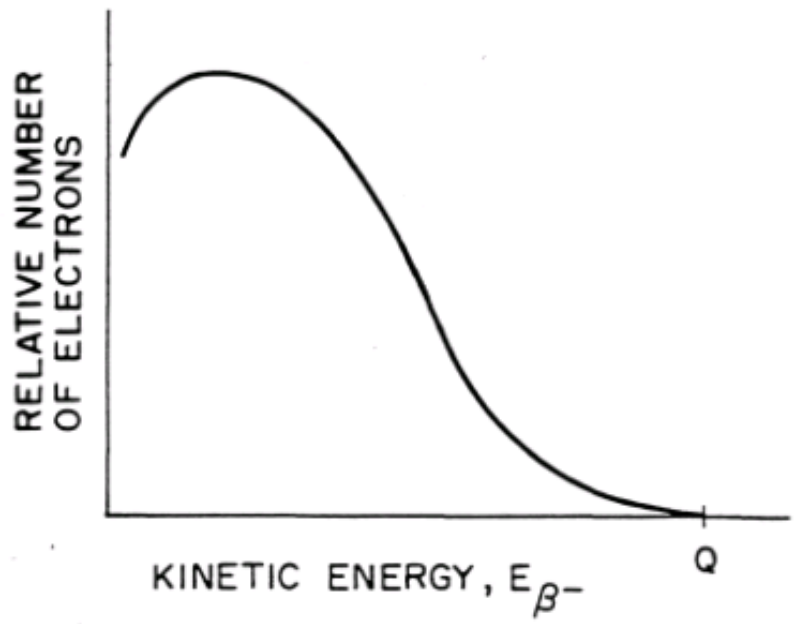
It is worthwhile to note that emitted beta particles, unlike other emitted radiations, have a continuous a spectrum of energies.



Shape of typical beta-particle energy spectrum.

It is worthwhile to note that emitted beta particles, unlike other emitted radiations, have a continuous a spectrum of energies.

The β-radiation are electrons are emitted in the decay process with a certain kinetic energy that originate from the energy difference between the decaying nucleus and the decay product. As part of the energy is distributed to a third particle (a neutrino), the β-energy spectrum is continuous.



Shape of typical beta-particle energy spectrum.

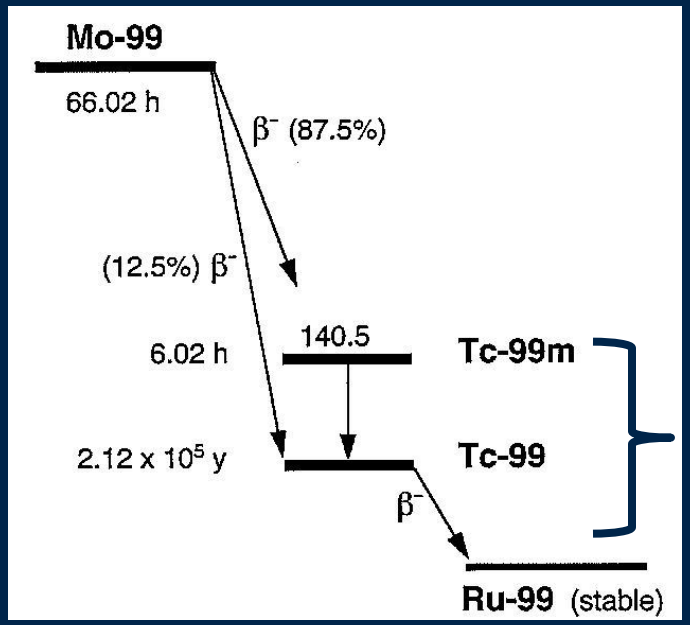
Gamma Emission

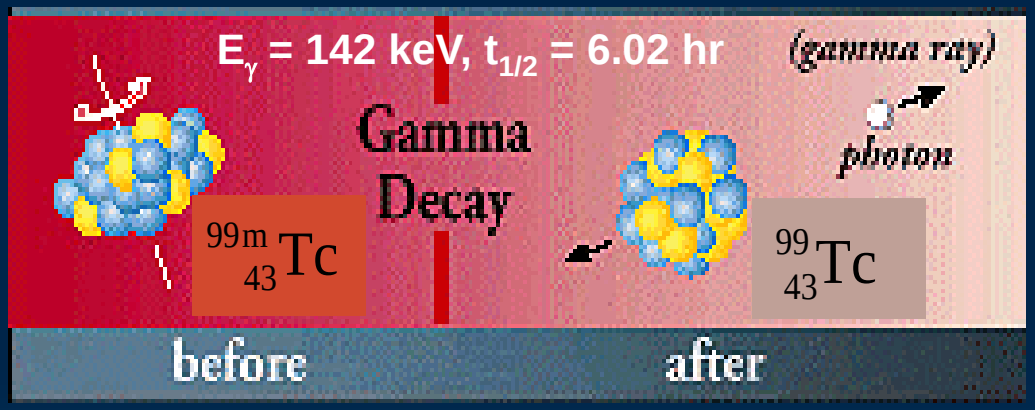
Nuclei can be in excited states following another type of transformation.

Depending on the available energy, the atoms can emit heavy particles, however, if the energy to be released is below the binding energy of the last n, p, or α particle, the de-excitation (or movement towards stability) can be by emission of electromagnetic energy (i.e., a photon).

The emitted photon (usually called a gamma ray) has a characteristic wavelength determined by its energy. For example, a 0.5 MeV gamma photon has a wavelength on the order of 50 nuclear diameters.

Example: decay of Technetium-99m (the primary radionuclide used in diagnostic nuclear medicine)





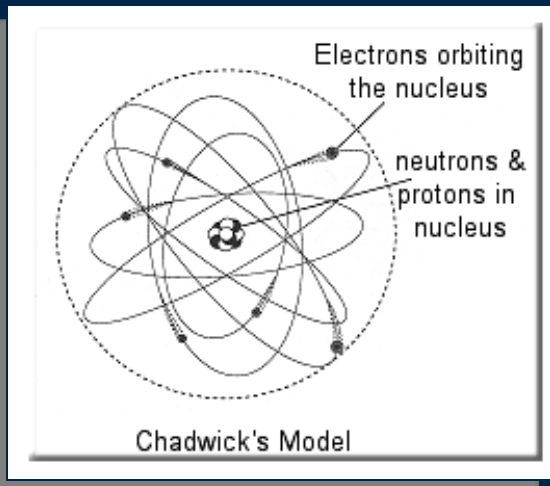
Note that neither Z or A changes as a result of gamma emission.

$$^{99m}_{43}Tc \rightarrow {}^{99}_{43}Tc + \gamma$$

Understanding radioactivity….

Some things you should know:

- **What are radionuclides?**
- **What are their half-lives?**
- **What are their origins?**
- **Which of their properties are relevant to dosimetry?**
- **What is activity?**
- **What is its units?**



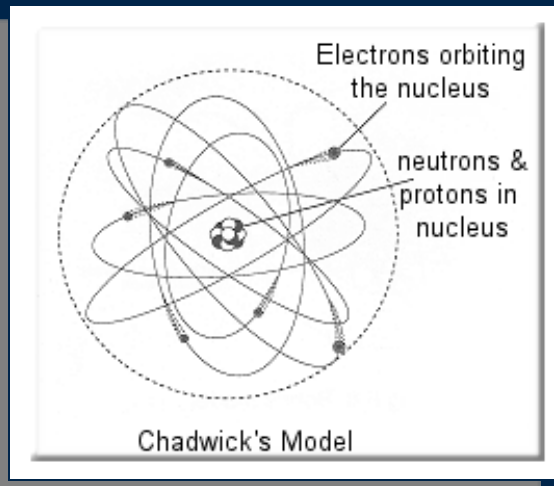
REMINDER

protons = Z where Z is called the 'atomic number.'

neutrons = N

A = Z + N, where is the 'atomic mass.'

- A nuclide is an atom of a particular atomic mass A
- Nuclides are written as: $^{A}_{Z}X$
- A radionuclide is a nuclide which is unstable against radioactive decay.



REMINDER

protons = Z where Z is called the 'atomic number.'

neutrons = N

A = Z + N, where is the 'atomic mass.'

- A nuclide is an atom of a particular atomic mass A
- Nuclides are written as: $^{A}_{Z}X$
- A radionuclide is a nuclide which is unstable against radioactive decay.

Nuclides with identical Z are called "isotopes."

Nuclides with identical A are called "isobars."

Nuclides with identical N are called "istotones."

A nuclide in an 'excited' (excess energy) state is called an "isomeric" or "metastable" state.

EXAMPLES of NUCLIDES

$$^{A}_{Z}X$$

Nuclides with identical Z are called “isotopes.”

Nuclides with identical A are called “isobars.”

Nuclides with identical N are called “istotones.”

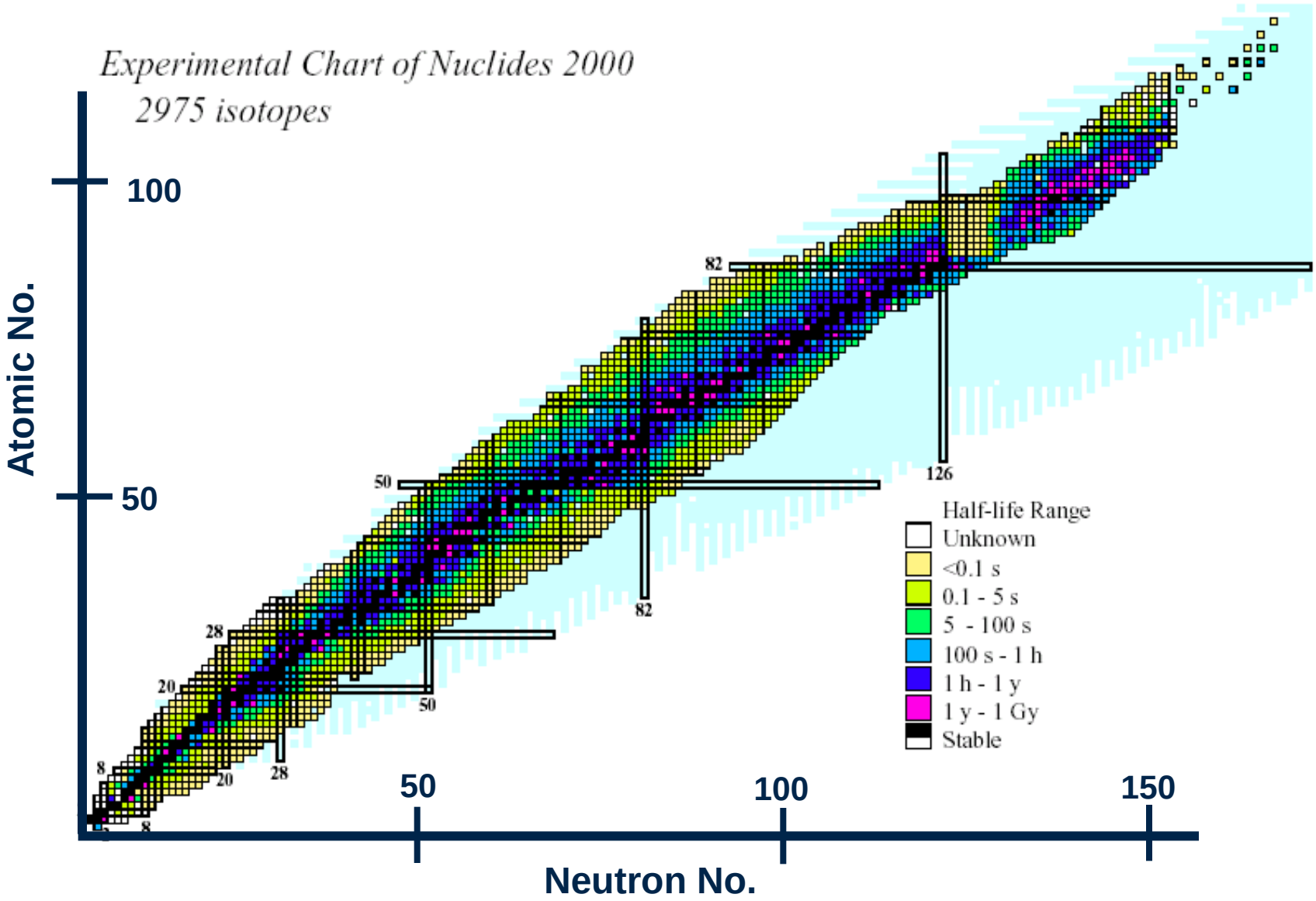
A nuclide in an ‘excited’ (excess energy) state is called an “isomeric” or “metastable” state.

Isotopes: $^{123}_{53}I$, $^{124}_{53}I$, $^{125}_{53}I$, $^{126}_{53}I$, $^{127}_{53}I$, $^{128}_{53}I$, $^{129}_{53}I$, $^{130}_{53}I$, $^{131}_{53}I$, $^{132}_{53}I$

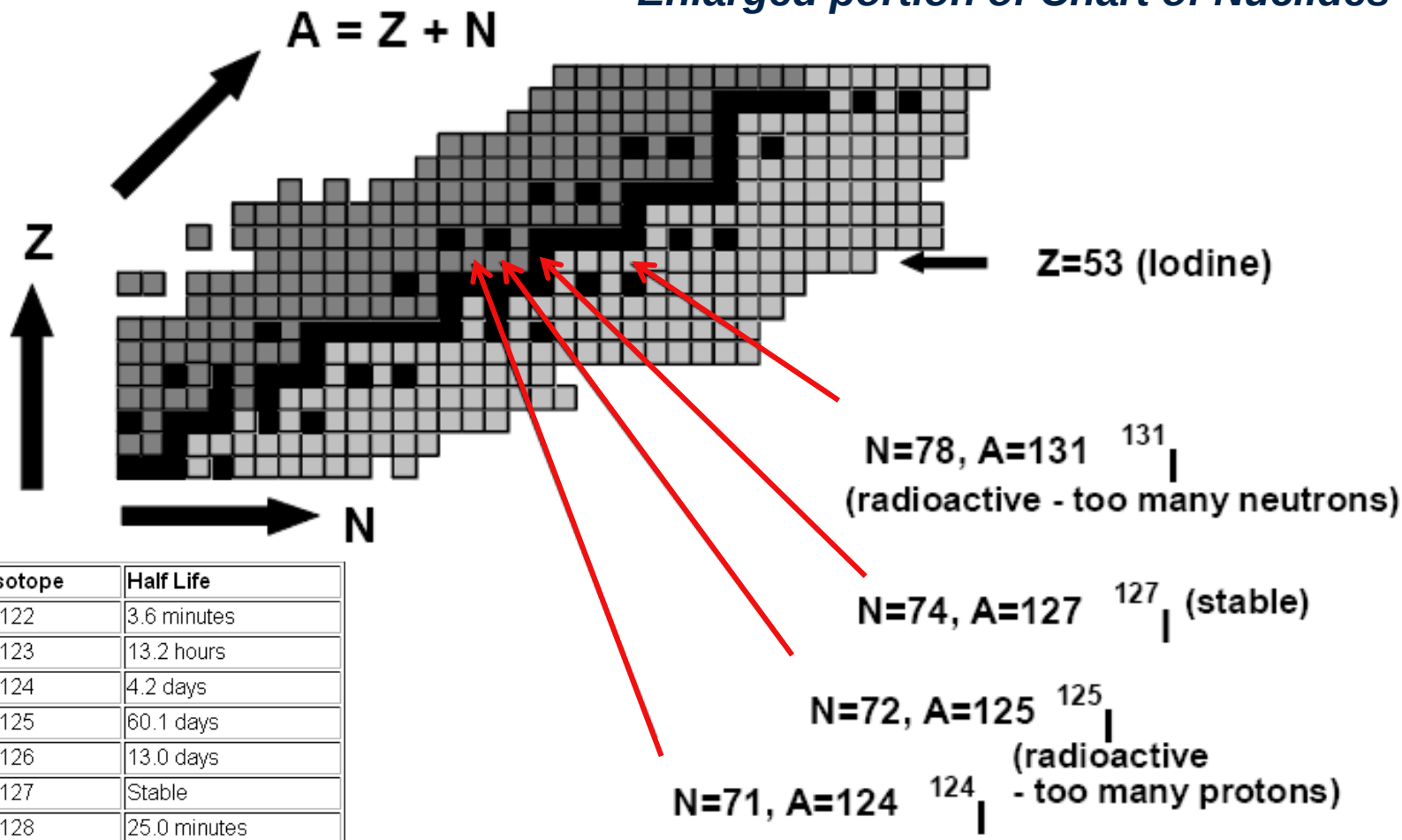
Isobars: $^{131}_{50}Sn$, $^{131}_{51}Sb$, $^{131}_{52}Te$, $^{131}_{53}I$, $^{131}_{54}Xe$, $^{131}_{55}Cs$

Isotones: $^{125}_{48}Cd$, $^{126}_{49}In$, $^{127}_{50}Sn$, $^{128}_{51}Sb$, $^{129}_{52}Te$

Metastable state: $^{130m}_{53}I$ ($t_{1/2}$ = 9 min), $^{132m}_{53}I$ ($t_{1/2}$ = 1.4 hr)


Experimental Chart of Nuclides 2000
2975 isotopes
Atomic No.
100
50
Neutron No.
50
100
150
82
126
50
82
28
20
50
8
20
28
8
Half-life Range
Unknown
<0.1 s
0.1 - 5 s
5 - 100 s
100 s - 1 h
1 h - 1 y
1 y - 1 Gy
Stable

Enlarged portion of Chart of Nuclides



Isotope	Half Life
I-122	3.6 minutes
I-123	13.2 hours
I-124	4.2 days
I-125	60.1 days
I-126	13.0 days
I-127	Stable
I-128	25.0 minutes
I-129	1.57E7 years
I-130	12.4 hours
I-131	8.0 days
I-132	2.3 hours
I-133	20.8 hours
I-134	52.6 minutes
I-135	6.6 hours
I-136	1.4 minutes

Isotopes of Iodine

Some important points about radionuclides

- While there are about 113 known chemical elements, there about 3,100 nuclides found in nature.

- About 25 nuclides have sufficiently long half-lives to half survived from the formation of the earth until now.

- Another 35 nuclides have shorter half-lives but are being continuously produced by the decay of parent nuclides.

- About 1,000 artificially produced nuclides have been discovered.

  Artificially produced nuclides with Z>92 (uranium) have been produced by bombarding lighter atoms with neutrons and/or α particles.

  Those artificially produced elements beyond U are called 'transuranics.'

Radionuclides important points (con't.):

- Possibly the most important transuranic is ^{239}Pu which is produced by bombardment of ^{238}U with neutrons.

  Plutonium-239 can be induced to fission and thus constitutes the primary fuel for fission-type nuclear weapons.
- Exposure to transuranics is generally related to activities associated with the nuclear weapons program. The importance of transuranics to doses received from nuclear power is usually minor.

There are 4 families of naturally occurring radionuclides.

Each family begins with a parent radionuclide that decays through a number of progeny nuclides to a final stable nuclide.

The transition between each successive nuclide is by one (or more) of the decay processes just discussed: primarily alpha and beta decay.

Two series are particularly important to human exposure: Uranium-238 (^{238}U) and Thorium-232 (^{232}Th):

The uranium series begins with ^{238}U and ends with ^{206}Pb.
The thorium series begins with ^{232}Th and ends with the stable nuclide ^{208}Pb.

The most important nuclide in these series, in terms of public exposure, is ^{222} Rn (radon-222).

There are 4 families of naturally occurring radionuclides.

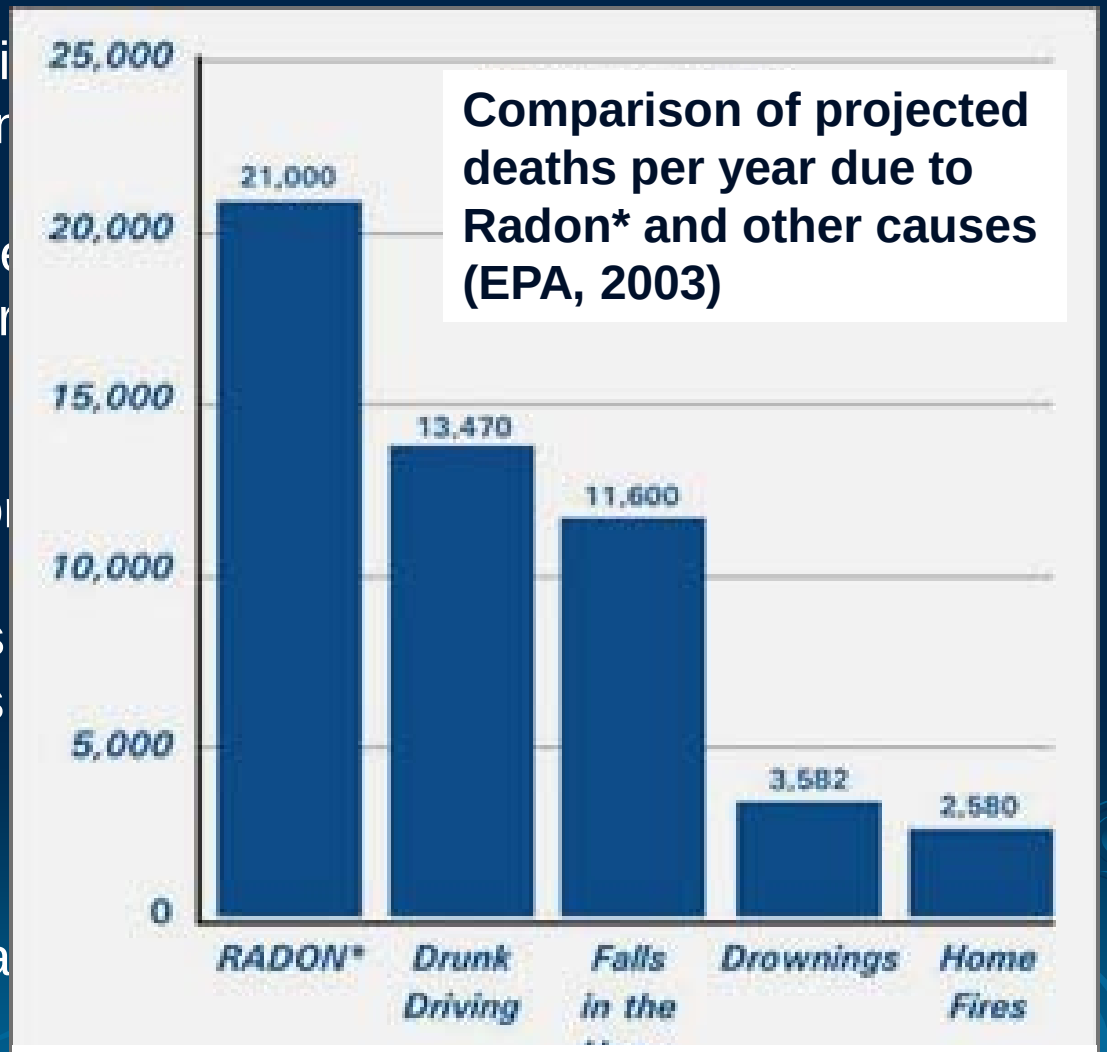
Each family begins wi
a number of progeny r

The transition betwee
more) of the decay pr
beta decay.

Two series are impor
(^{232}Th):

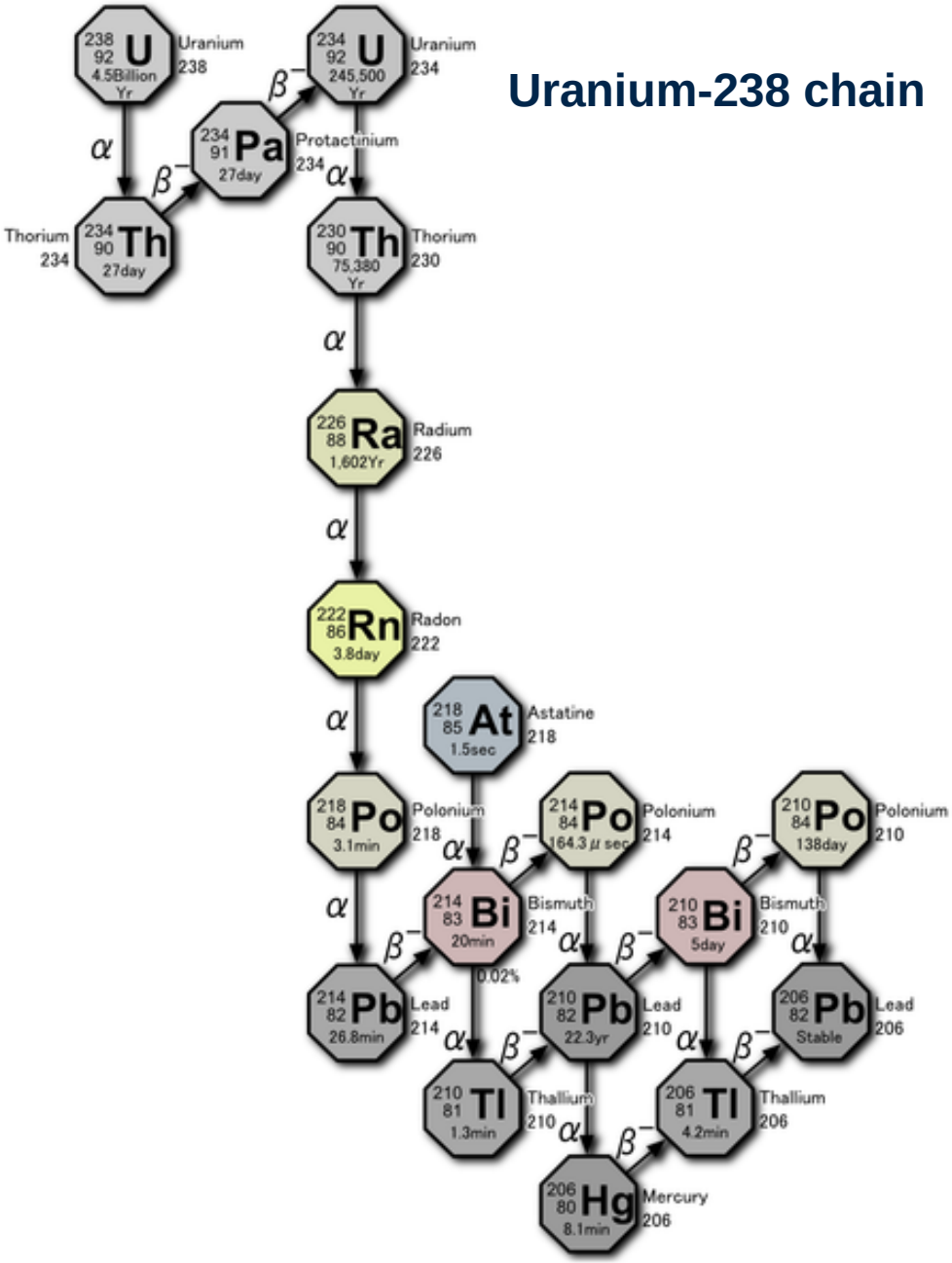
The uranium series
The thorium series
nuclide ^{208}Pb.

The most important
exposure, is ^{222} Rn (ra

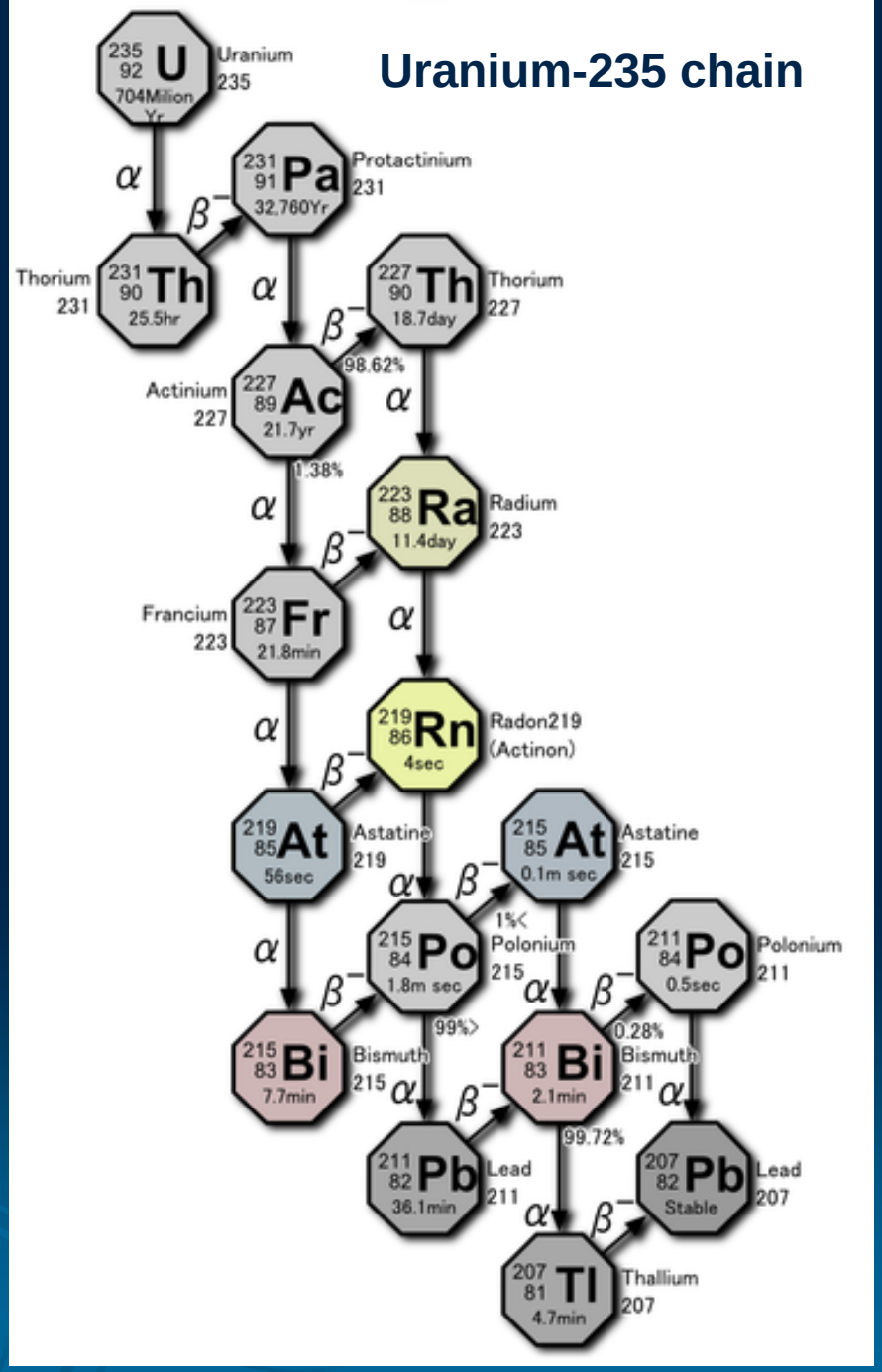


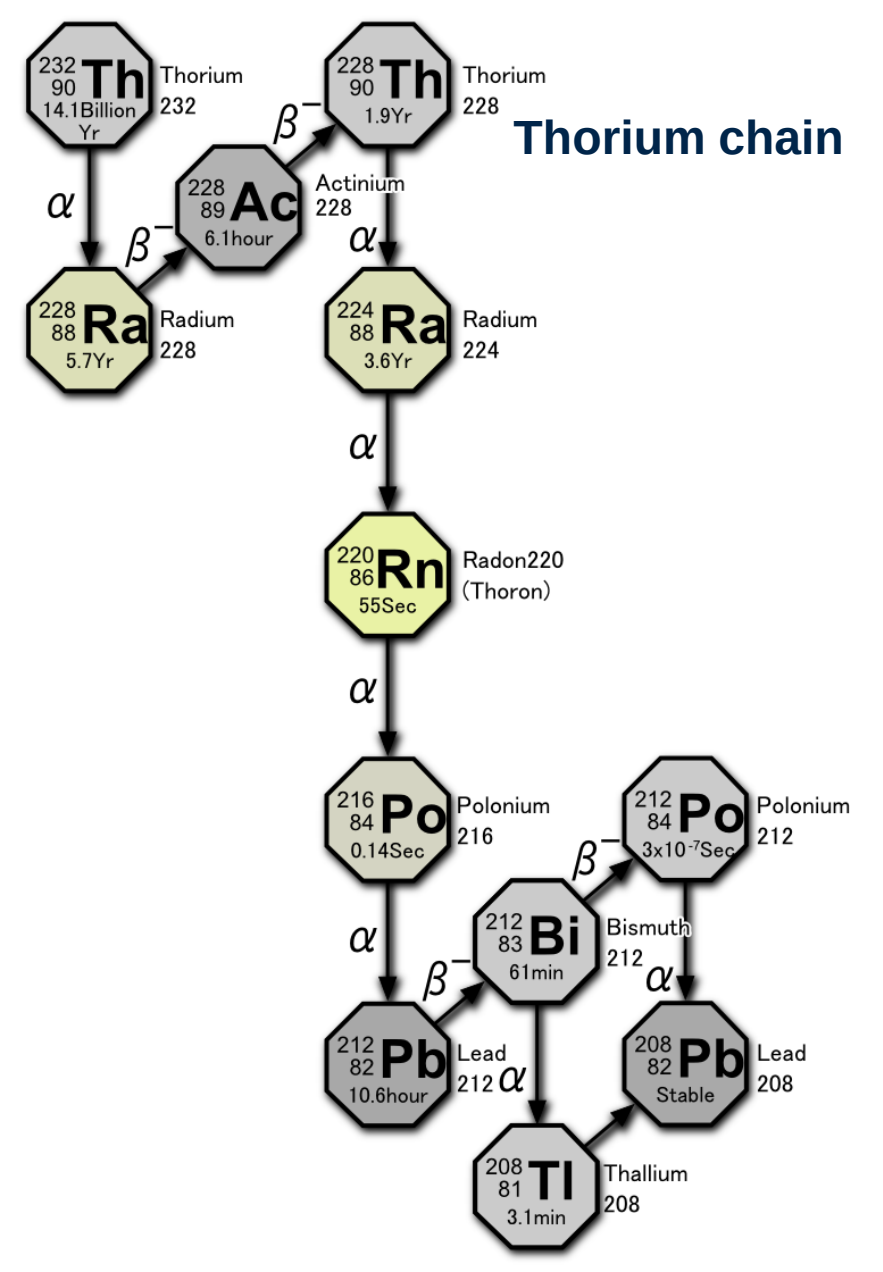
*next major cause of lung cancer after smoking (~440,000 deaths/yr)

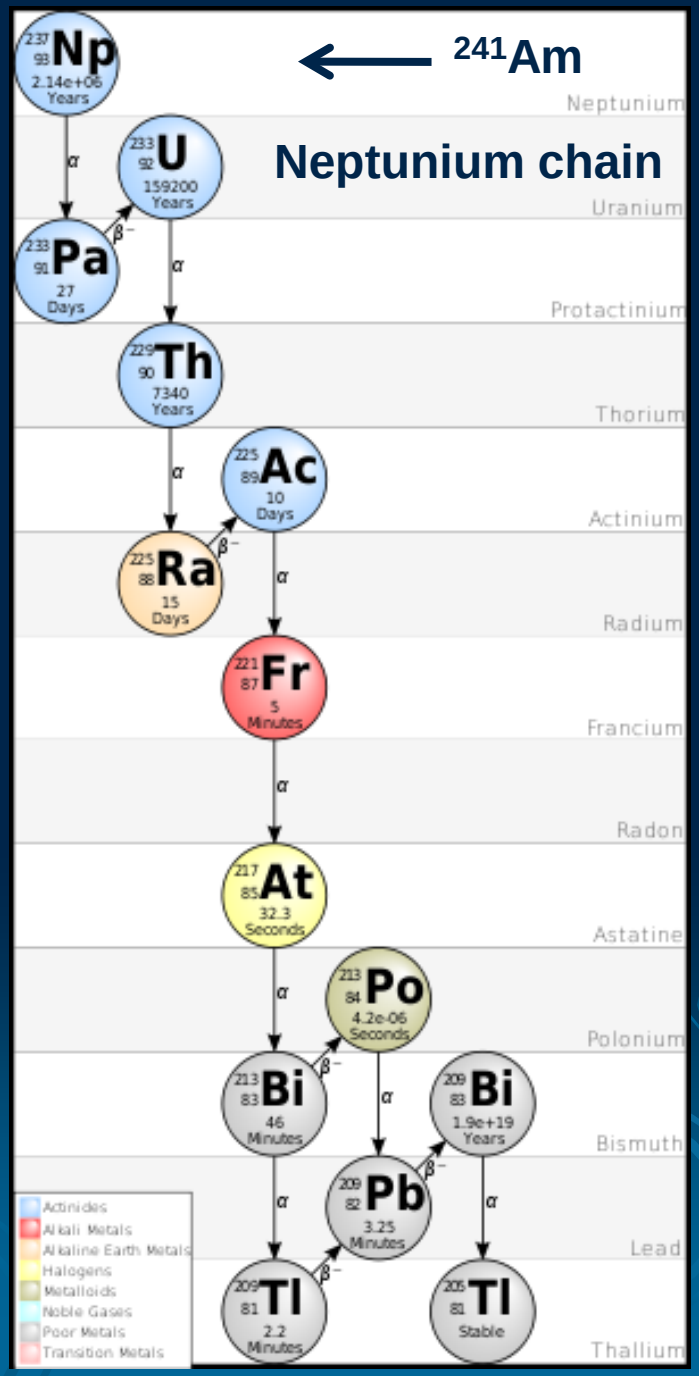
Uranium-238 chain



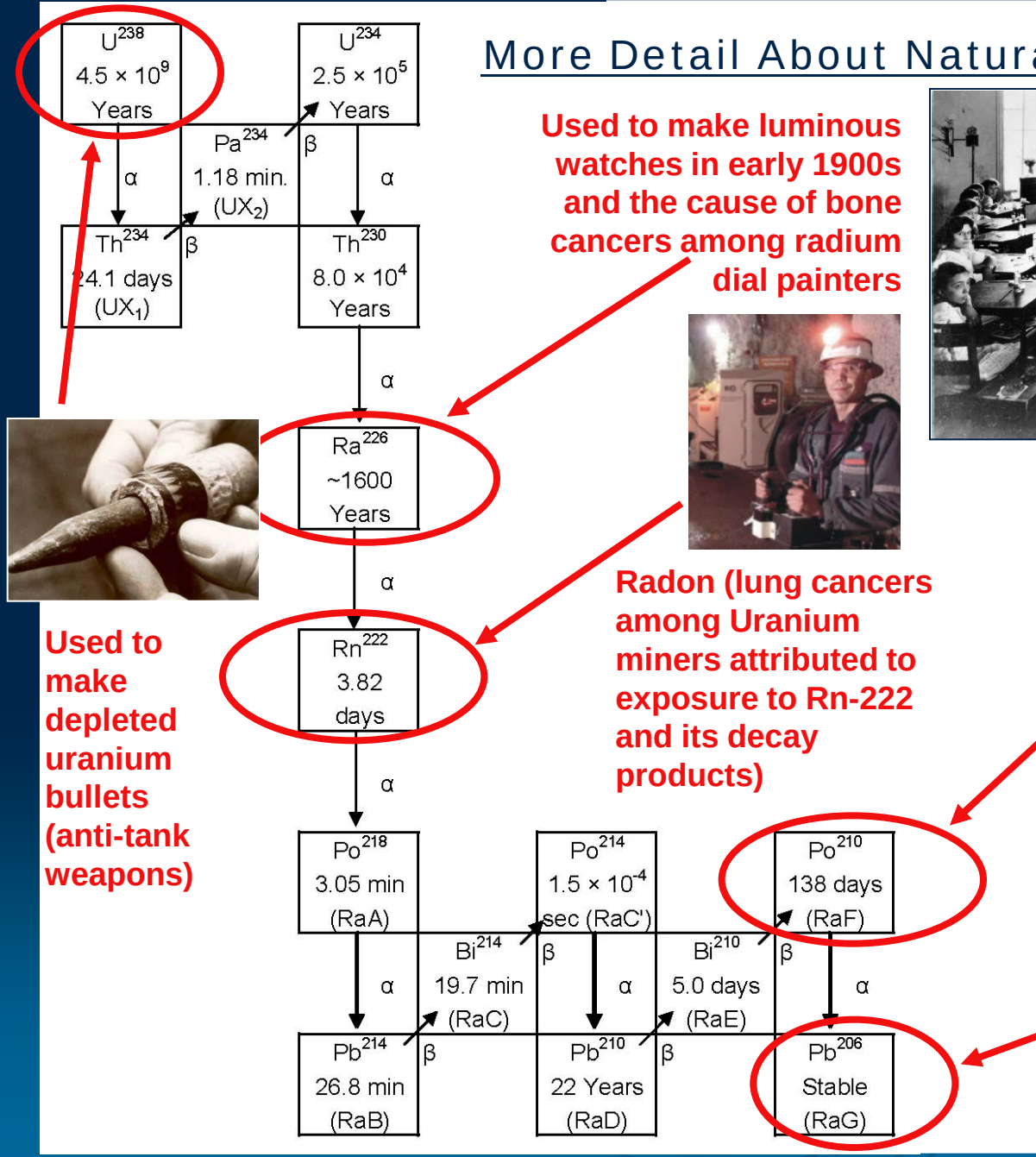
Uranium-235 chain




Thorium chain
232 90 Th 14.1Billion Yr
Thorium 232
228 90 Th 1.9Yr
Thorium 228
228 89 Ac 6.1hour
Actinium 228
228 88 Ra 5.7Yr
Radium 228
224 88 Ra 3.6Yr
Radium 224
220 86 Rn 55Sec
Radon220 (Thoron)
216 84 Po 0.14Sec
Polonium 216
212 84 Po 3x10-7Sec
Polonium 212
212 83 Bi 61min
Bismuth 212
212 82 Pb 10.6hour
Lead 212
208 82 Pb Stable
Lead 208
208 81 Tl 3.1min
Thallium 208
α
β−


241Am
Neptunium chain
237 93 Np 2.14e+06 Years
233 92 U 159200 Years
233 91 Pa 27 Days
229 90 Th 7340 Years
225 89 Ac 10 Days
225 88 Ra 15 Days
221 87 Fr 5 Minutes
217 85 At 32.3 Seconds
213 84 Po 4.2e-06 Seconds
213 83 Bi 46 Minutes
209 83 Bi 1.9e+19 Years
209 82 Pb 3.25 Minutes
209 81 Tl 2.2 Minutes
205 81 Tl Stable
Neptunium
Uranium
Protactinium
Thorium
Actinium
Radium
Francium
Radon
Astatine
Polonium
Bismuth
Lead
Thallium
Actinides
Alkali Metals
Alkaline Earth Metals
Halogens
Metalloids
Noble Gases
Poor Metals
Transition Metals
α
β−

More Detail About Natural U-238 series



Used to make luminous watches in early 1900s and the cause of bone cancers among radium dial painters

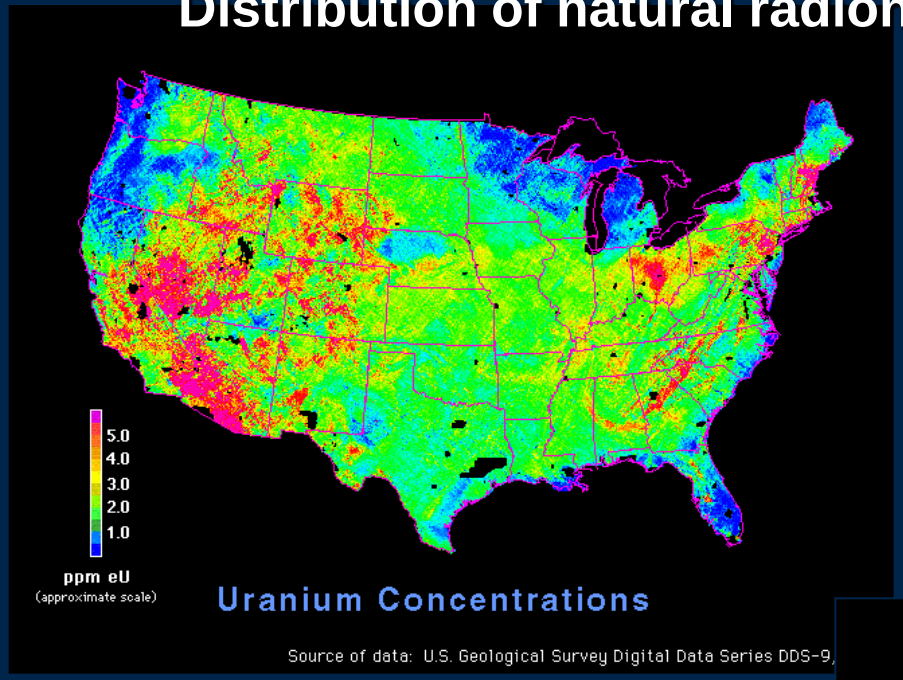
Used to make depleted uranium bullets (anti-tank weapons)

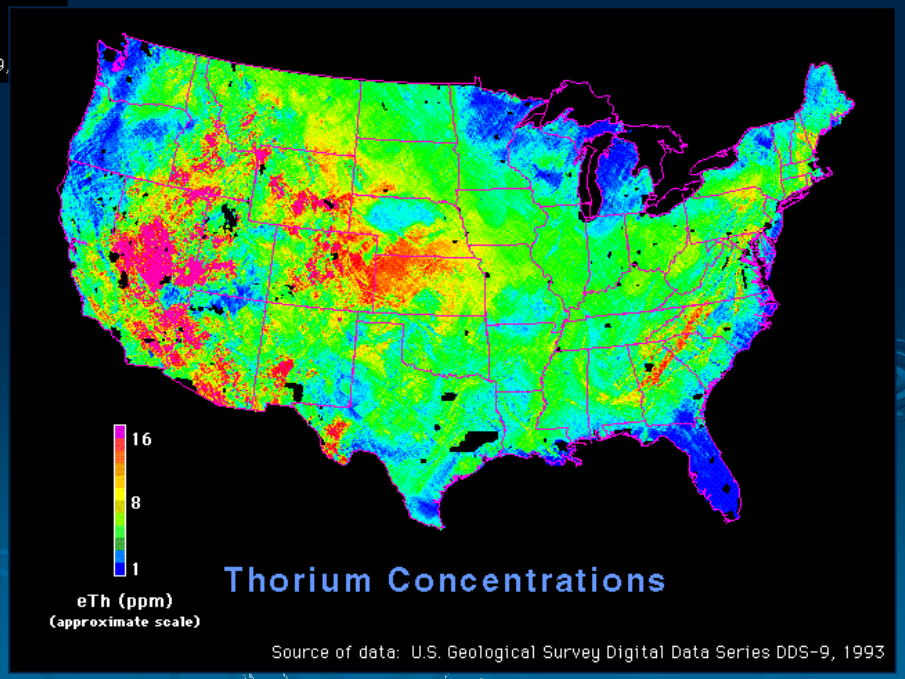
Radon (lung cancers among Uranium miners attributed to exposure to Rn-222 and its decay products)

^{210}Po- the "spy killer"

Metallic lead, heaviest natural nuclide (the original "heavy metal"

Distribution of natural radionuclides in the continental U.S.





Source: USGS

"Activity" is simply a measure of the rate of decay (i.e., rate of spontaneous disintegration) of the atoms of a nuclide.

The unit of radioactivity historically was the Curie and was defined to be equal to the disintegration rate of 1 gm of ^{226}Ra, or 3.7×10^{10} disintegrations per second (d/s).

All nuclides also use the definition of 3.7×10^{10} d/s to define one Ci.

You can have subunits of:

milliCi (mCi, 10^{-3} Ci),
microCi (μCi, 10^{-6} Ci)
nanoCi (nCi, Ci)
picoCi (pCi, 10^{-12} Ci), etc.

The units of radioactivity in the international system of units (SI units) is the Becquerel (Bq) which is simply equal to 1 d/s. Hence, 1 Bq $\approx$ 27 pCi.

The Bq is much simpler to understand and to use. The U.S. should adopt it!

“Activity” is simply a measure of the rate of decay (i.e., rate of spontaneous disintegration) of the atoms of a nuclide.

In an ensemble of atoms of a single nuclide, the number of atoms that decay in a unit time interval is proportional to the number available. Hence, the rate of decay is exponential:

$$N(t) = N_o e^{-\lambda t}$$

where λ is a constant = $\log_e(2)$/half-life

Half-Life

Half-life is the length of time for half of the atoms of a given nuclide to decay.

The half-life a unique characteristic of each nuclide.

Half-lives range from millionths of a second to millions of years.

Note that the half-life also determines the rate at which the nuclide releases energy, thus,

> Radiation doses potentially received from individual nuclides within a unit time are a function of the rate of decay (half-life) as well as the energy released in each decay.

Radionuclides are thus uniquely distinguished by:

Half-life

Type of radiations emitted

Energy of emitted radiations

The number of atoms of the nuclide determines the “activity” at any moment.

The “radiation dose” that a nuclide can deliver is determined, in part, by all of these factors.

It is worthwhile to note that the decay schemes of some radionuclides can be very complex. Even well-known Iodine-131 has a complex emission spectrum

Beta particles, x-rays and γ-rays emitted from Iodine-131

Beta Decays of ^{131}I (8.02 d)

E_β endpoint (keV)	I_β (%)	Decay mode
247.89	2.10	β^-
303.86	0.651	β^-
333.81	7.27	β^-
606.31	89.9	β^-
629.66	0.050	β^-
806.87	0.48	β^-

X-rays from ^{131}I (8.02 d)

E (keV)	I (%)	Assignment
4.11	0.215	Xe $L_{\alpha 1}$
4.41	0.133	Xe $L_{\beta 1}$
29.46	1.40	Xe $K_{\alpha 2}$
29.78	2.59	Xe $K_{\alpha 1}$
33.56	0.24	Xe $K_{\beta 3}$
33.62	0.46	Xe $K_{\beta 1}$
34.42	0.14	Xe $K_{\beta 2}$

Gammas from ^{131}I (8.02)

Eγ (keV)	Iγ (%)	Decay mode
80.185	2.62	β^-
85.9	0.00009	β^-
163.93		β^-
177.21	0.270	β^-
232.18	0.0032	β^-
272.50	0.0578	β^-
284.31	6.14	β^-
295.8 *2*	0.0018	β^-
302.4 *2*	0.0047	β^-
318.09	0.0776	β^-
324.65	0.0212	β^-
325.79	0.274	β^-
358.4 *2*	0.016	β^-
364.49	81.7	β^-
404.81	0.0547	β^-
503.00	0.360	β^-
636.99	7.17	β^-
642.72	0.217	β^-
722.91	1.773	β^-

Part II.
INTERACTIONS OF RADIATION AND MATTER

To develop a means to estimate radiation dose (i.e., the energy absorbed by tissue), one needs to understand the processes by which radiation interacts with tissue - as it those interactions that result in the transfer of energy to the tissue.

Now…a discussion of the interactions of ionizing radiation with matter

Types of interactions of ionizing radiation with matter
(most important processes in blue)

INCIDENT RADIATION	IN COLLISION WITH	TYPE OF COLLISION		
		ELASTIC[a]	INELASTIC[b]	COMPLETE ABSORPTION
Alpha	Nucleus	**Rutherford**	Bremsstrahlung	Transmutation
	Orbital electron	(negligible)	**Ionization and excitation**	None
Electrons (β^- and β^+)	Nucleus	Rutherford scattering	**Bremsstrahlung**	Electron capture
	Orbital electron	Causes some scattering	**Ionization and excitation (characteristic x rays)**	Annihilation (for positrons)
Neutrons	Nucleus	**Recoil with moderation of neutrons**	Resonance scattering	Radio-activation and other nuclear reactions
	Orbital electron	(negligible)	(negligible)	None
Photons (x and gamma rays)	Nucleus	Thomson scattering	Mossbauer effect	Photo-disintegration
	Orbital electron	Rayleigh scattering	**Compton effect**	**Photoelectric effect and internal conversion**
	Field	Delbruck scattering	(negligible)	**Pair production**

[a]elastic collisions are those where the total kinetic energy is conserved.
[b]inelastic collisions are those where the total kinetic energy is not conserved

sometimes thought of

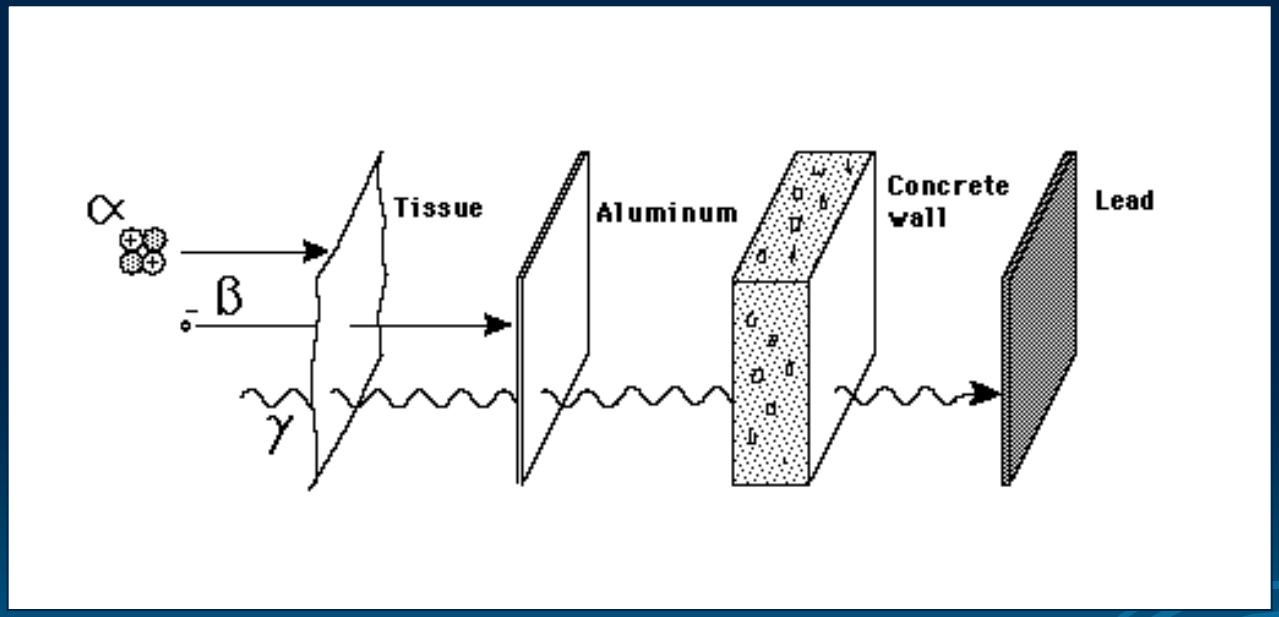
Probably the most important

rarely thought of

Most commonly thought of

Understanding how radiation interaction with matter leads to an understanding of the why different types of radiation have greater penetrating power and how to protect against each type of radiation.

Penetrating power: Gamma rays > β particles > α particles



Photon (x and γ ray) radiation

- Photon beams interact with the matter through which they pass and consequently, the beam intensity is attenuated.

- These interactions attenuate the beam as well as deliver energy to the matter through which the particles pass. It is that energy that is the concern of dosimetry.

- There are a variety of types of interactions for photons, however, there are 3 phenomena that are of primary importance in radiation dosimetry:

  Photoelectric absorption,
  Incoherent (Compton) scattering,
  Pair production.

Photon (x and γ ray) radiation con't.

Photoelectric absorption,
Incoherent (Compton) scattering,
Pair production.

- The likelihood of each of these phenomenon taking place is dependent on a number of factors, in particular, the energy of the incident photons and the **Z** of the irradiated material.

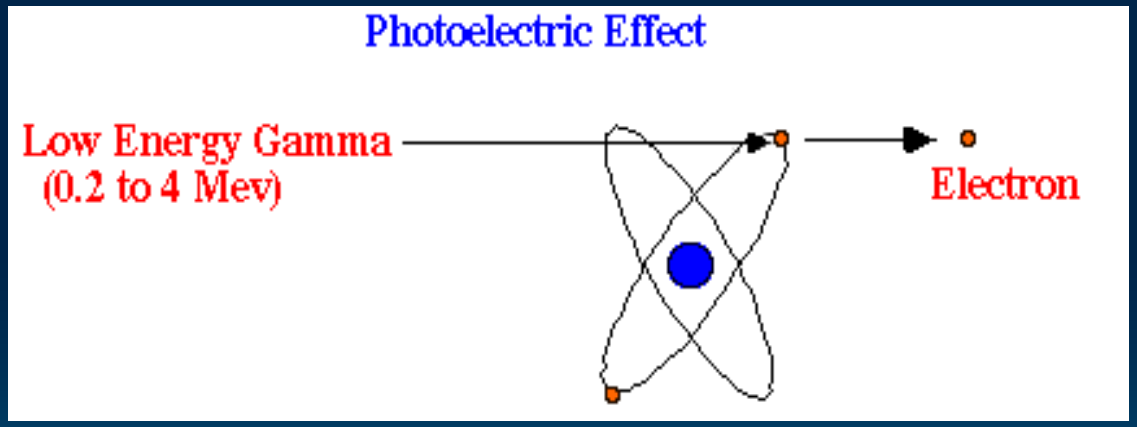
- The degree to which photon beams are attenuated, and the degree to which each interaction type contribute to the tissue dose can be calculated using the (incident) energy and Z dependent "cross-section" data that are available in tables.

Photoelectric Effect

This process completely removes the incident photon.

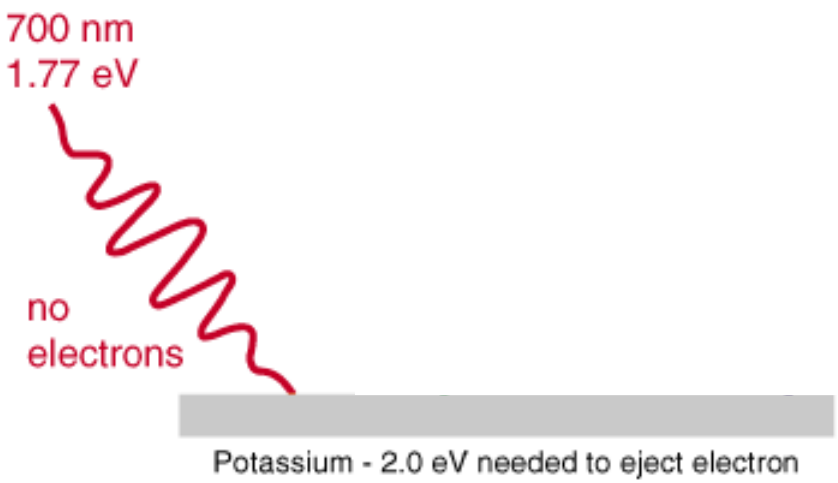
The photon is absorbed by an atom, and an electron is ejected with kinetic energy (KE) from the atom:

$KE = E_i - BI$ (E_i is the incident photon energy, BE is the binding energy of the atomic shell from which the electron is ejected)



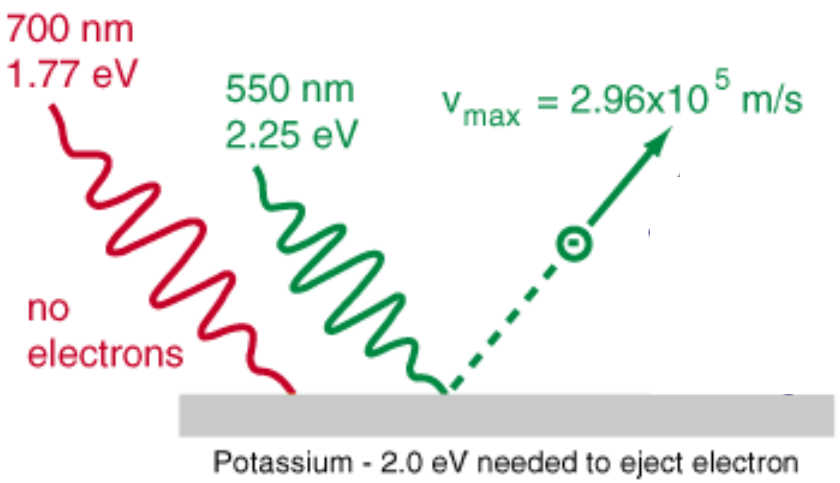
The cross-section or probability for interaction of this type is proportional to Z^4/E_i^3.

$$E_{photon} = h\nu$$

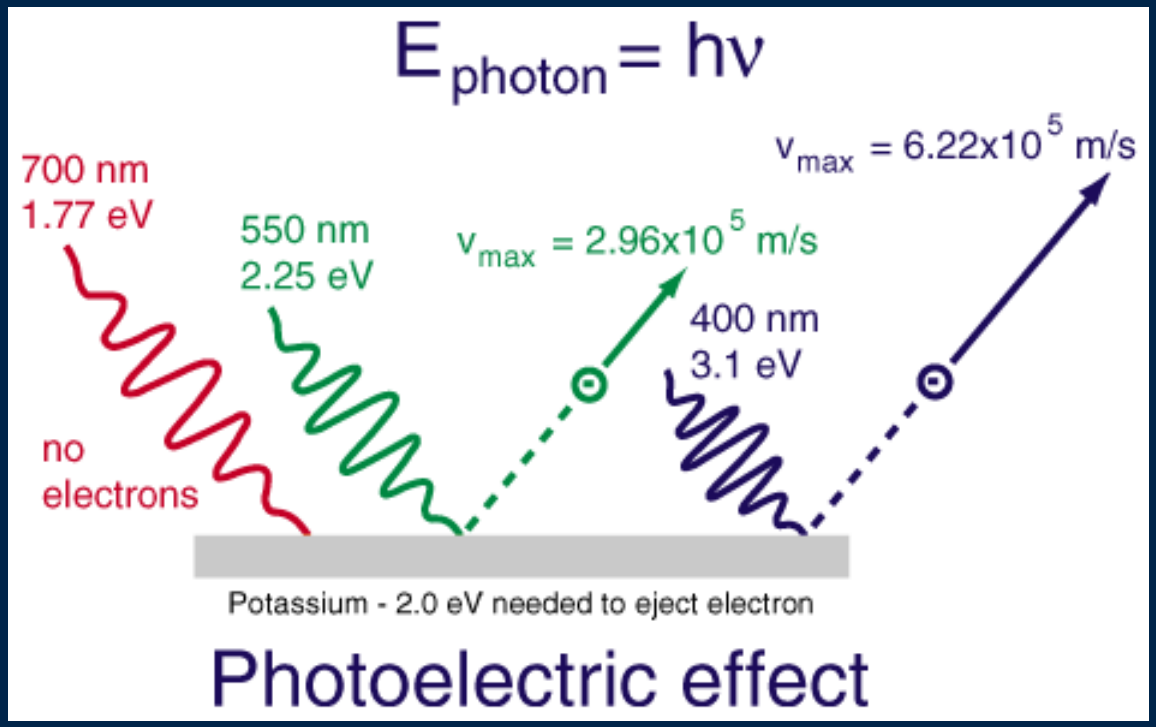


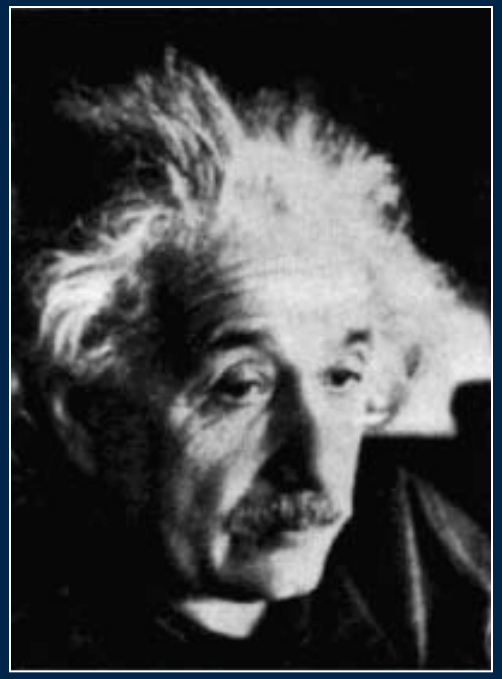
Photoelectric effect

$$E_{photon} = h\nu$$



Photoelectric effect



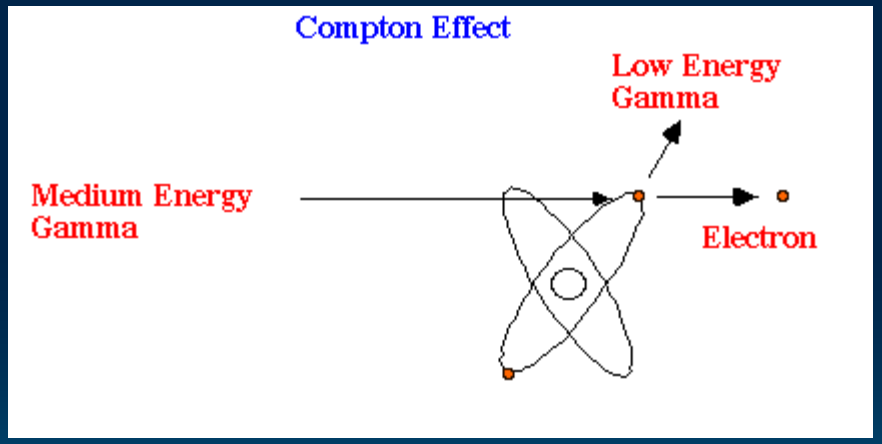


The photoelectric effect was such an important discovery, that Albert Einstein was awarded the Nobel Prize in 1921 for his 1905 discovery.

Compton Scattering (Compton Effect)

Named for nuclear physicist Arthur Compton, this process describes the scattering between an incident photon and an atomic electron.

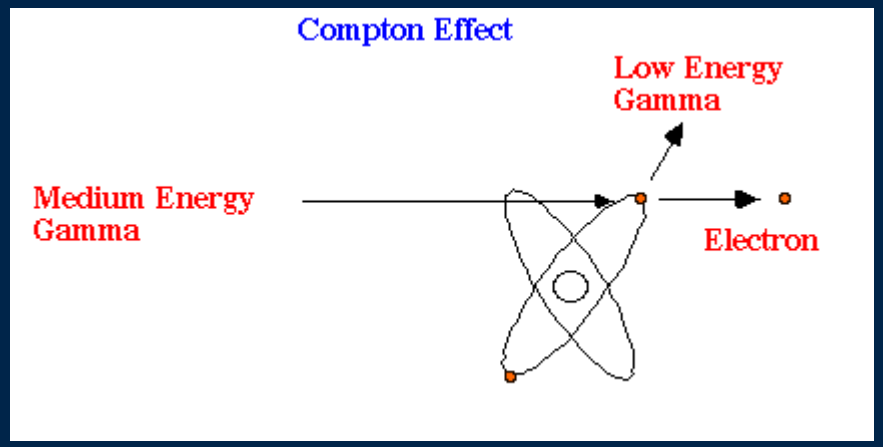
The incident photon is not completely absorbed but rather scattered out of the incident beam with a reduced energy (or conversely, with an increased wavelength). An electron is also ejected.



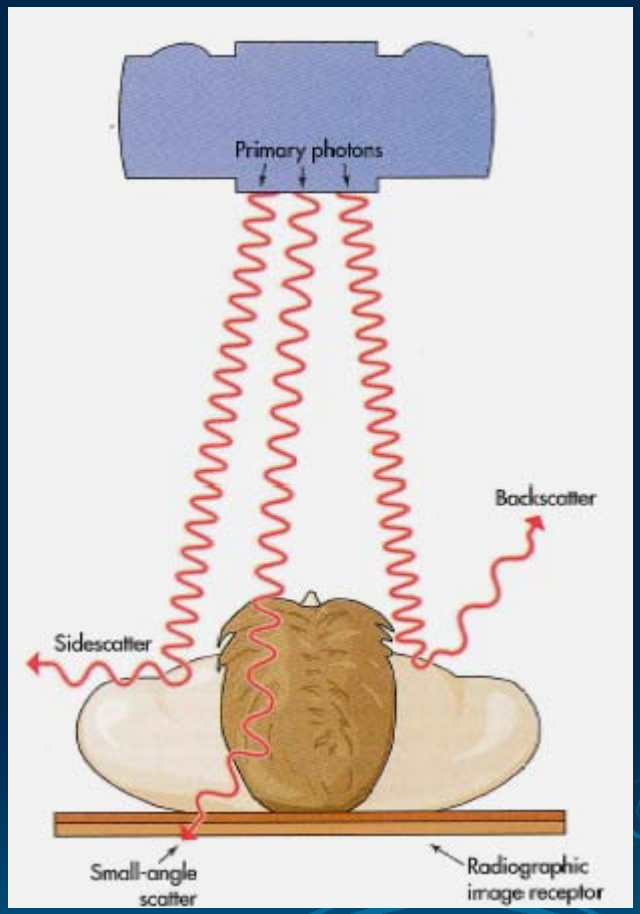
Multiple interactions (scattering events) are likely for the same incident photon.

The Compton cross-section increases rapidly with increasing Z, and decreases with increasing energy, approximately as $1/E_i^2$.

SIDEBAR on Compton Scattering



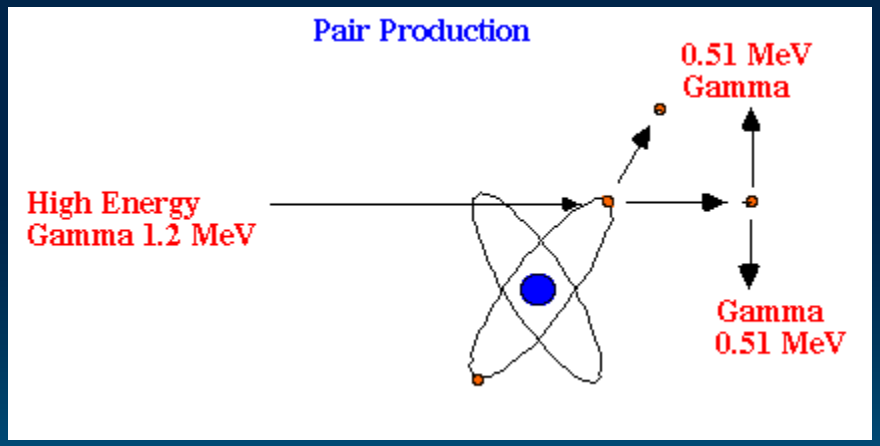
Compton scatter has many real-world occurrences, e.g., scatter of x-rays from a patient.



Pair Production

The incident photon disappears and an electron and positron (positive electron) pair are created with a total energy equal to the energy of the incident photon.

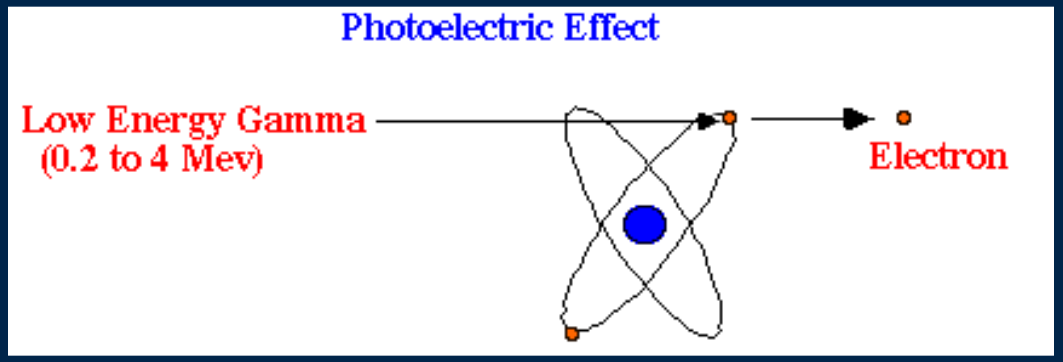
Pair production can only take place when the incident photon energy exceeds the energy equivalent of the rest mass of the electron/positron pair, i.e., E_i must > $2m_oc^2$ or 1.02 MeV.



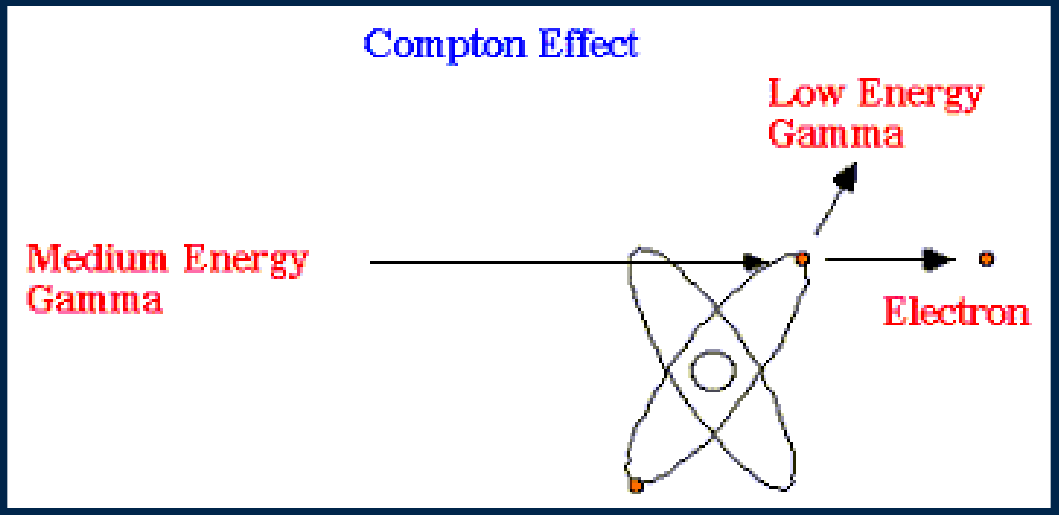
The cross-section increases ~Z^2 and ~$\ln(E_i)$.

SUMMARY OF PHOTON INTERACTIONS

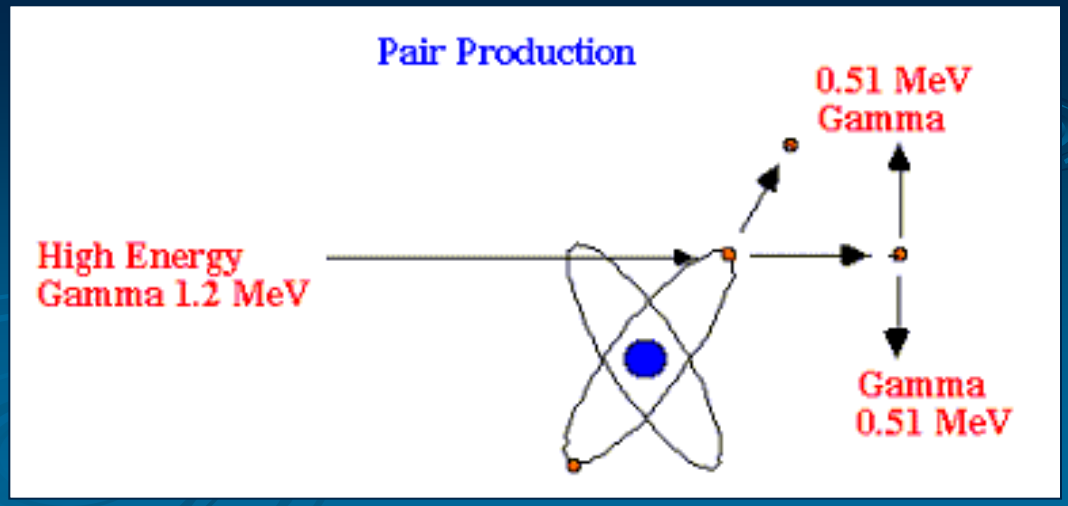
Interaction at low photon energies

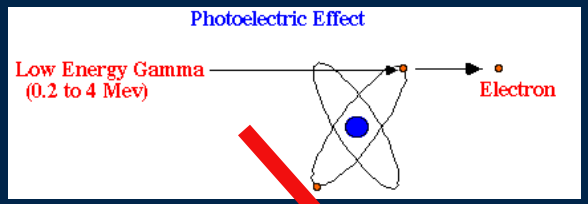


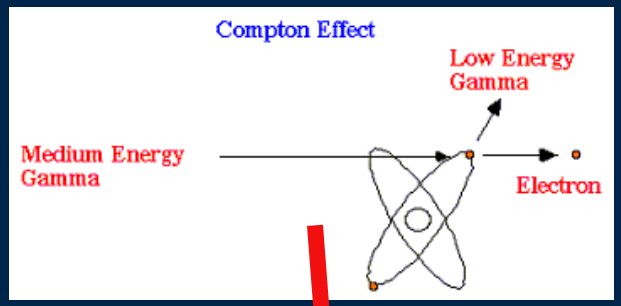
Interaction at intermediate photon energies

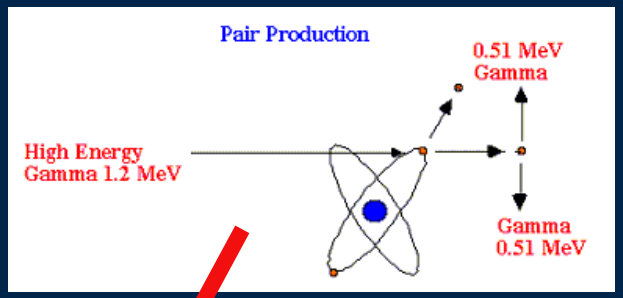


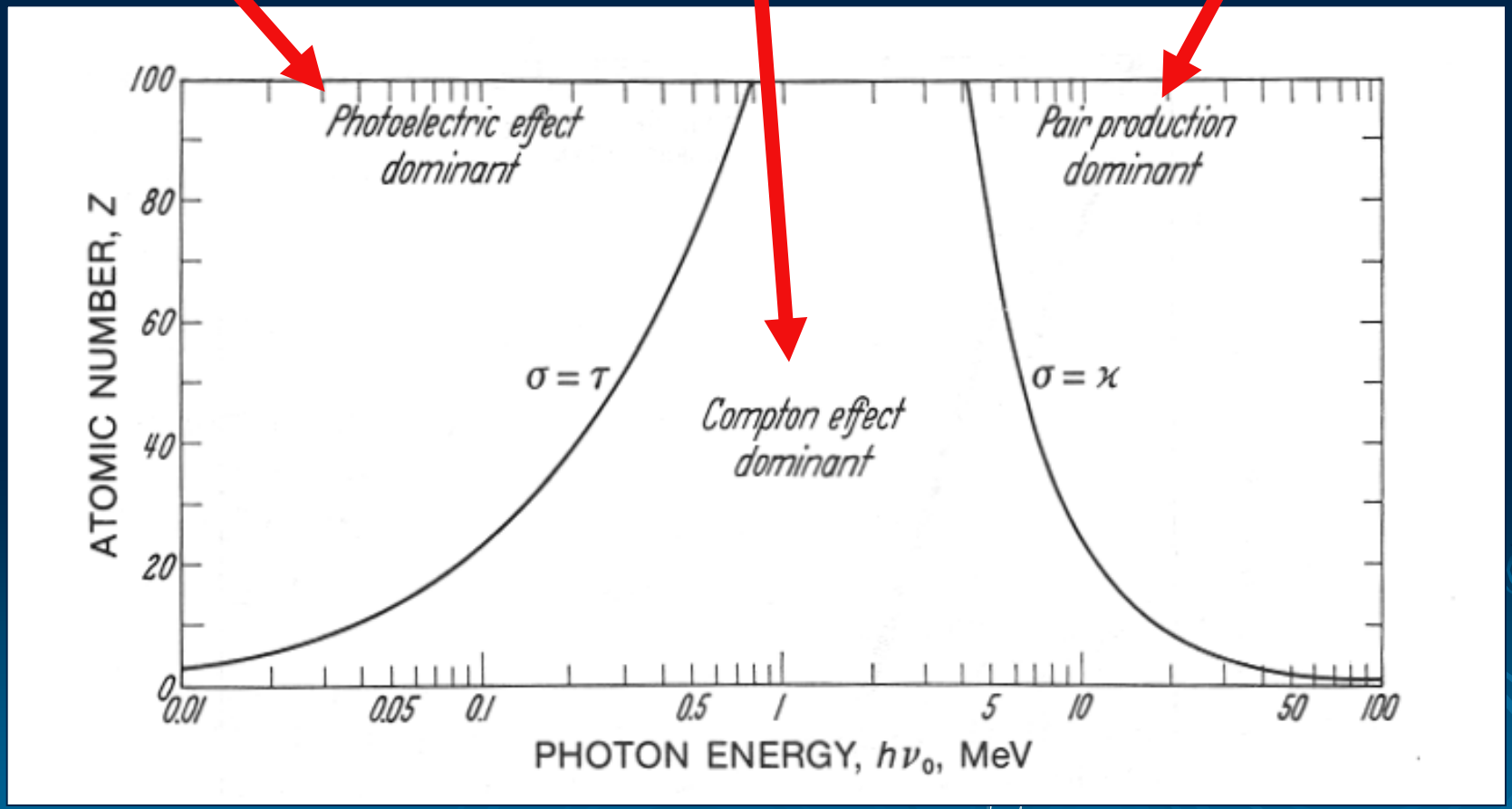
Interaction at high photon energies




Photoelectric Effect
Low Energy Gamma
(0.2 to 4 Mev)
Electron


Compton Effect
Low Energy
Gamma
Medium Energy
Gamma
Electron


Pair Production
0.51 MeV
Gamma
High Energy
Gamma 1.2 MeV
Gamma
0.51 MeV


Photoelectric effect
dominant
Pair production
dominant
Compton effect
dominant
σ = τ
σ = κ
ATOMIC NUMBER, Z
100
80
60
40
20
0
0.01
0.05
0.1
0.5
1
5
10
50
100
PHOTON ENERGY, hν₀, MeV

Mass absorption coefficients for each type of interaction also show the importance of the processes as a function of the incident photon energy.

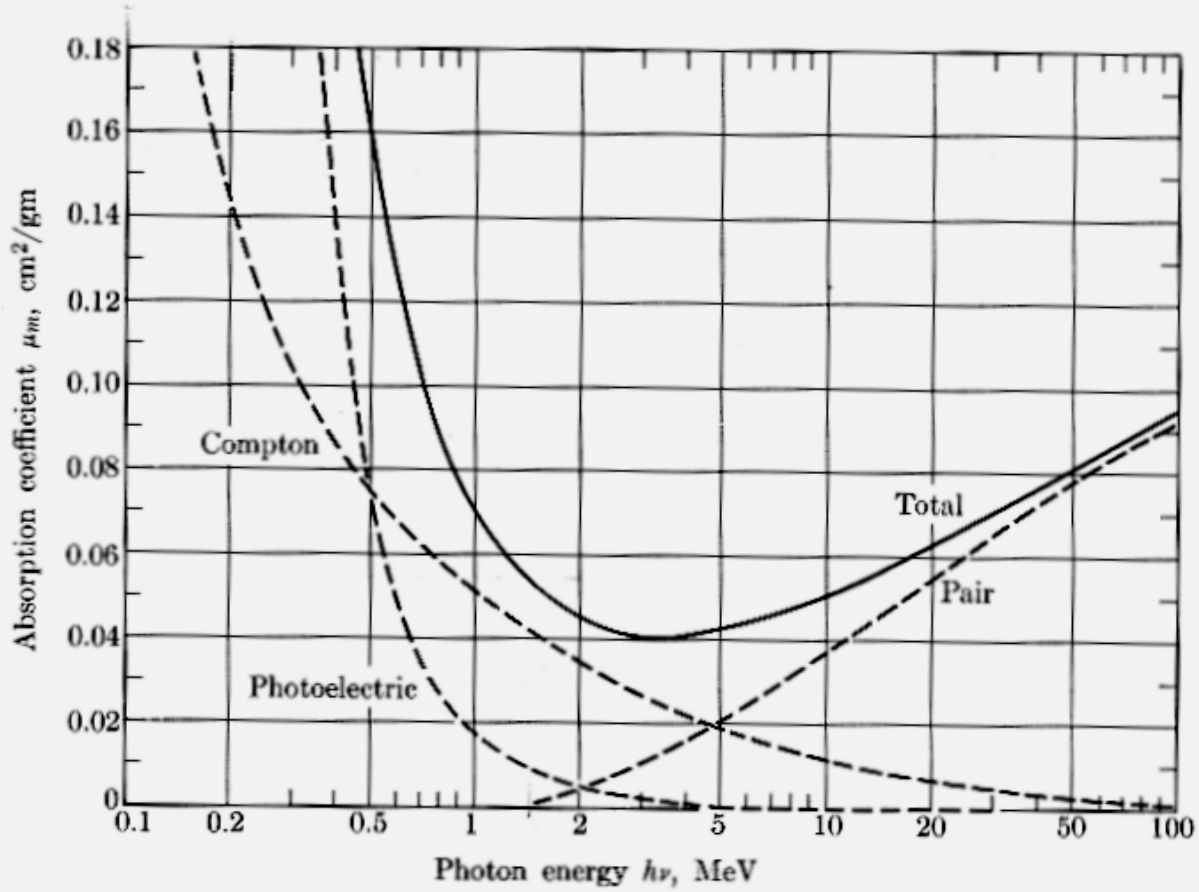


Fig. 7–6. Total mass-absorption coefficients for gamma rays in lead and the contributions from the photoelectric effect, the Compton effect, and pair production.

Note that the single common outcome of the photon interactions in materials was the release of electrons!

What happens to those electrons?

INCIDENT RADIATION	IN COLLISION WITH	TYPE OF COLLISION		
		ELASTIC[a]	INELASTIC[b]	COMPLETE ABSORPTION
Alpha	Nucleus	**Rutherford**	Bremsstrahlung	Transmutation
	Orbital electron	(negligible)	**Ionization and excitation**	None
Electrons (β^- and β^+)	Nucleus	Rutherford scattering	**Bremsstrahlung**	Electron capture
	Orbital electron	Causes some scattering	**Ionization and excitation (characteristic x rays)**	Annihilation (for positrons)
Neutrons	Nucleus	**Recoil with moderation of neutrons**	Resonance scattering	Radio-activation and other nuclear reactions
	Orbital electron	(negligible)	(negligible)	None
Photons (x and gamma rays)	Nucleus	Thomson scattering	Mossbauer effect	Photo-disintegration
	Orbital electron	Rayleigh scattering	**Compton effect**	**Photoelectric effect and internal conversion**
	Field	Delbruck scattering	(negligible)	**Pair production**

[a]elastic collisions are those where the total kinetic energy is conserved.
[b]inelastic collisions are those where the total kinetic energy is not conserved

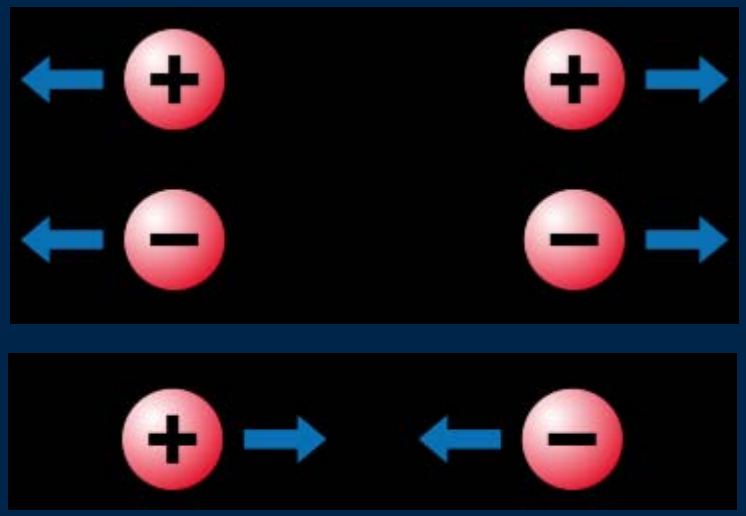
WHAT HAPPENS TO THOSE PARTICLES IS TERMED PARTICLE INTERACTIONS

- Particles, unlike photons, have mass, and some have charge.
- Hence, the processes that govern what happens to particles differ from those than govern what happens to photons
- Understanding particle interactions in matter (e.g., tissue) is the last major requirement to understanding the phenomenon that contribute to radiation dose.

Particles (except for neutrons) are charged and cause atomic ionization or excitation as they move through matter as a result of Coloumb forces

Opposite charges attract. Like charges repel.

Particles (except for neutrons) are charged and cause atomic ionization or excitation as they move through matter as a result of Coloumb forces (repulsion of charges of the same electrical sign).



$$F = \frac{kq_1q_2}{r^2} = \frac{q_1q_2}{4\pi\varepsilon_0 r^2}$$ *Coulomb's Law*

Electrons

Remember that electrons are released by all photon interactions and from β decay and will be moving in the tissue with some kinetic energy.

Coulomb interactions with neighboring atoms will gradually slow them down.

Rate of energy loss with distance is proportional to '*e*' (electron charge), and electron density (NZ) of the material.

The important point is the electrons cause ionization and excitation and as they lose their energy in the material, energy is imparted to the material through which they pass, and the "dose" is delivered.

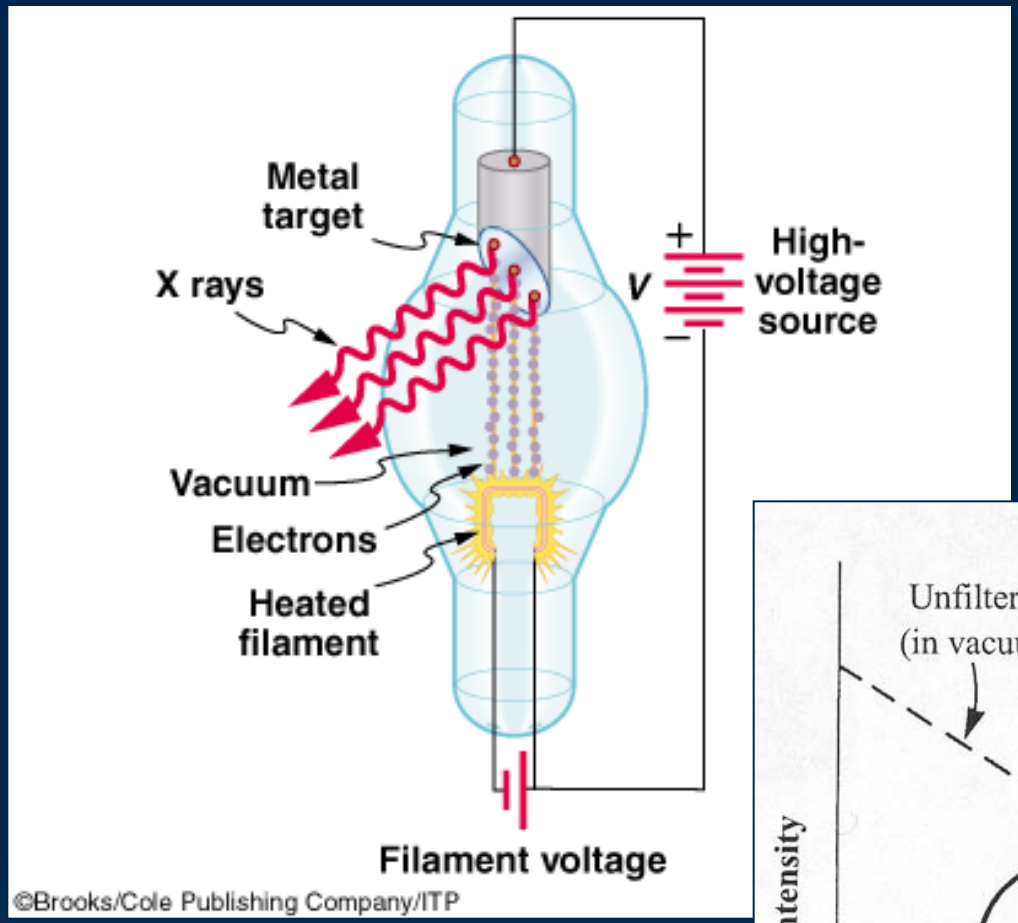
Electrons not only cause ionization…but also re-radiate some energy through ***brehmsstrahlung***

Brehmsstrahlung? What's that?

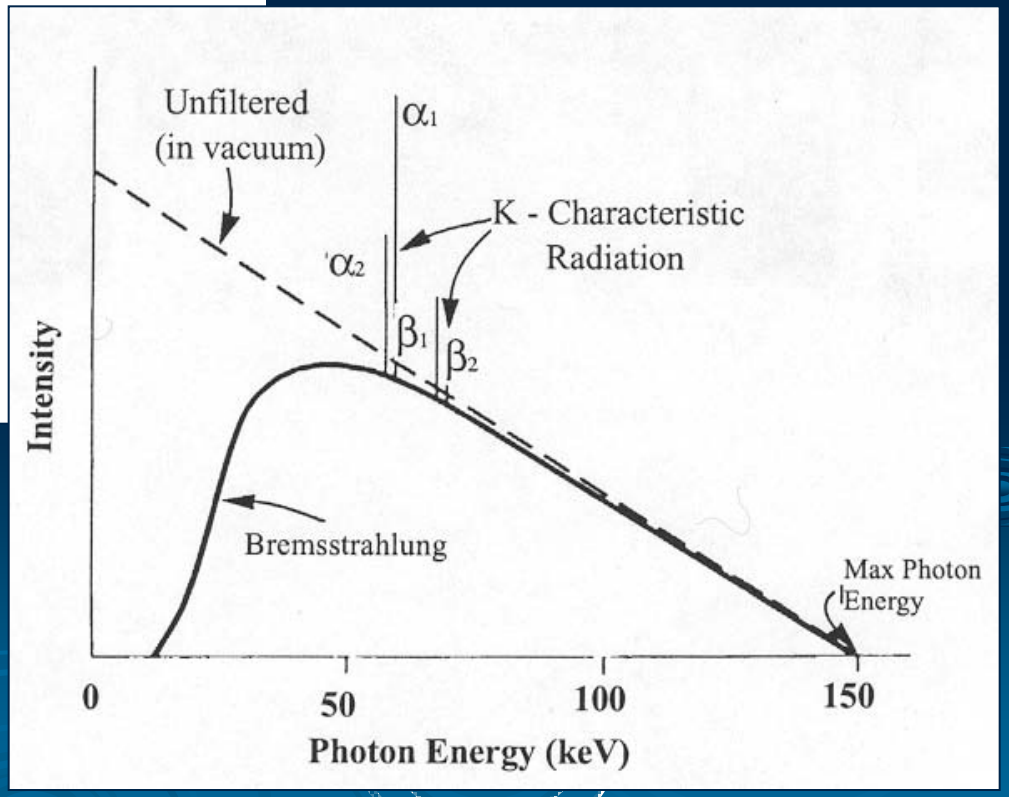
Charged particles (e.g. electrons) when (de)accelerated in the electric field of the nucleus or of the orbital electrons, will radiate energy, known as "braking" or "brehmsstrahlung" radiation.

The radiation loss is proportional to the kinetic energy (KE) of the incident electron and Z of the material: $-dE/dx \approx Z\ e\ KE$.

Sidebar on the use of Brehmsstrahlung radiation



Brehmsstrahlung **is the mechanism used to generate x-rays for medical use.**

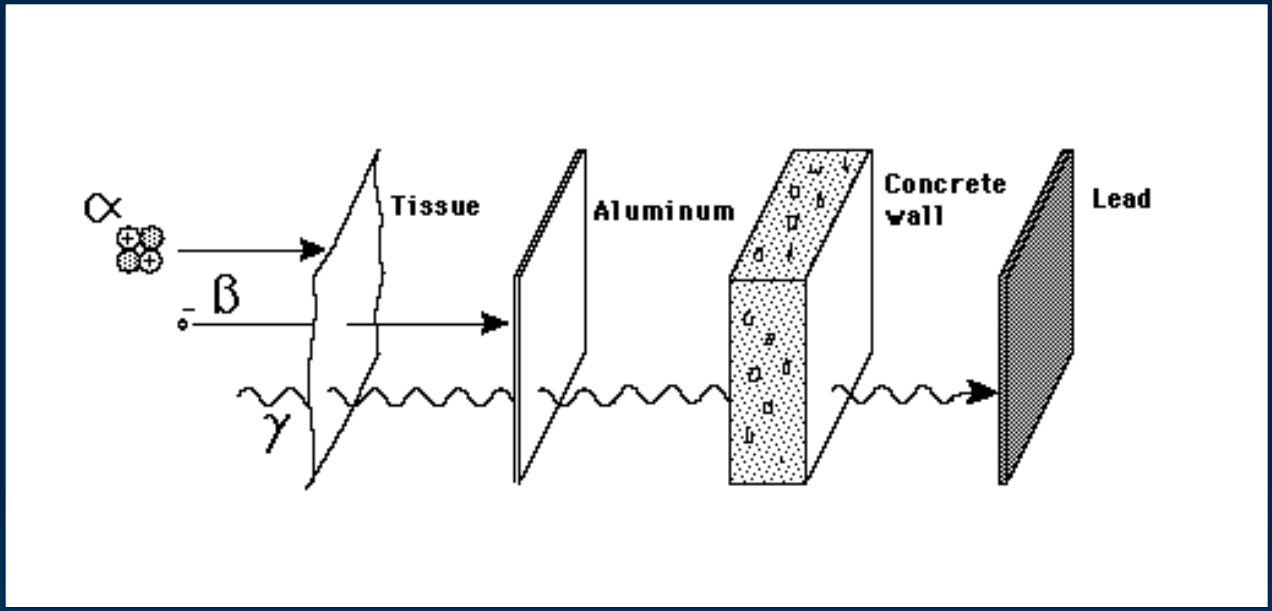


Typical x-ray energy spectrum (example is for 150 keV peak)

What about the interactions of other types of particles with matter?

Alpha particles

Alpha particles are relatively heavy (~7300x that of electron) and have 2 units of charge, thus, they have much shorter range…because each Coloumb interaction is greater.



Typical range of alpha particles in tissue is 40 μm. This explains why alpha particles are normally only a hazard as an “internal emitter.”

Neutrons

The processes for slowing of neutrons in matter is the reverse of that of charged particles.

Because neutrons are of neutral charge, there is no Coulomb interaction.

Neutrons are primarily slowed as a result of ‘collisions’ and scattering from nuclei and are eventually absorbed in by the nuclei in neutron-capture reactions.

In elastic scattering (this is where the kinetic energy is conserved through the collision), the maximum energy (Q_{max}) that a particle of mass M and energy E can transfer to a free particle of mass m is

$$Q_{max} = 4mM/(M+m)^2$$

Since neutrons and protons have near equal mass, large energy transfers are possible in proton rich material, e.g., water or tissue. Less energy is transferred (per collision) to ^{12}C or heavier atoms (because their mass m is larger).

Neutrons (con't.)

Not all energy is transferred, however, in all neutron interactions.

There is a distribution of energy transferred per interaction and multiple interactions may be necessary before the neutron is 'thermalized' (moving at speeds representative of typical thermal energy, i.e. within the 'eV' range) where the neutron can be captured by a nucleus.

A common neutron capture reaction is: $^{1}H + n , \gamma) \, ^{2}H$ which releases a 2.22 MeV γ photon that can irradiate surrounding tissue.

Another neutron capture reaction is: $^{23}Na + n \longrightarrow \, ^{24}Na + \gamma$ results in the production of ^{24}Na which is radioactive ($t_{1/2}$ = 15 hr).

Sodium-24 releases 2 γ's, one each of 1.37 and 2.75 MeV. This 'activation' of sodium in human blood can be used to indicate personnel exposures after a nuclear criticality accident.

Comparing Interactions of Photons and Other Charged Particles

Comparing Interactions of Photons and Other Charged Particles

Photons

- Not charged
- Zero rest mass
- V = c
- No Coulomb force
- Random and rare interactions
- Infinite range (in theory)

Comparing Interactions of Photons and Other Charged Particles

Photons

- Not charged
- Zero rest mass
- V = c
- No Coulomb force
- Random and rare interactions
- Infinite range (in theory)

Electrons

- Charged
- Finite mass
- V < c
- Coulomb force
- Continuous interactions
- Finite range

SIDEBAR on Radiation Interaction

Q: Why can bones be distinguished from soft tissue in an x-ray image?

Part III.
DOSIMETRY: The Basics

Dosimetry is not a basic science, but is simply applied physics.

The primary goal goal of radiation dosimetry in the context of this lecture is a quantitative estimation of the absorbed energy in tissue, with an emphasis on the organ average dose.

To make estimates of radiation dose (i.e., the energy absorbed by tissue), one needs to understand the processes by which radiation interacts with tissue as it those interactions that result in the transfer of energy to the tissue.

What did we learn from the discussion on interactions of radiation with matter?

There are several different types of interactions, but all result in either releases of electrons or photons.

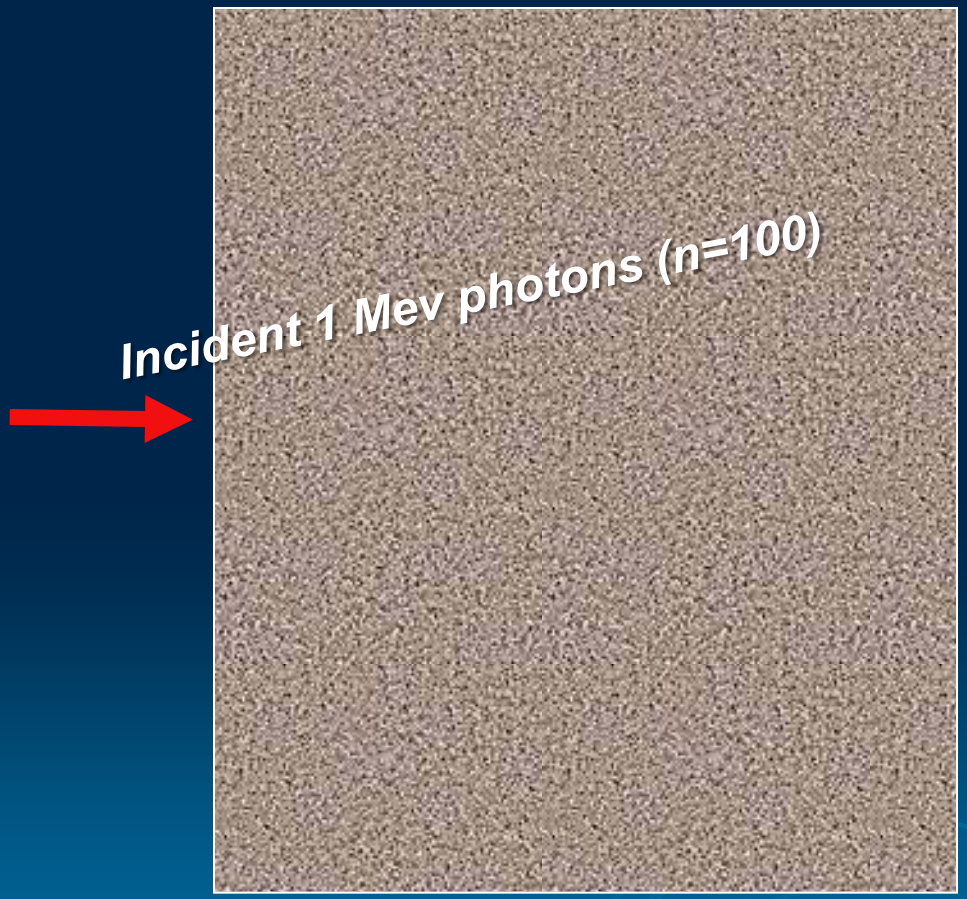
Because not all of the energy from an incident particle or photon is absorbed in a single interaction, **radiation exposure causes a cascade of events before all of the incident energy is absorbed**.

Example:

Suppose 1 Mev photons are incident on carbon (as a simulation of tissue). Let's see what happens inside the material from the exposure.

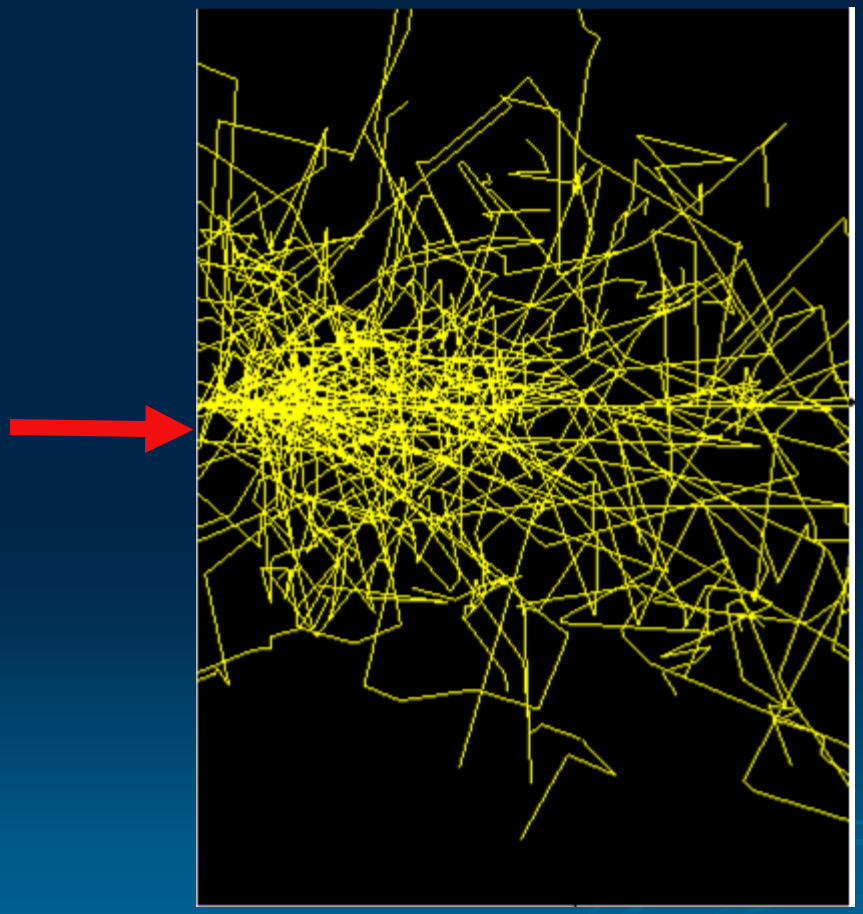
20 cm radius target, 30 cm deep

Photons and electrons calculated by SLAC EGS code.



20 cm radius target, 30 cm deep

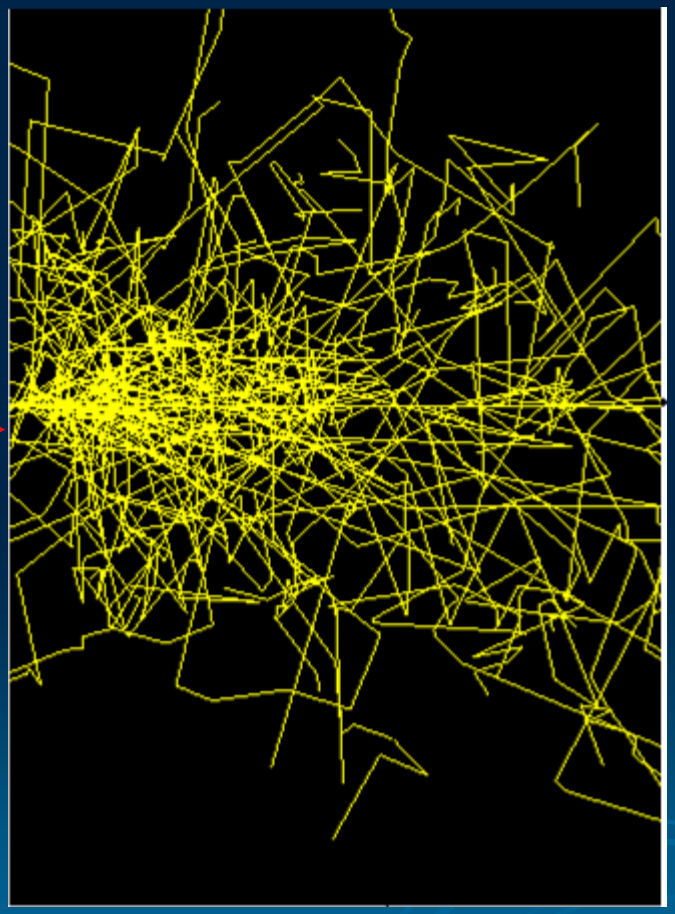
Photons and electrons calculated by SLAC EGS code.



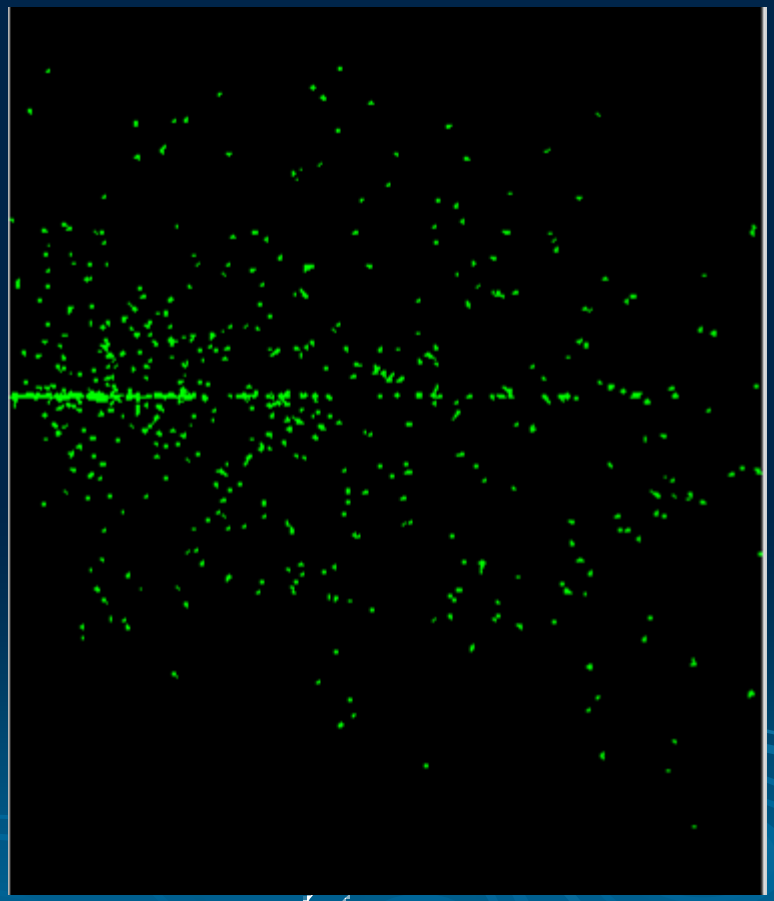
Scattered photons

20 cm radius target, 30 cm deep

Photons and electrons calculated by SLAC EGS code.

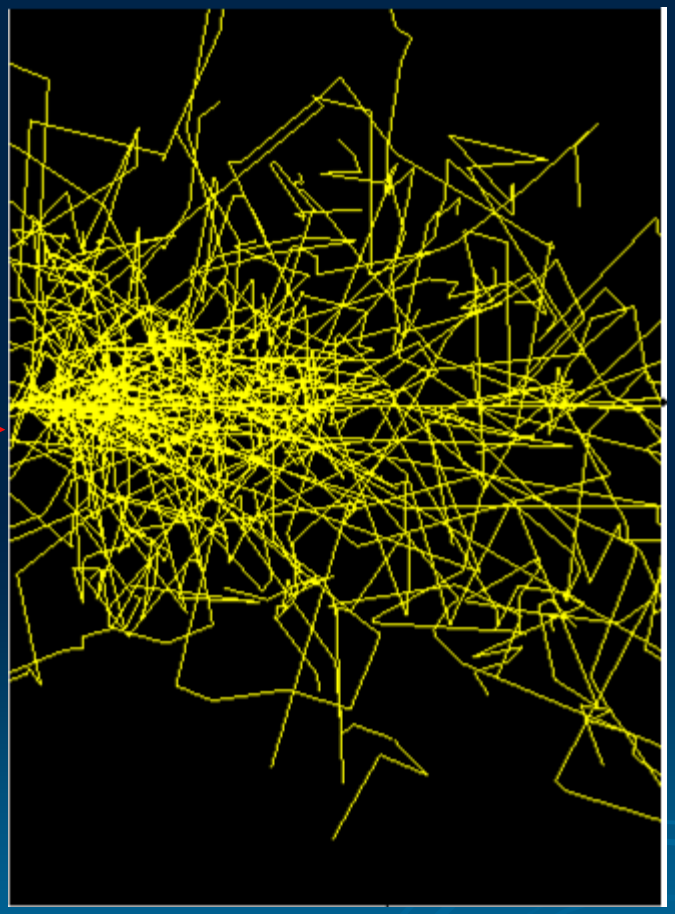


Scattered photons

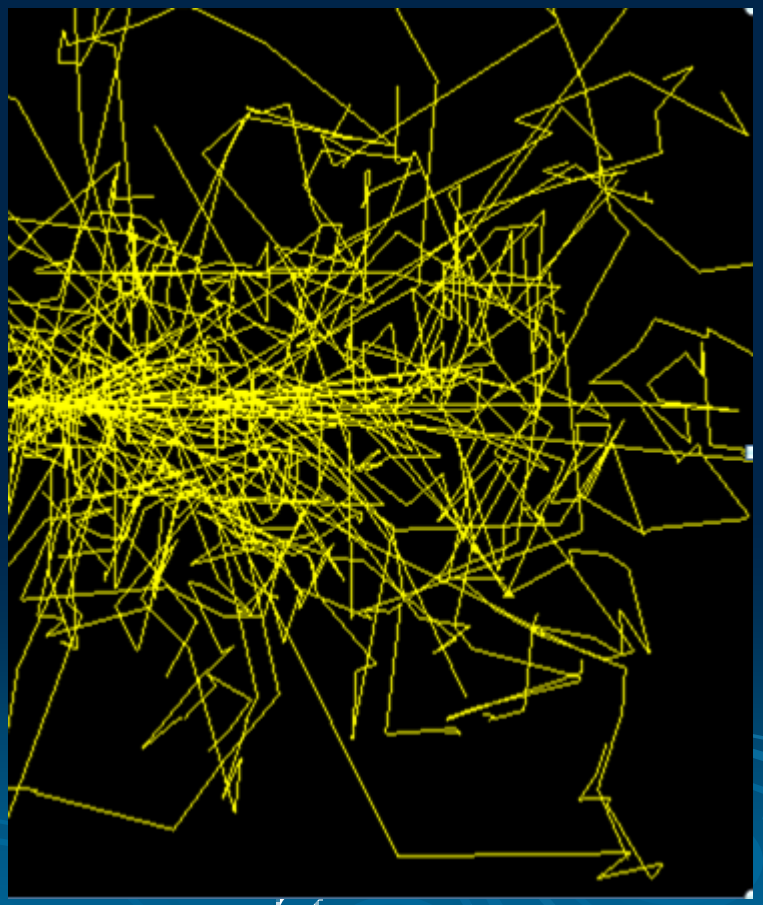


Electrons produced

Interactions are random on a micro-scale but result in a predictable average ionization



1st 100 photons



2nd 100 photons

Radiation Dose Quantities and Units

Three physical quantities are basic to radiation dosimetry of photon beams:

exposure,
kerma, and
absorbed dose.

The conventional units for these quantities were:

- Roentgen (R) for exposure (amount of ionizing x-ray exposure that would liberate 1 electrostatic unit of negative or positive charge per cm^3 of air)

- rad for kerma and absorbed dose (where 100 erg/g = 1 rad)

The International System of Units (SI) uses:

- Coulomb per kilogram (C/kg) for exposure (2.58 x 10-4 C/kg = 1 R) and
- Joule per kilogram for kerma and absorbed dose (1 Gy = 1 J/kg)

The special name for the joule per kilogram is the Gray. The SI system has no special name for units of exposure.

Exposure

(the technical definition in radiation dosimetry, not the generic meaning of "being in contact with…")

First, 'exposure' is a sometimes useful, but somewhat outdated concept.

The 'exposure' X is defined as:

X = dQ/dm

where dQ is the absolute value of the total charge of one sign produced in air within the volume element dm as a result of ionization of the air.

Units: Roentgen (conventional units) or C/kg (coulomb per kilogram of air, SI units).

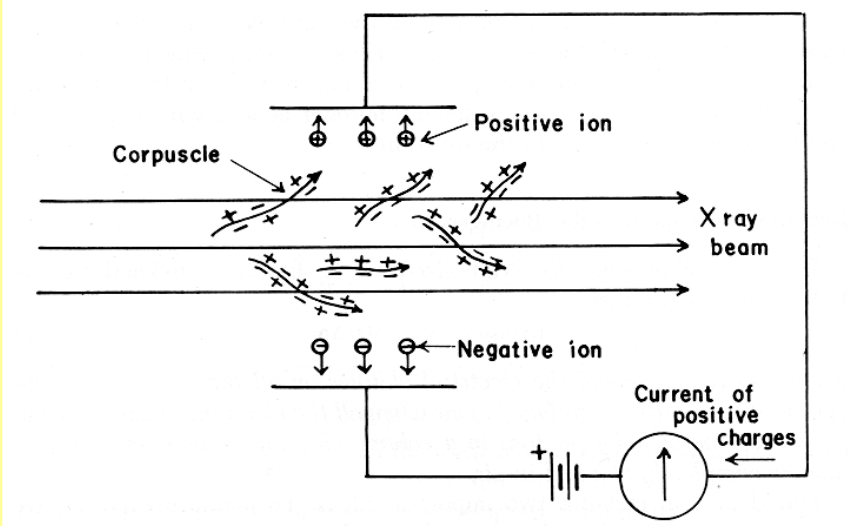


FIGURE VII-2. Diagram illustrating the ionization produced in air by an x-ray beam.

KERMA

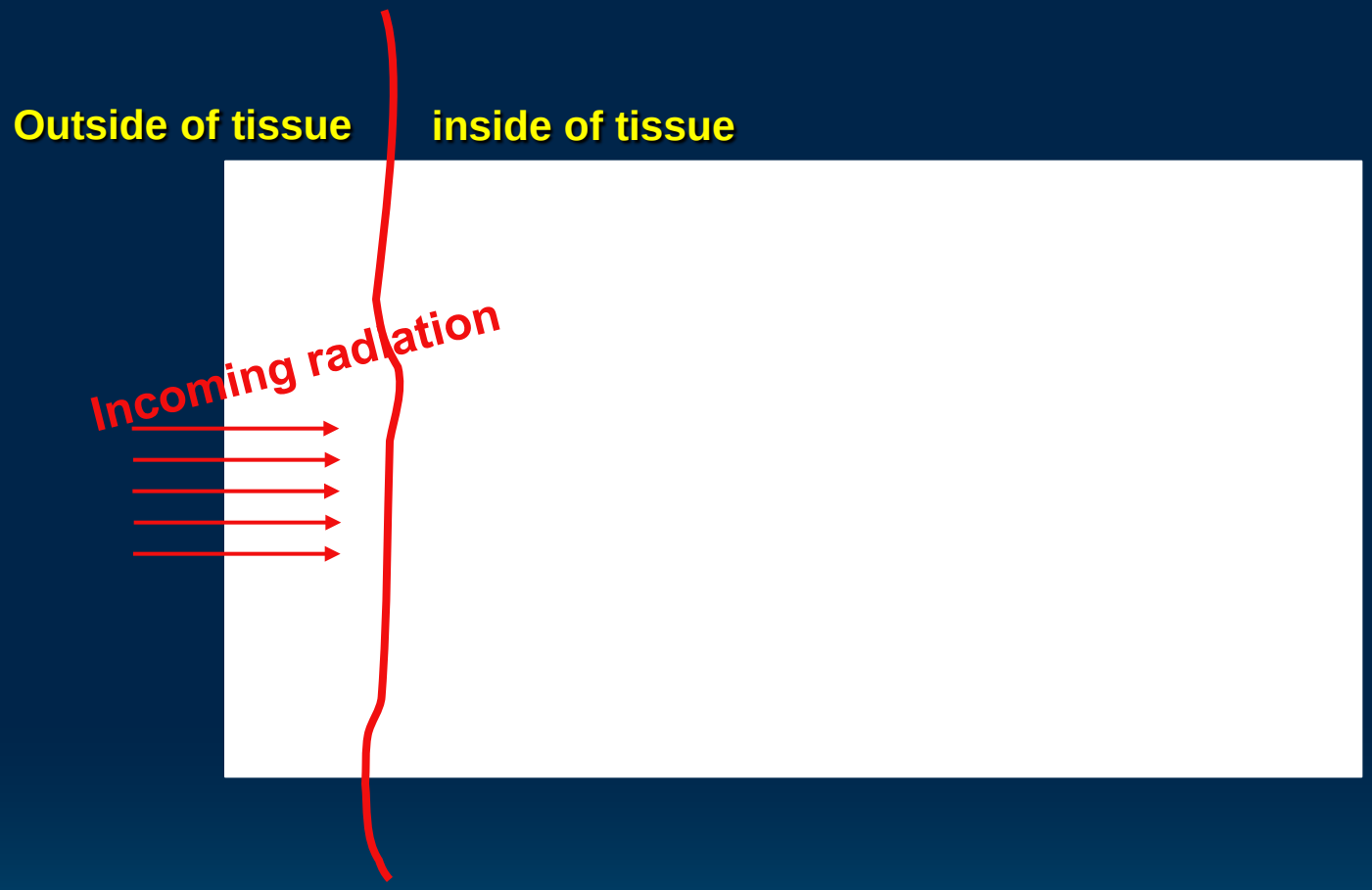
The ‘kerma’ (‘kinetic energy released in medium’) K is defined as:

$K = (dE_{tr}/dm)$

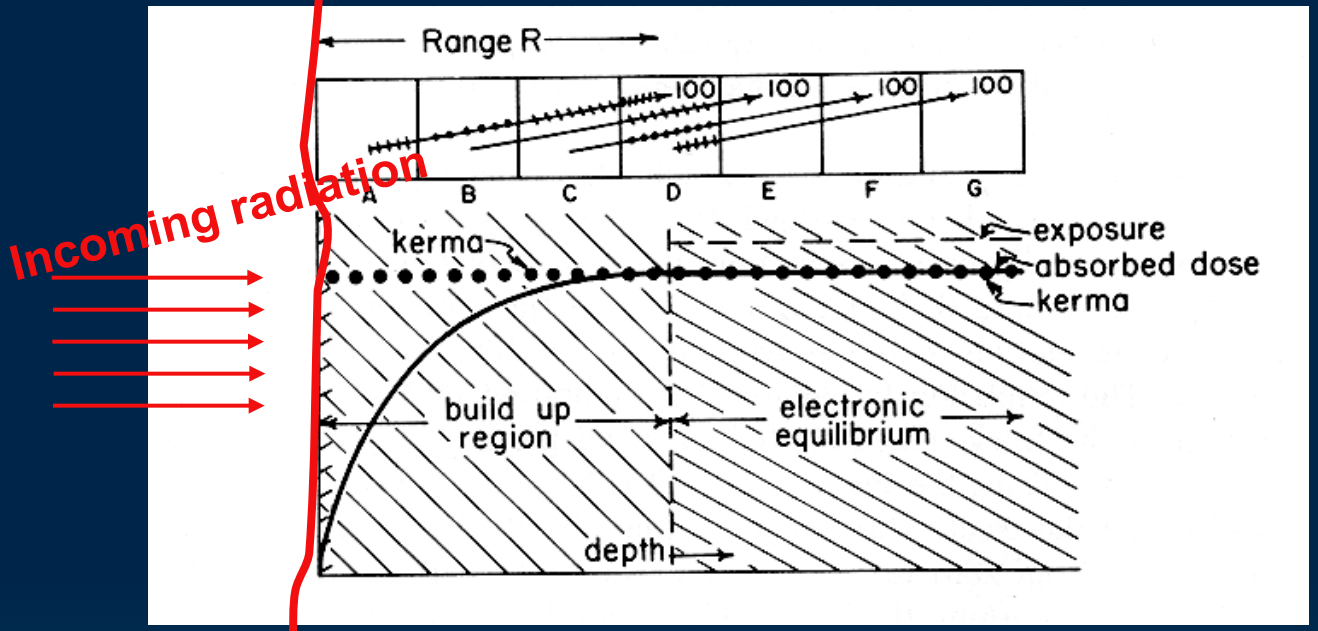
where dE_{tr} is the sum of the initial kinetic energies of the charged particles liberated by the photons (photons are often called ‘indirectly ionizing particles, whereas, electrons are called ‘directly ionizing’ particles) in the volume element.

Units: joule/kg (SI with special name Gray), erg/gm (conventional with special name rad)

Kerma is closely related, but not exactly the same as absorbed dose


Outside of tissue
inside of tissue
Incoming radiation

Outside of tissue | inside of tissue



Kerma > dose

Kerma = dose (region where number of secondary electrons entering equals those leaving)

Fundamental to understanding 'absorbed dose' is the concept of the 'energy imparted', ε , within a volume:

$$\varepsilon = R_{in} - R_{out} + \Sigma Q$$

where,

R_{in} is the incident energy on the volume, i.e., the sum of the energies (including 'rest energies') of the charged and uncharged ionizing particles that enter the volume,

R_{out} is the energy emerging from the volume, i.e., the sum of the energies (including 'rest energies') of the charged and uncharged ionizing particles that leave the volume,

ΣQ is the sum of the all changes of the rest mass energy of the nuclei and particles in any interactions which occur in the volume.

The absorbed dose D is:

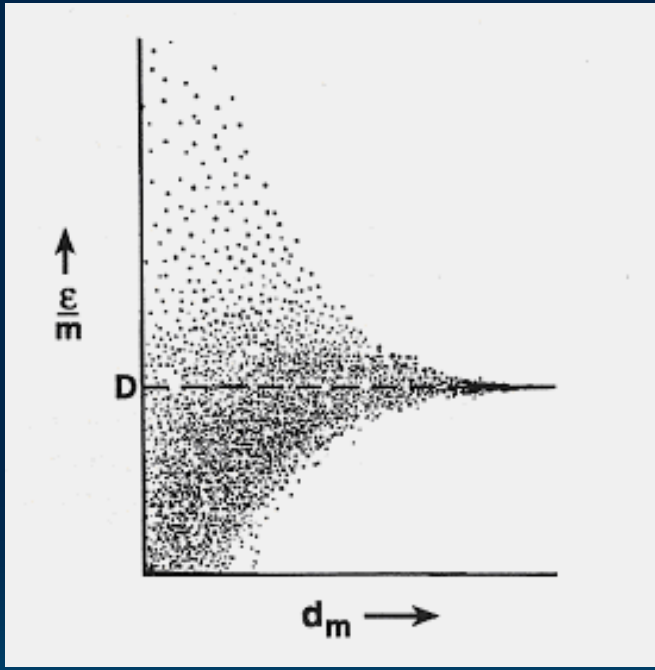
$$D = k_1 \frac{d\varepsilon}{dm}$$

where $d\varepsilon$ is the mean (average) energy imparted by ionizing radiation to matter in a volume element dm. As the volume approaches zero, the absorbed dose is defined at that point.

Note: The coefficient k_1 has the value of 1.0 for SI absorbed dose units (joule/kg with the special name of Gray [Gy]) and a value of 100 for conventional dose units (ergs/gram with the special name of rad).

For small volumes, there is statistical variation of the absorbed dose since the likelihood of interaction per unit distance is characterized by a probability.

The stochastic (random) variation of absorbed dose as a function of volume is shown here.



When averaged over the mass of an organ, the '<u>organ absorbed dose</u>' is probably the most useful measure of radiation dose for epidemiologic studies.

While the energy absorbed per unit mass defines ‘absorbed dose’ on a macroscopic scale, it may not properly define the spatial pattern of absorbed energy delivered on the microscopic level.

Q: Does the deposition of energy on a micro-scale differ according to radiation type?
(Remember …the Coulomb interaction differs for particles of different charges)

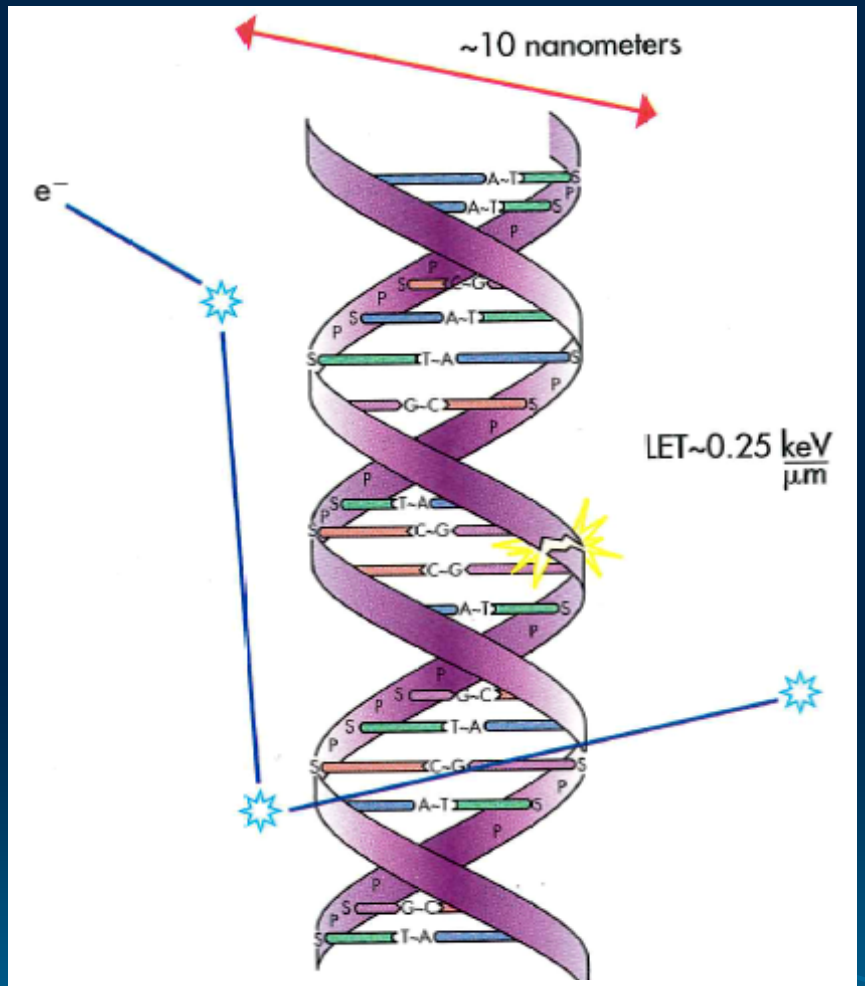
Q: How might we specify how the energy is deposited on a micro-scale?

Radiobiology and, to some extent, dosimetry, considers the linear rate of transfer of energy to the irradiation medium (e.g., tissue).

The quantity, LET, i.e., “linear energy transfer”, captures this concept.

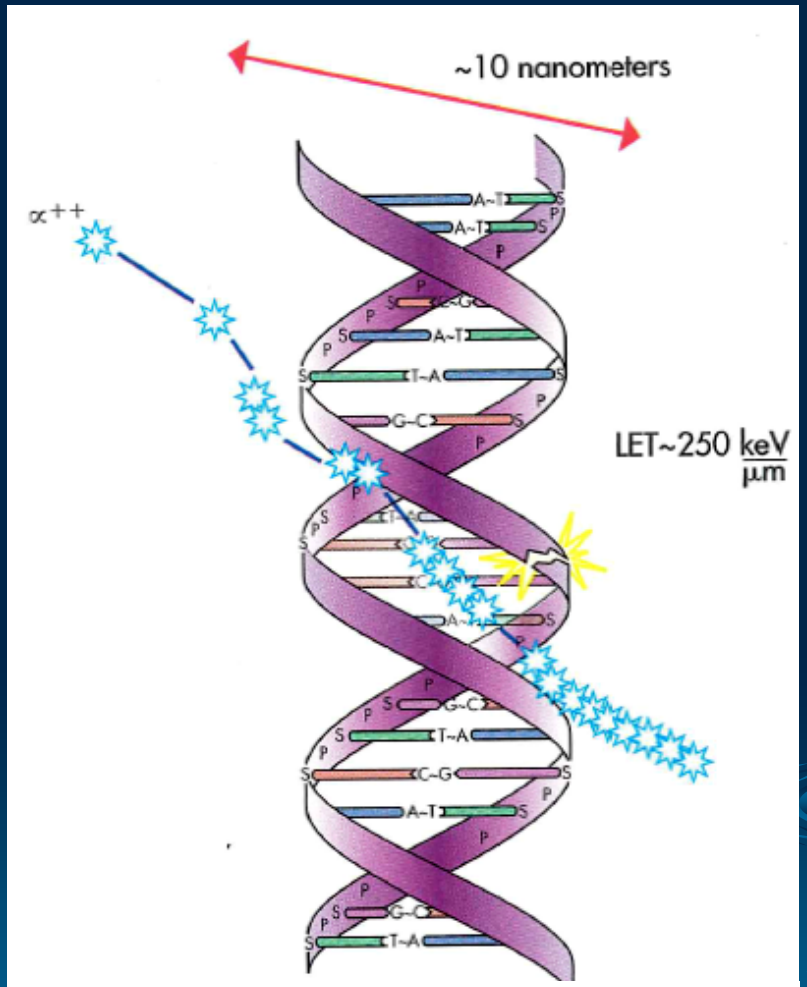
Note: The rate of transfer of energy with path-length can differ for photons and charged particles and this has implications for the degree of local damage.

Example of "low" LET radiation damage for photons and electrons, ~0.25 keV energy lost per micron



Low likelihood of double strand DNA breakage (to be discussed in rad bio)

Example of "high" LET radiation damage for alpha particles, ~250 keV energy lost per micron



Higher likelihood of double strand breakage

Reminder: Absorbed dose (Gy) considers only the energy absorbed in the irradiation medium.

An additional metric of dose, the Equivalent dose (Sv), accounts for the LET relative to photons by a multiplicative radiation weighting factor, W_R.

Equivalent dose may have use in radiation epidemiology though the occasions will be few.

Reminder: Absorbed dose (Gy) considers only the energy absorbed in the irradiation medium.

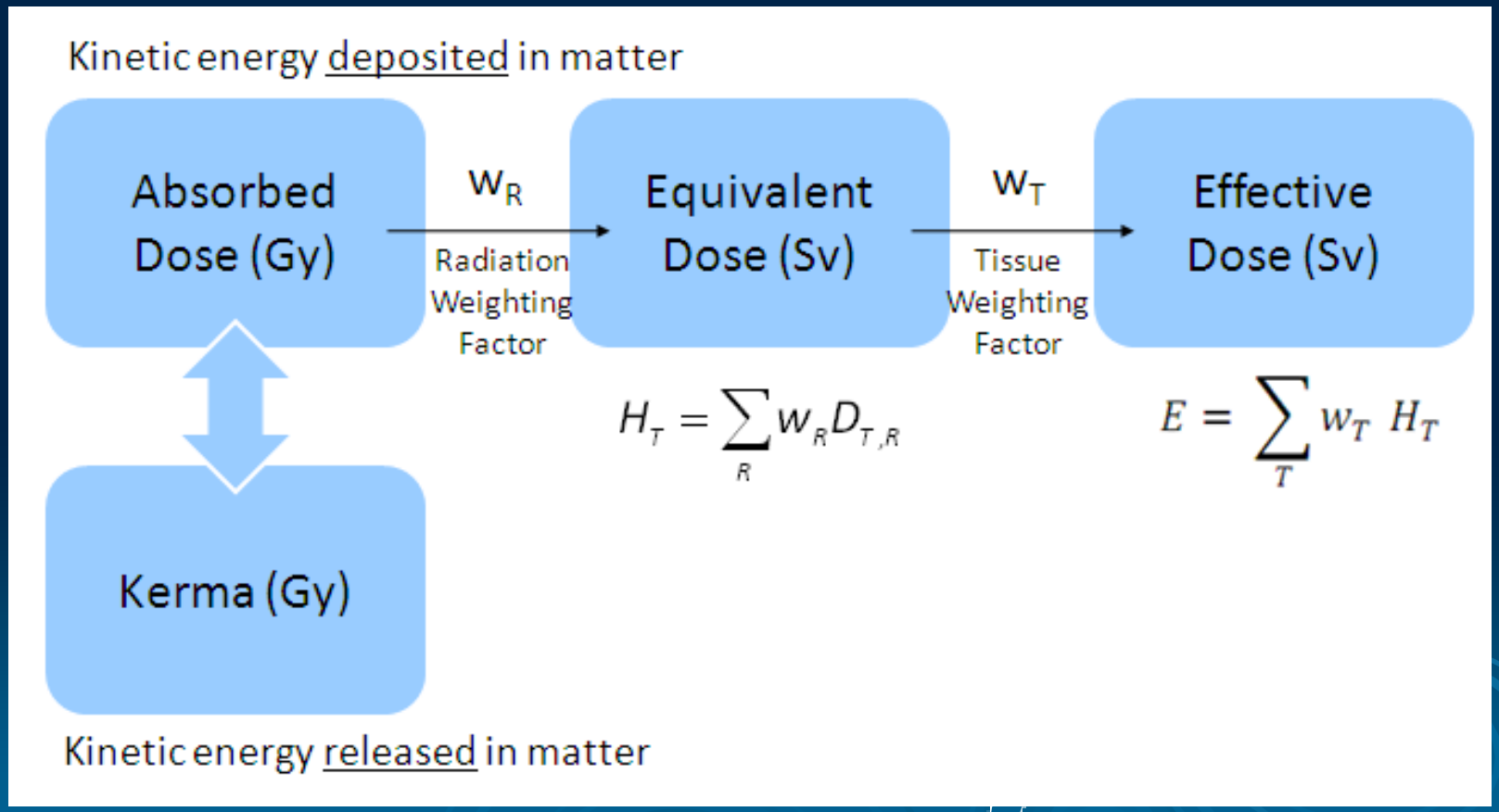
An additional metric of dose, the Equivalent dose (Sv), accounts for the LET relative to photons by a multiplicative radiation weighting factor, W_R.

Equivalent dose may have use in radiation epidemiology though the occasions will be few.

An additional metric of dose, the Effective Dose (also with units of Sv) is a radiation protection quantity, normally without value in radiation epidemiology* since it approximately accounts for the radiation sensitivity of individual tissues (with a multiplicative factor W_T). Determination of tissue sensitivity is one of the primary objectives of radiation epidemiology to determine.

** may be used for approximate projection of total fatal cancers based on published risk coefficient (averaged over population).*

Reminder: Absorbed dose (Gy) considers only the energy absorbed in the irradiation medium while Equivalent Dose accounts for differences in LET. These metrics of dose are MOST useful for epidemiology. Effective Dose accounts for approximate differences in tissue sensitivity for radiation protection (regulatory) purposes.



Reminder: Absorbed dose (Gy) considers only the energy absorbed in the irradiation medium while Equivalent Dose accounts for differences in LET. These metrics of dose are MOST useful for epidemiology. Effective Dose accounts for approximate differences in tissue sensitivity for radiation protection (regulatory) purposes.

Table 2. Recommended radiation weighting factors.

Radiation type	**Radiation weighting factor, w_R**
Photons	1
Electrons[a] and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy (see Fig. 1 and Eq. 4.3)

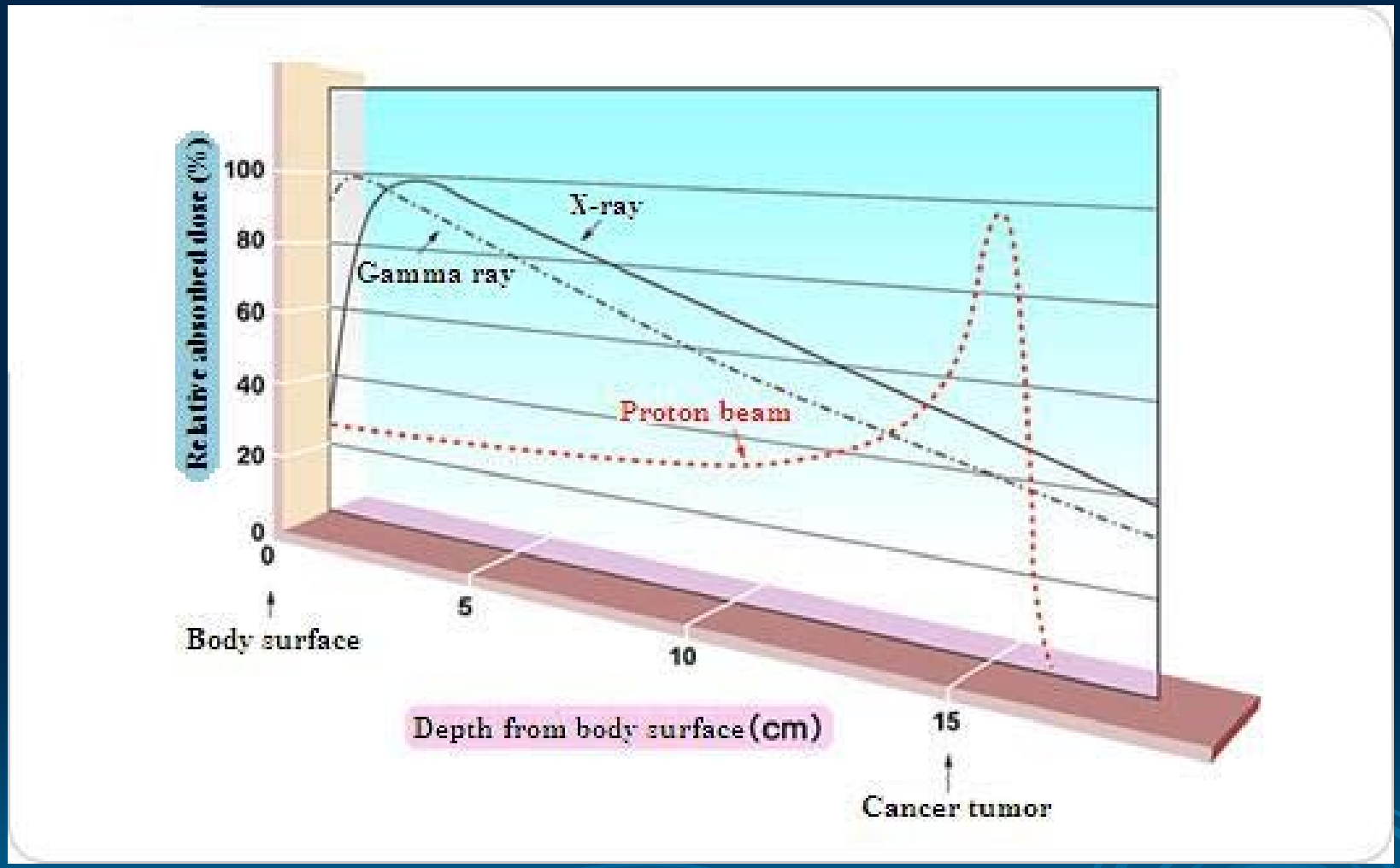
$$w_R = \begin{cases} 2.5 + 18.2\, e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0\, e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leqslant E_n \leqslant 50 \text{ MeV} \\ 2.5 + 3.25\, e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases}$$

Reminder: Absorbed dose (Gy) considers only the energy absorbed in the irradiation medium while Equivalent Dose accounts for differences in LET. These metrics of dose are MOST useful for epidemiology. Effective Dose accounts for approximate differences in tissue sensitivity for radiation protection (regulatory) purposes.

NOTE: Weighting factors have changed over time and can lead to confusion about published "doses."

tissue or organ	w_T (ICRP 60)	w_T (ICRP 103)
gonads	0.20	0.08
bone marrow (red)	0.12	0.12
colon	0.12	0.12
lung	0.12	0.12
stomach	0.12	0.12
bladder	0.05	0.04
breast	0.05	0.12
liver	0.05	0.04
oesophagus	0.05	0.04
thyroid	0.05	0.04
skin	0.01	0.01
bone surface	0.01	0.01
salivary glands	–	0.01
brain[1]	–	0.01

SIDEBAR on Radiation Dose



Radiation dose usually decreases with increasing depth in tissue. Is this always true?

Let’s move now from theory to practice…

What is there to consider about radiation exposure that might be relevant to radiation dosimetry <u>and</u> to radiation epidemiology?

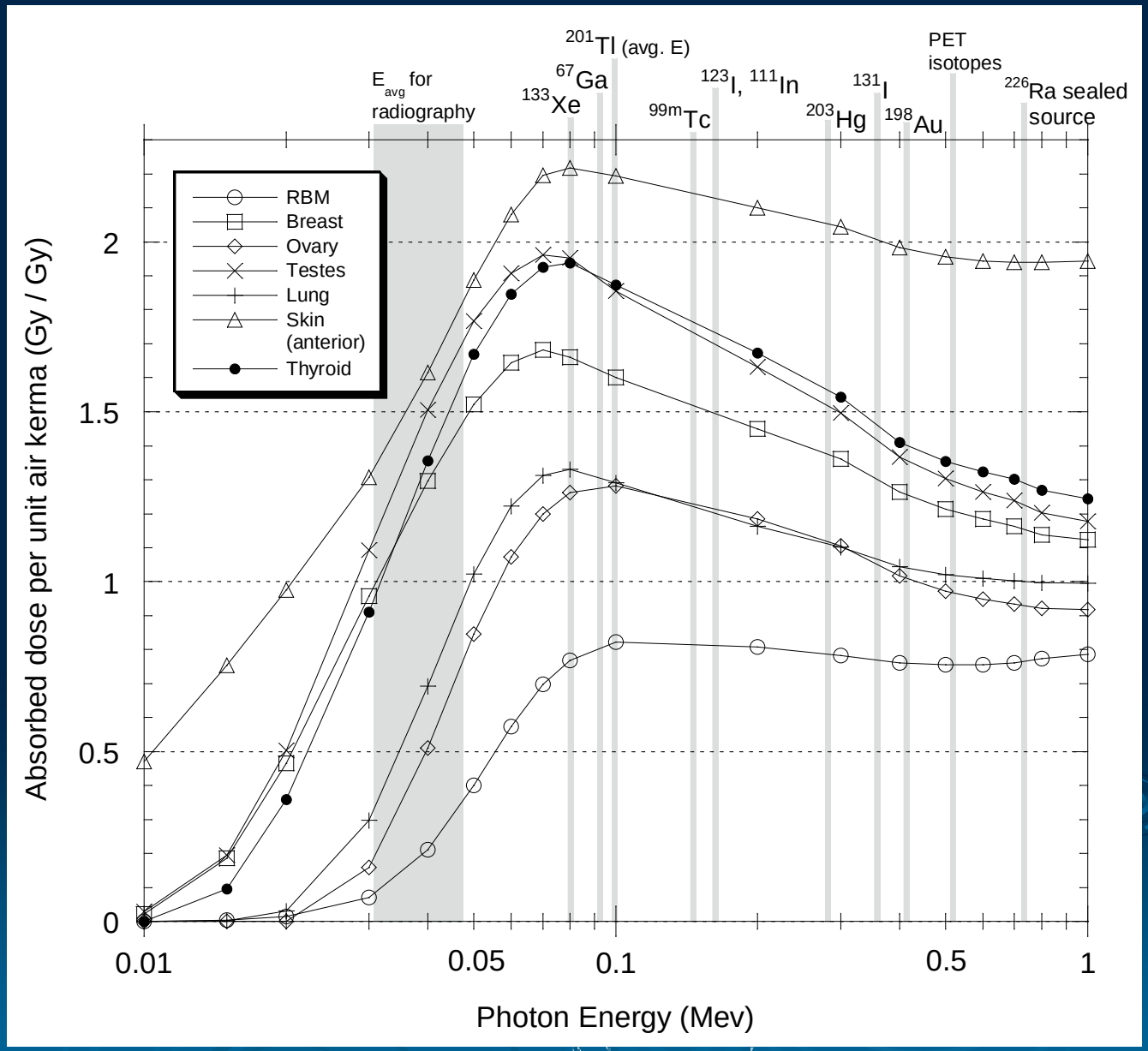
1) Specifics about the radiation
    a) Type of radiation
    b) Energy of radiation

2) Specifics about the exposure conditions
    a) Internal or external exposure
    b) Geometry of exposure conditions
    c) Part of the body exposed
    d) Length of time of exposure
    e) Rate of exposure
    f) Total exposure

3) Specifics about the person exposed
    a) Age, gender, body mass index, health status, etc.

EXTERNAL RADIATION DOSE to different body tissues depends greatly on energy of radiation and geometry of exposure, as well as the model of the human body.

Variation of organ dose per unit of air dose with energy



INTERNAL RADIATION DOSE is a more complex subject because it also depends greatly on:

- Specific Radionuclide
- Type of radiation emitted
- Half-life
- Energy of radiation
- Chemical form of radionuclide
- Chemical and temporal behavior of nuclide in body (residence time in the body and accumulation in organs) , i.e., biokinetics
- Specifics about the exposed individual (age, health status), etc.

EXAMPLE: Iodine-131

The general equation to determine the dose following an accidental intake or following an oral medical administration of ^{131}I is:

$$D = \int_0^{\infty} \frac{A\ f_1\ f_2\ R(t)}{M_T(a)} [\ \sum_{i=1}^{n} Y_i\ E_i\ AF_i(T \leftarrow S, a)\ ] dt$$

where,

A is the activity intake (or the administered activity of ^{131}I (Bq),

f_1 is the fraction of the iodine intake that is transferred to blood (generally assumed to be close to 100%)

f_2 is the fraction of the iodine intake that is absorbed by the thyroid (the rest is excreted primarily through urine),

R(t) is the fraction of the amount that enters the thyroid that is retained at any time, t,

Y_i is the fractional yield of radiation type i, per nuclear transformation,

E_i is the energy released per decay (~0.19 MeV β and ~0.36 MeV γ per nuclear transformation).

$AF_i(T \leftarrow S,a)$ is the fraction of the energy emitted in the source organ S that is absorbed, in the target organ T, and is a function of age, a,

$M_{th}(a)$ is the mass of the thyroid in this case) and is a function of age, *a*

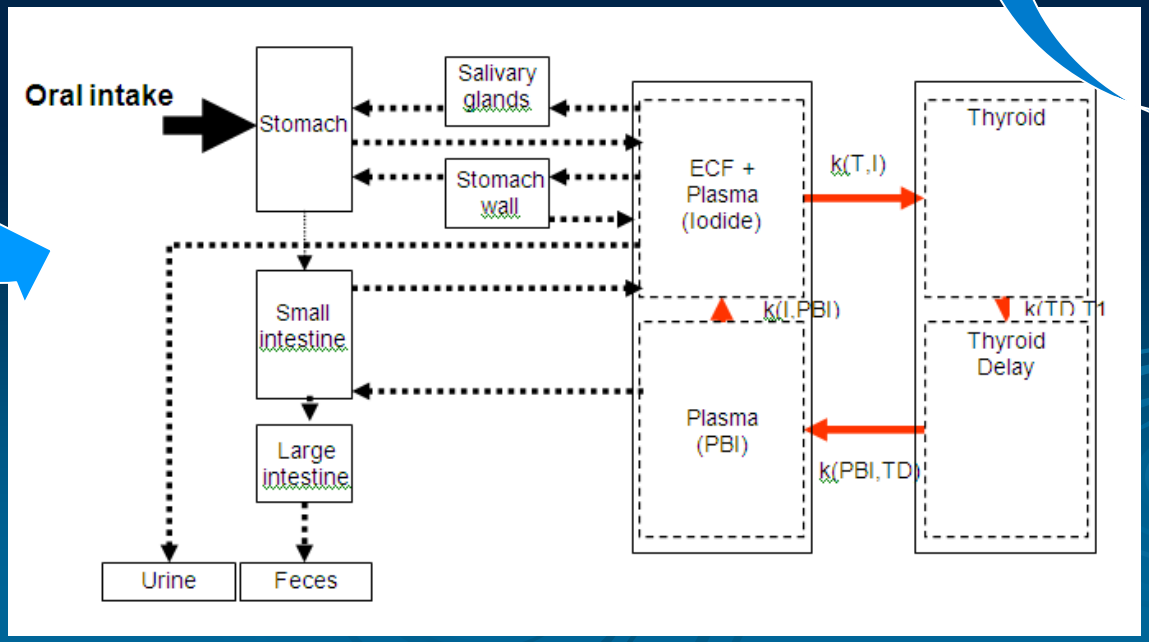
Simplified internal dosimetry equation incorporates all of previous factors.

$$D = \tilde{A}\, S$$

Dose = Time integral of decays in organ of interest x S factor

Equation is conveniently separated into components of biology (biokinetics, i.e., $\tilde{A}$) and physics (dosimetric factors, S)

Previous slides



Q: Why is I-131 so important?

A: Two primary reasons:

- Use in nuclear medicine,
- Possible releases from nuclear reactor accidents, and presence in radioactive fallout (see Friday's lecture on Introduction to Nuclear Accidents).

Part IV.
Sources of Radiation Exposure
(short version !)

- Sidebar on Energy Units
- Comparison of categories of radiation sources
- Environment (natural sources)
- Medical practice (diagnostic and therapeutic procedures)

<u>Not</u> discussed here due to lack of time are doses from:

- Occupations (industrial practices)
- Consumer products
- Accidental exposures and releases

SIDEBAR: Comparisons of the magnitude of units of energy used in radiation physics and dosimetry.

- Photons of visible light have energies of ~1.6 to 3 eV
- It takes about 34 eV to create ionize a single atom of air.
- X-rays have energies from about 1 keV (1,000 eV) to a few hundred keV (a few 100,000 eV)
- Iodine-131 has a prominent gamma ray emission of 364 keV
- Many radionuclides have gamma ray emissions of ~10^6 ev (1 MeV)
- 10^{12} eV is about the kinetic energy of a flying mosquito
- 6×10^{20} eV of energy is needed to power a 100 watt light bulb for one second
- One joule (J) = 6×10^{18} eV = 6×10^{12} MeV
- One Gray is 1 joule of energy absorbed in 1 kg of material

SIDEBAR (con't.)

Assuming that a fatal acute dose of 10 Gy = 10 J/kg and in a 70 kg adult, that would equal 700 J.

How much is 700 J in other terms?

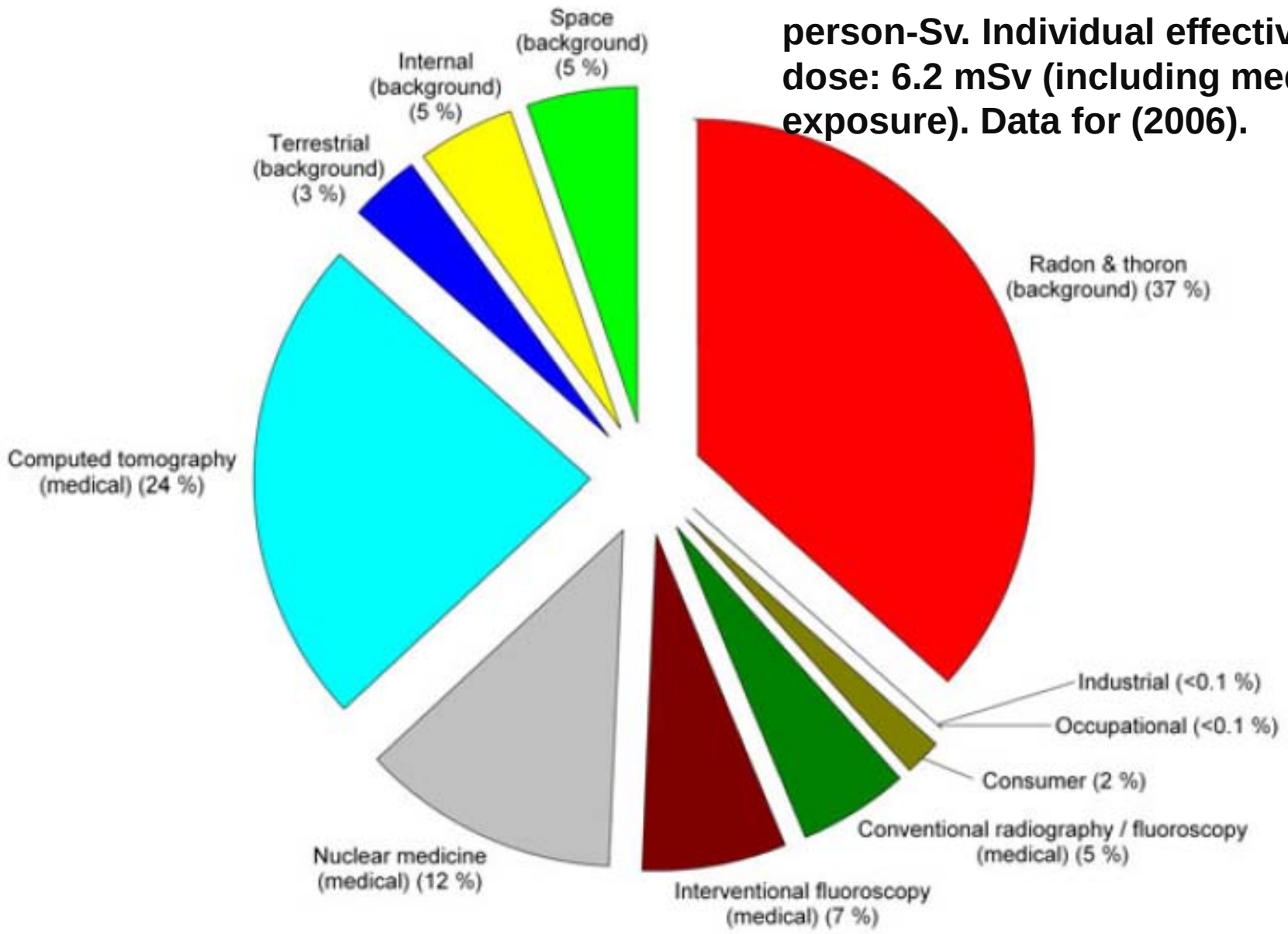
- The energy of sunlight received on 1 square meter in bright daylight in 7/10 of a second.
- The metabolic energy derived from digestion of about 5 mg of carbohydrate, e.g., rice (typical serving is 200 g)

Other Comparisons:

- The chemical energy in a barrel of oil is equal to 8.5 million "doses" of 700 J each.
- The energy released by the Hiroshima atomic bomb is equal to about 8.8 $\times 10^{10}$ "doses" of 700 J each - fatal doses to the population of about 13 planet earths (with today's population of 6.8 billion people).

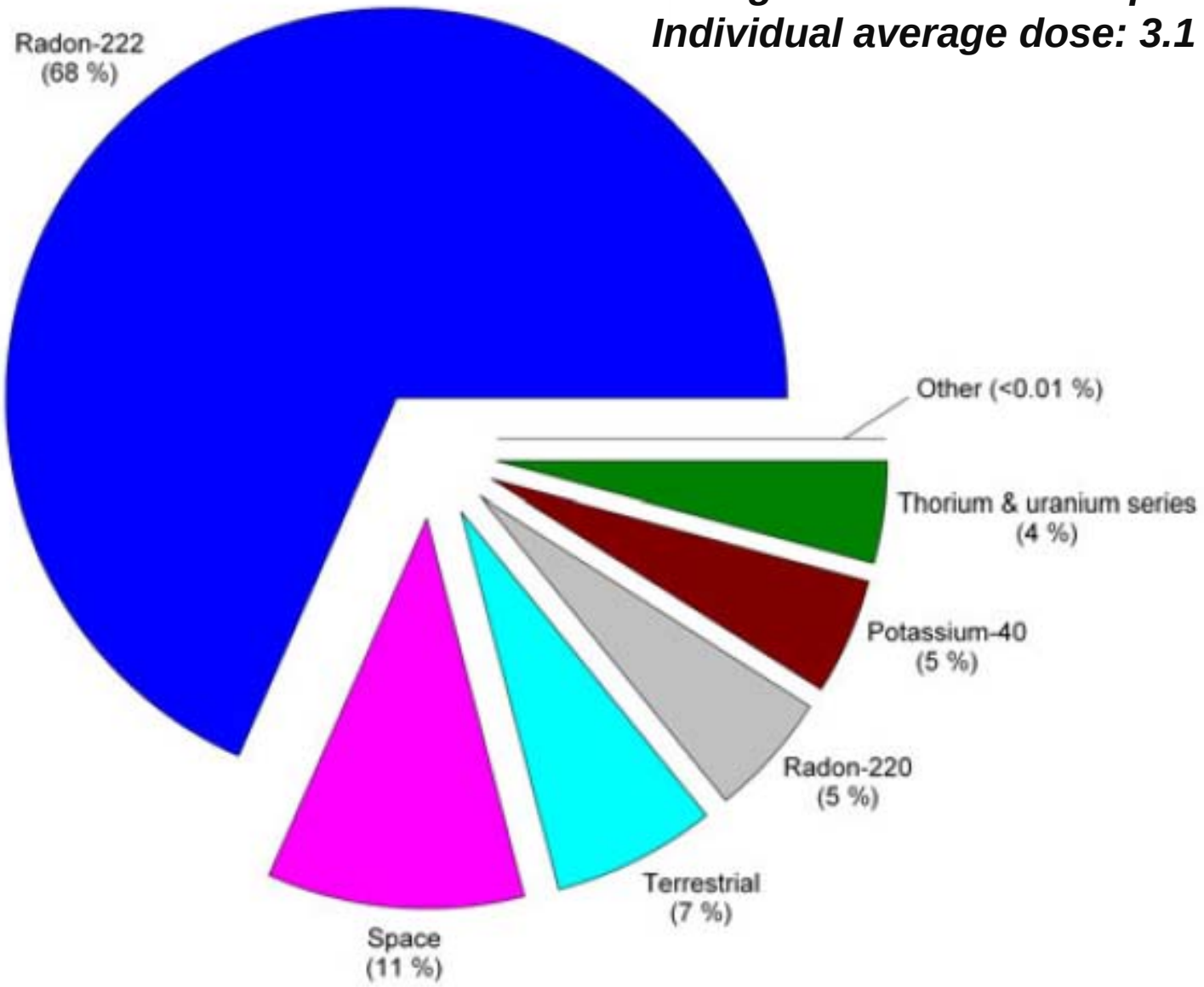
  Of course, most energy was released as heat.

Collective dose in U.S.: 1.9 M person-Sv. Individual effective dose: 6.2 mSv (including medical exposure). Data for (2006).

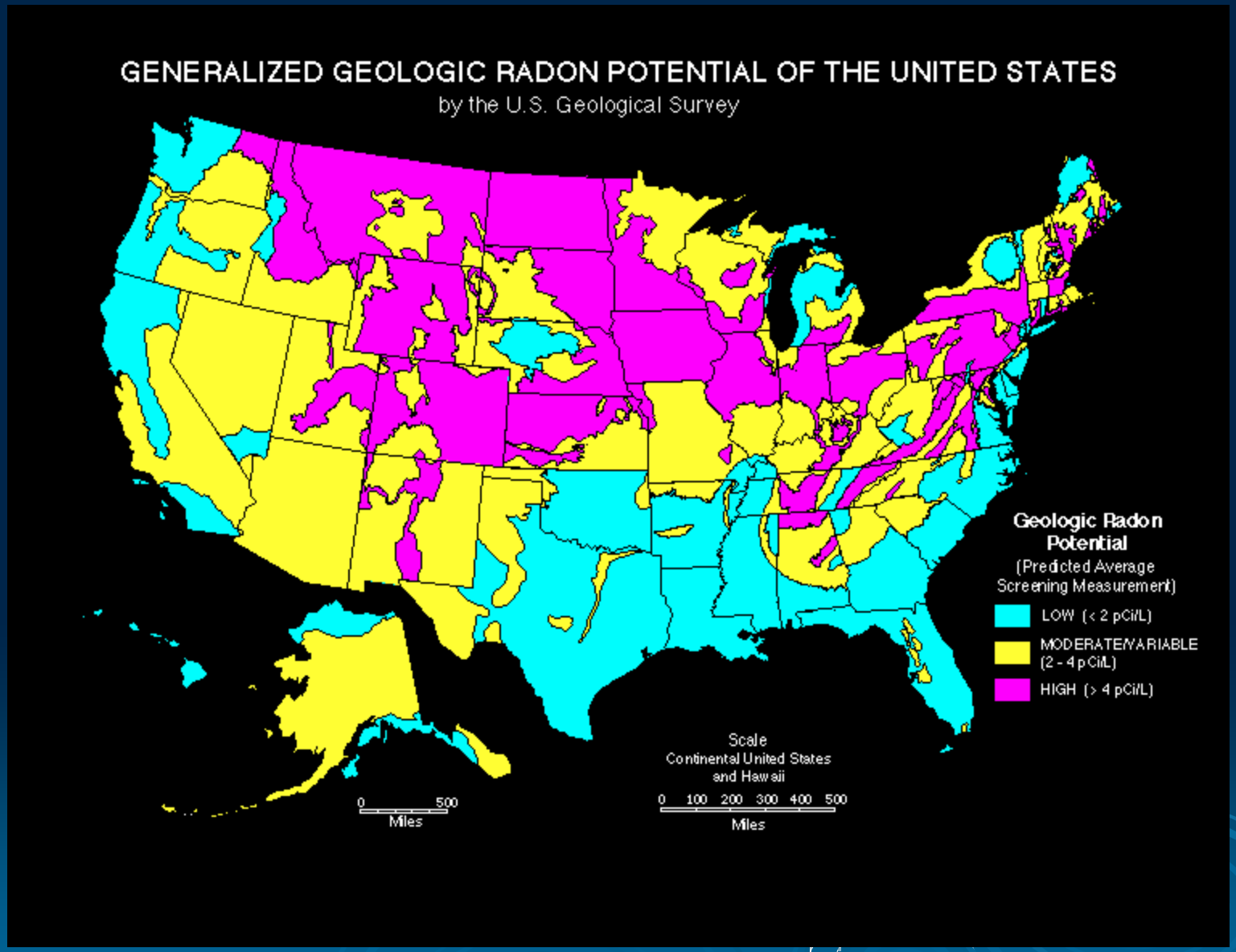


NCRP Report 160, 2009

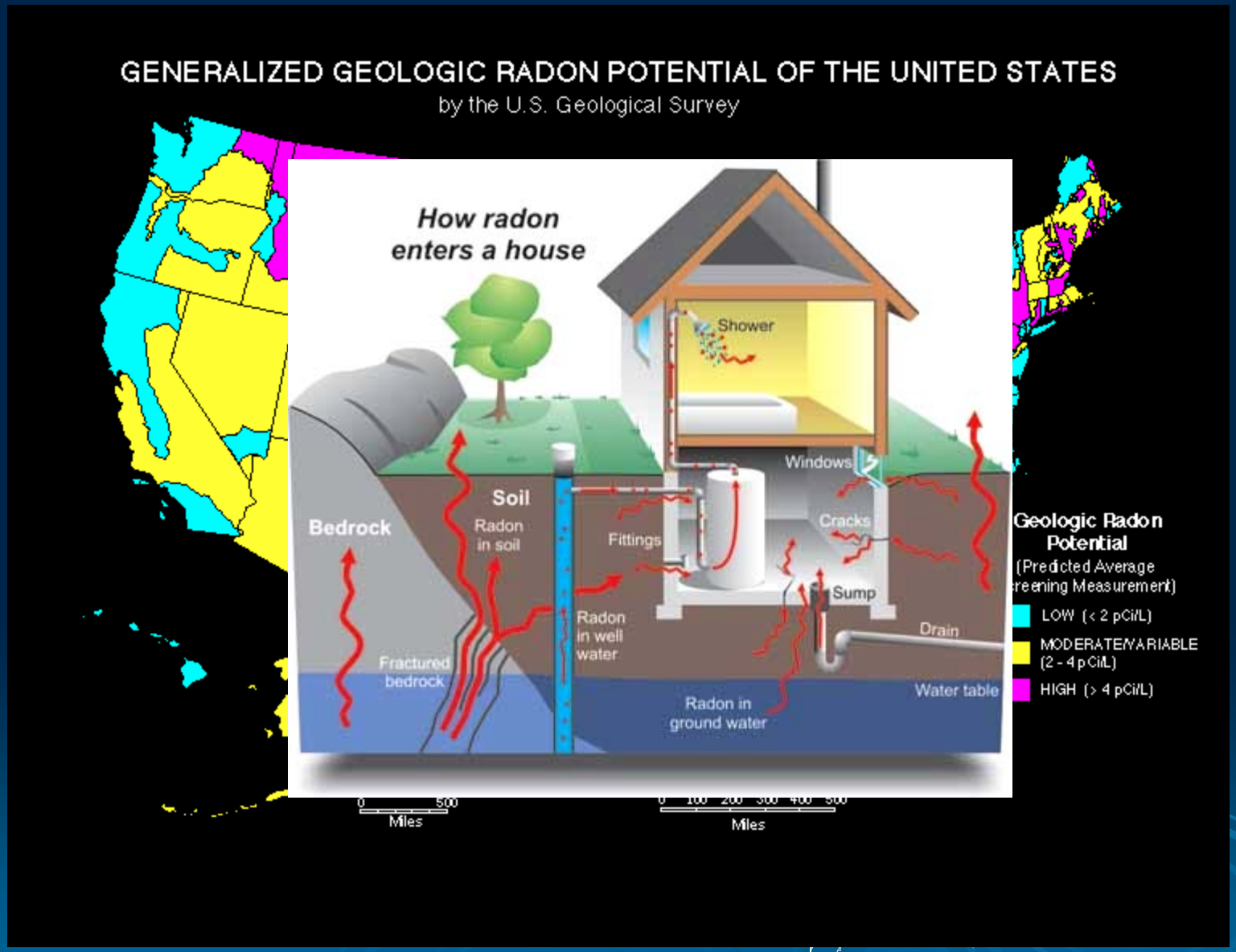
Background radiation exposure. Individual average dose: 3.1 mSv



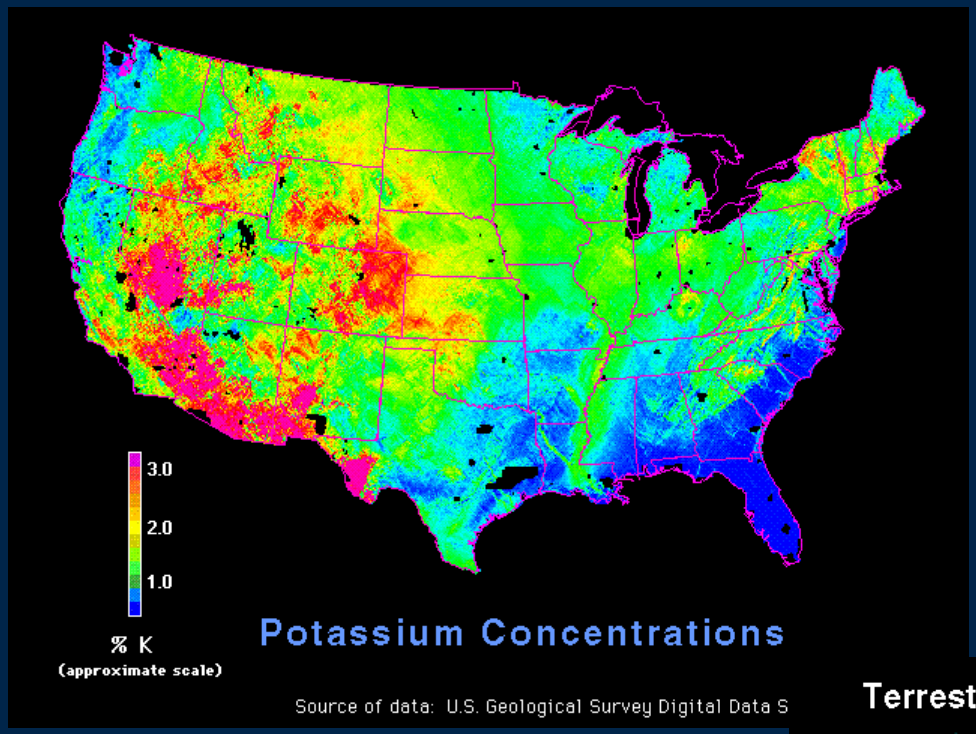
NCRP Report 160, 2009


GENERALIZED GEOLOGIC RADON POTENTIAL OF THE UNITED STATES
by the U.S. Geological Survey
Geologic Radon Potential
(Predicted Average Screening Measurement)
LOW (< 2 pCi/L)
MODERATE/VARIABLE (2 - 4 pCi/L)
HIGH (> 4 pCi/L)
Scale
Continental United States and Hawaii
0 100 200 300 400 500
Miles
0 500
Miles

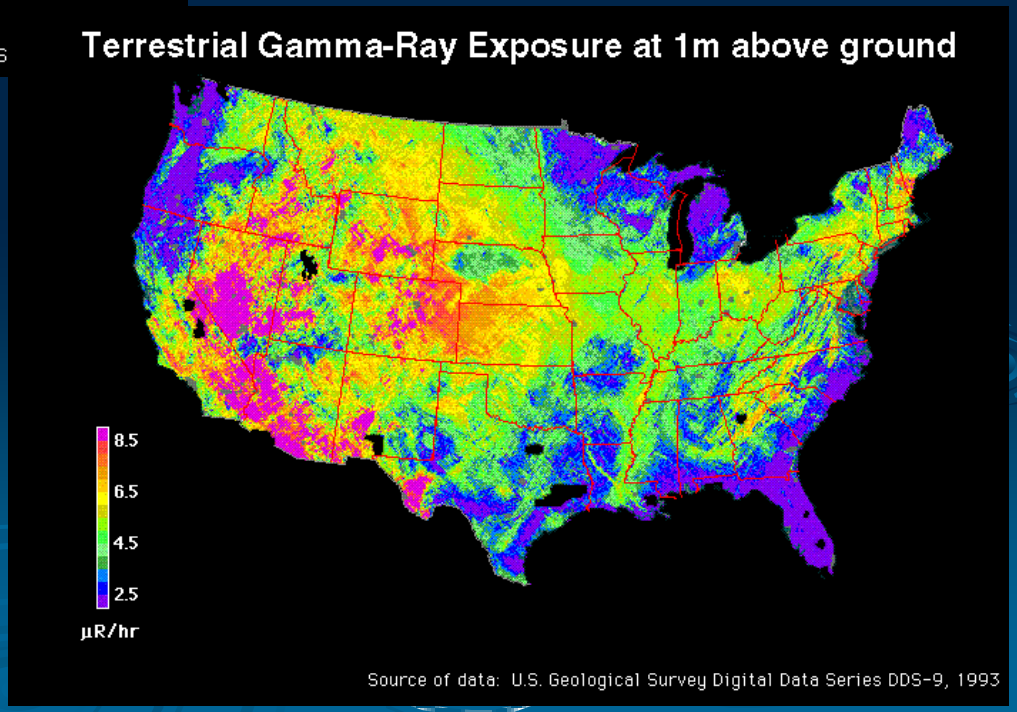
Source: USGS


GENERALIZED GEOLOGIC RADON POTENTIAL OF THE UNITED STATES
by the U.S. Geological Survey
How radon enters a house
Shower
Windows
Soil
Radon in soil
Bedrock
Fittings
Cracks
Sump
Drain
Radon in well water
Fractured bedrock
Water table
Radon in ground water
Geologic Radon Potential
(Predicted Average
LOW (< 2 pCi/L)
MODERATE/VARIABLE (2 - 4 pCi/L)
HIGH (> 4 pCi/L)
0 500
Miles
0 100 200 300 400 500
Miles

Source: USGS

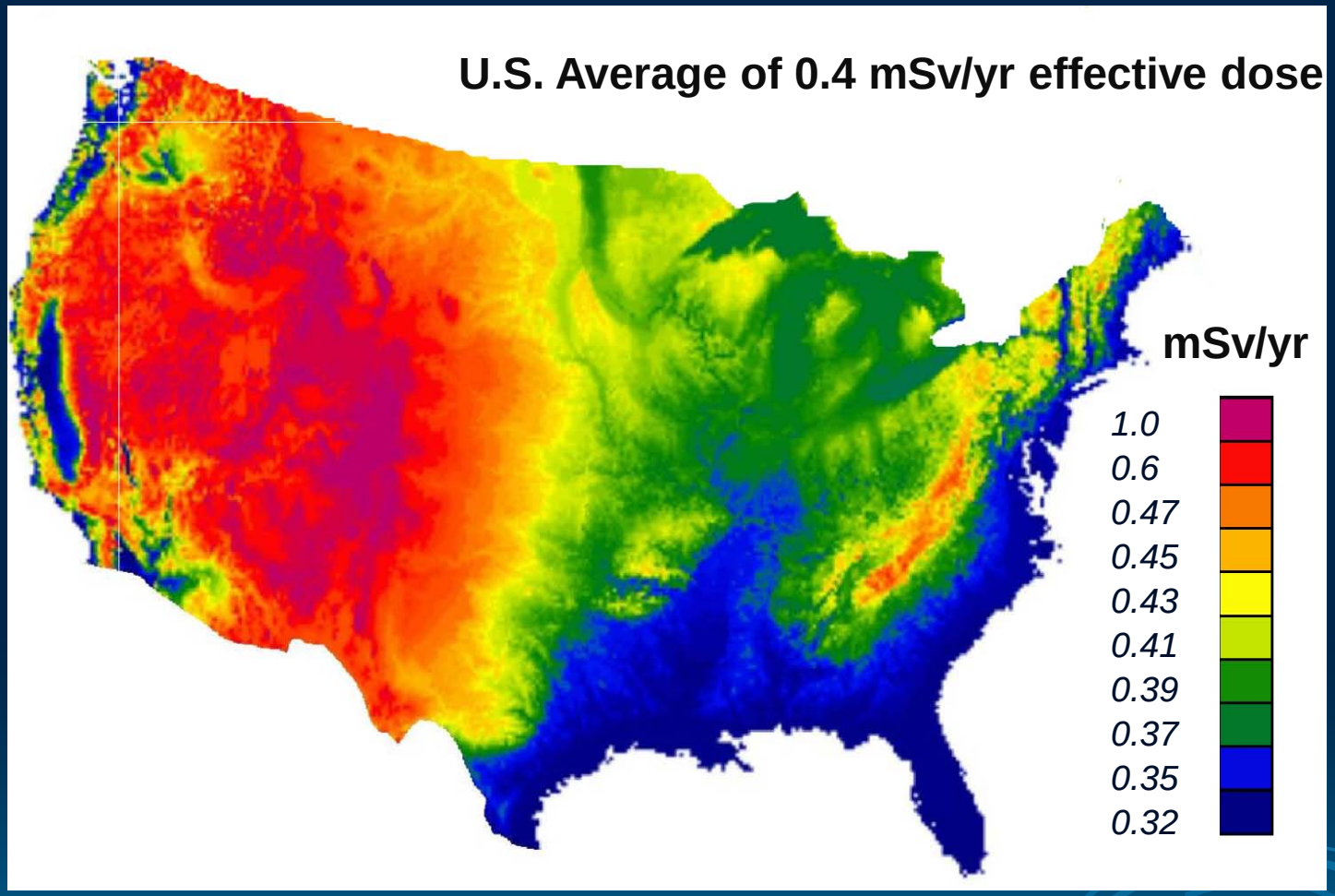


External dose from natural terrestrial sources significantly depends on mineral content of ground.



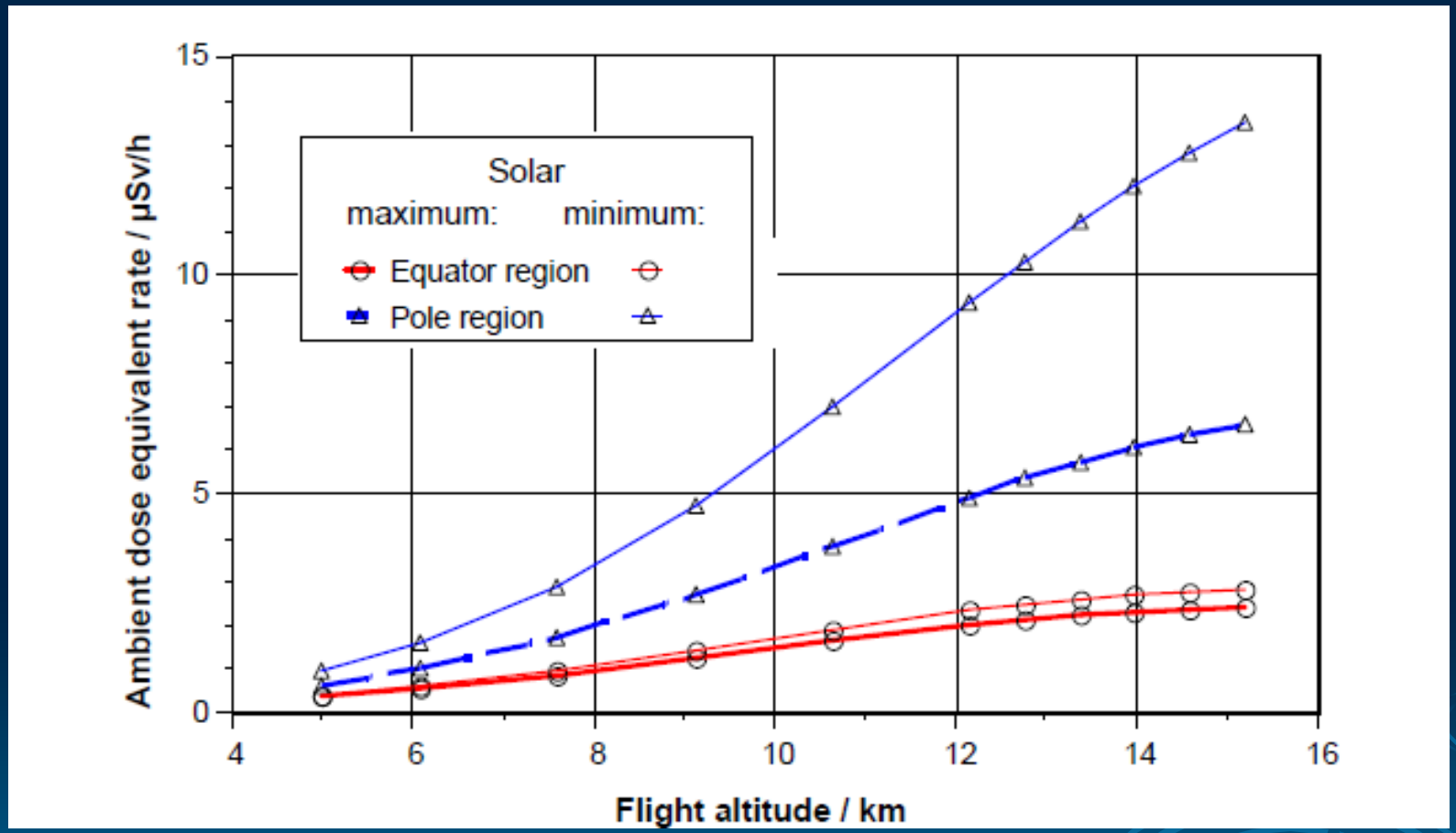
Source: USGS

Ground level cosmic ray dose in the U.S. (called 'space' radiation by some)



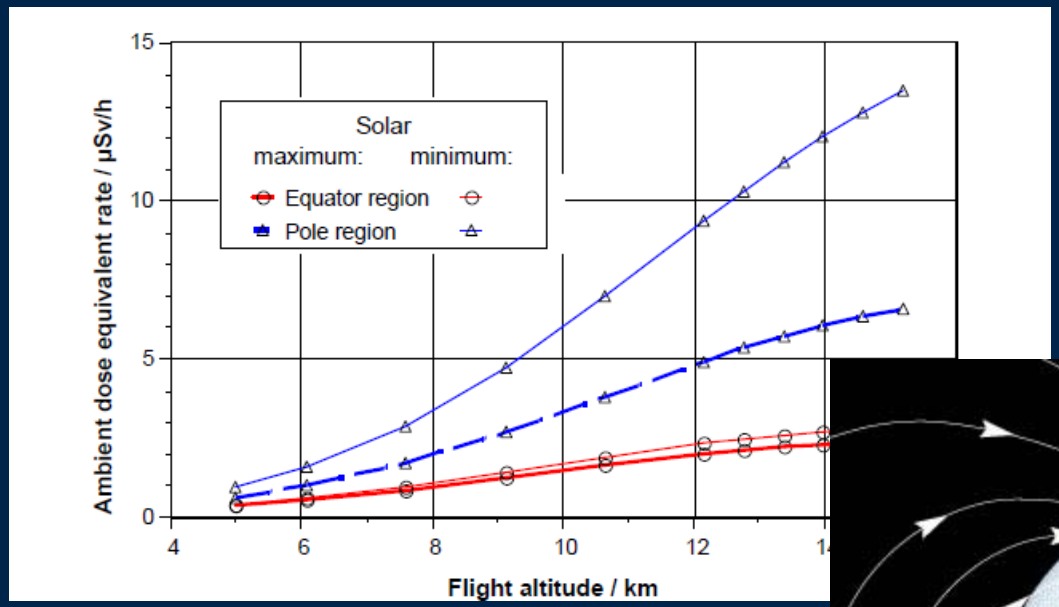
Dose (mGy) to red bone marrow of representative persons per year of exposure to cosmic ray radiation (map courtesy of Geological Survey of Canada) – primarily a function of altitude.

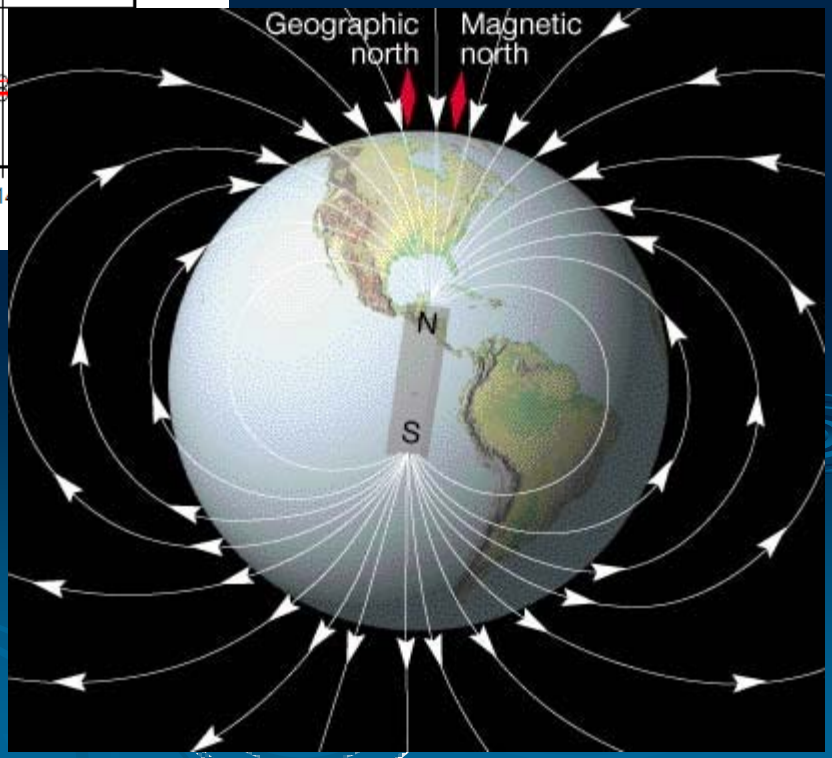
Cosmic ray dose is higher in polar regions for any given altitude. Can you guess why?



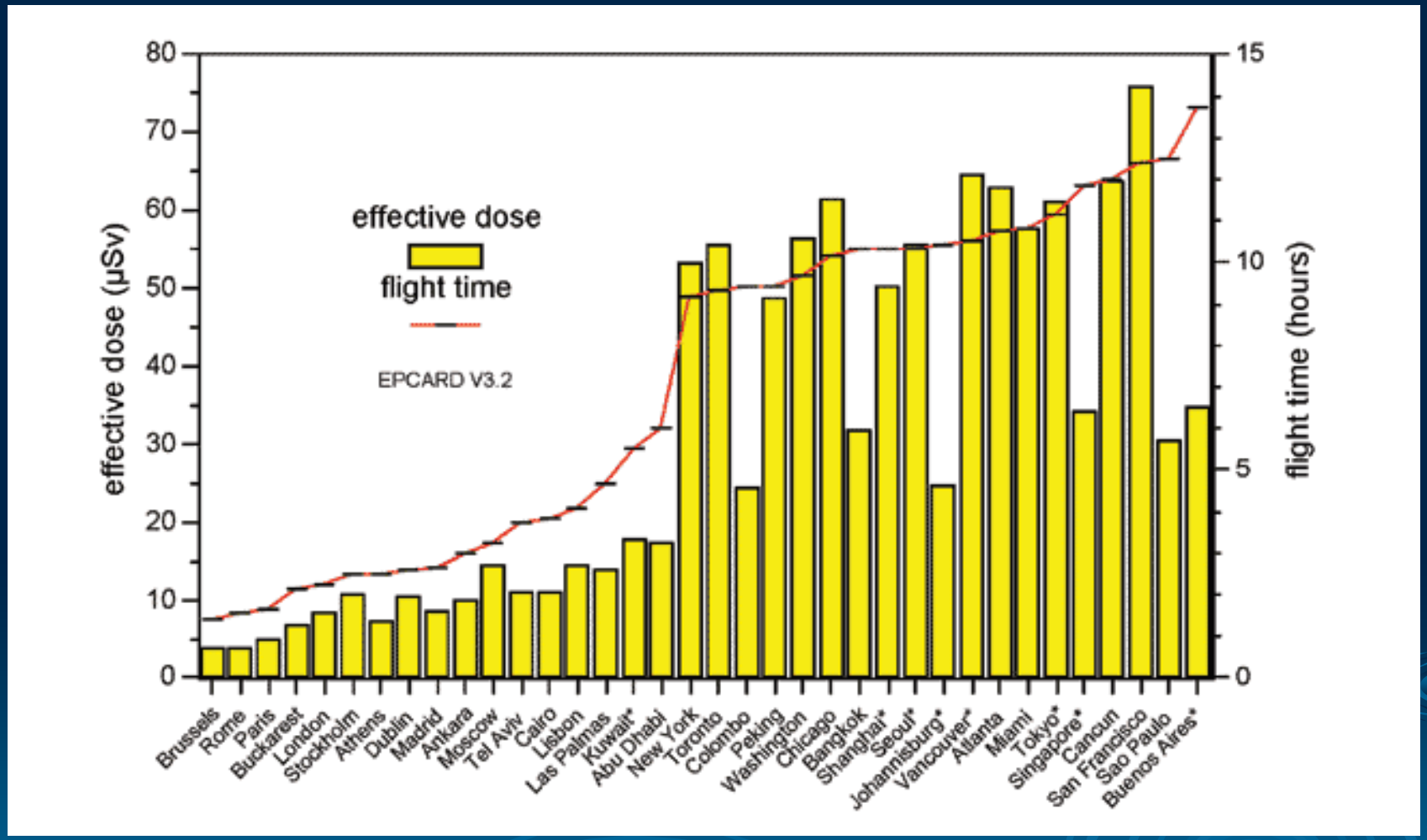
Data: Eurados 2004

Cosmic ray dose is higher in polar regions for any given altitude.





Cosmic ray dose increases with elevation or altitude and with time spent at high altitudes, e.g., when flying internationally.



Data: GSF

Radiation Exposure in Medicine: Doses from procedures vary widely. The inevitable radiation exposure with medical procedures is usually considered as part of the cost to receive that benefit.

Most procedures give doses on the order of a few mSv.

Complete Exams	Effective Dose mSv (mrem)[1]
Intravenous Pyelogram (kidneys, 6 films)	2.5 (250)
Barium Swallow (24 images, 106 sec. fluoroscopy)	1.5 (150)
Barium Enema (10 images, 137 sec. fluoroscopy)	7.0 (700)
CT Head	2.0 (200)
CT Chest	8.0 (800)
CT Abdomen	10.0 (1,000)
CT Pelvis	10.0 (1,000)
Angioplasty (heart study)	7.5 (750) - 57.0 (5,700)[3]
Coronary Angiogram	4.6 (460) - 15.8 (1,580)[3]

THE END IS NEAR

PART V.
Dosimetry to Epidemiology

- Completing the Circle -

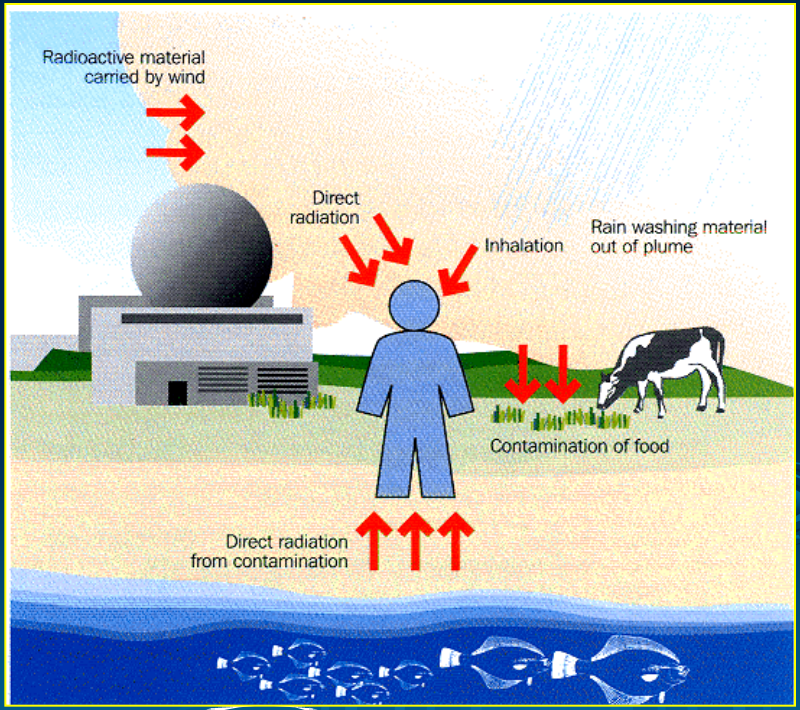
Up to this point, we've discussed dosimetry on a theoretical level, emphasizing the processes leading to the release and absorption of energy.

However, dosimetry, for the purposes of epidemiologic studies, depends primarily on applying these principles.

<u>Applied Dosimetry</u> can be loosely subdivided into:

- "**Internal Dosimetry**" where the energy delivered to tissue from sources within the body, e.g., radionuclides, and
- **"External Dosimetry"** where the energy delivered to tissue originates from sources of radiation outside the body.

Though there are specific techniques in internal and external dosimetry, <u>the principles of physics remain the same.</u>



Almost all of the differences in medical, occupational, and environmental dosimetry can be attributed to:

- Differences in the sources of the radiation, and
- Whether the amount received by individuals was controlled, as in medical exposures,
- Whether exposure was received with moderate control but with some monitoring (typical of occupational exposures), or
- Exposure was received with no control and no monitoring on the individual level (typical of environmental exposures).

The major technical challenge of dosimetry for epidemiologic purposes is not in applying the physics of radiation interactions (something already well understood), but in determining <u>how much</u> of the radioactive material and/or radiation a person was exposed to.

Dosimetry for purposes of epidemiologic studies requires not only the concepts of physics but also concepts of exposure analysis which in itself may include environmental pathways, chemistry, anatomy, physiology, behavior and lifestyle.

Dosimetry Physics + Exposure Assessment = Dose Assessment

To Reiterate: Because most dosimetry calculations conducted for epidemiologic studies are retrospective (i.e., doses are estimated that were received in the past), most of the difficulties are associated with determining the specifics of past exposure conditions and not the application of the physical principles.

Examples of Problems in Reconstructing Radiation Doses and Relative Difficulty

Relatively easy (exposure conditions are known):

- Medical x-ray procedures (therapeutic and diagnostic)
- Medical external beam radiation therapy

More difficult (exposure conditions are less well known, but relatively good information is still available):

- Internal medical radioisotope procedures for past decades.
- Occupational dose for medical radiation workers

Still more difficult (exposure conditions poorly known):

- Occupational doses for industrial situations, particularly for poorly monitored working conditions
- Nuclear fallout related external doses

Examples of Problems in Reconstructing Radiation Doses and Relative Difficulty (con't.):

Very difficult:

- Occupational doses for industrial situations, without radiation monitoring data
- A-bomb survivor dosimetry (easy and hard - both)
- Nuclear fallout related internal doses
- Any situation without an adequate description of the source of radiation (energy and geometry) and the exposure conditions (e.g., location of individual with respect to the source, the amount of radioactivity accidentally taken into the body, etc.)

Closing Remarks for Epidemiologists

There are a variety of ‘types’ of doses used in the literature and in radiation protection, including:

shallow dose,
deep dose,
deep equivalent dose,
absorbed dose,
dose equivalent,
equivalent dose,
effective dose,
effective dose equivalent,
committed dose,
committed effective dose,
committed effective dose equivalent, etc.

Having worked in radiation epidemiology, my advice is…

- Be wary of the many convoluted dose-related terms and dose estimates available in historical literature, particularly if no contact with the original investigators has been made.

- Understand that:
  - Some dose estimates serve purposes that are probably not of interest to you, such as for establishing compliance in radiation protection activities, etc.

  - Some dose estimates may have been calculated by methods, models, or with definitions that are no longer in use or accepted.

  - Doses may be averages over multiple organs or weighted by factors unknown to you or are irrelevant to you.

- Dose estimates other than **organ absorbed dose** will likely not be what is needed for your research purposes.

  Stick with Gy (or rad) in epidemiology, and possibly equivalent dose, though the applications for it will be few.

My advice (con't.) is…

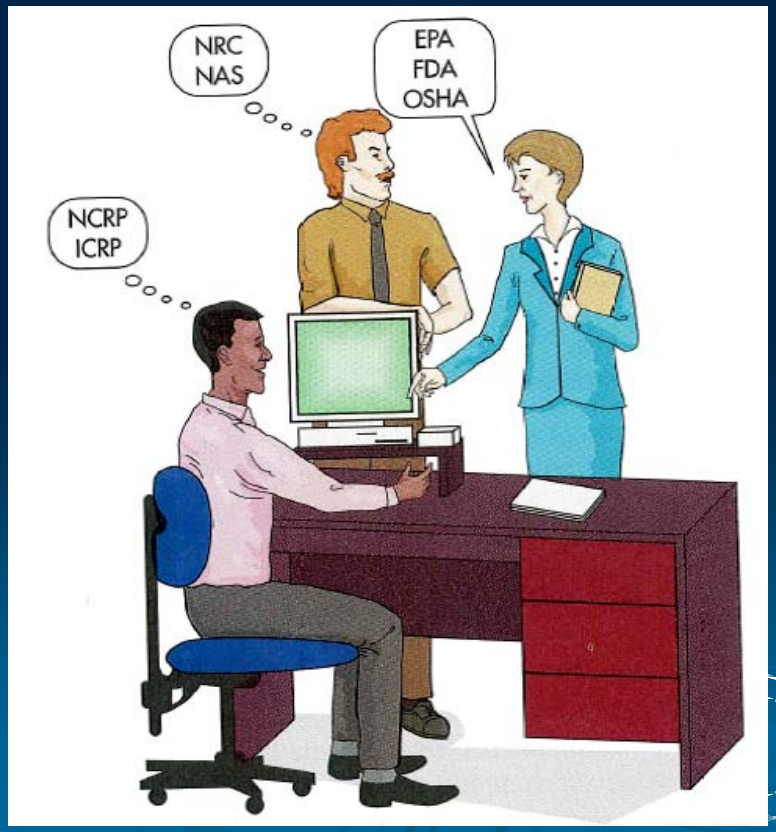
- When collaborating with other scientists who might not appreciate the requirements of epidemiology, seek clarification on exactly what *kind* of dose is being provided.

- Finally, ask for legitimate statements of uncertainty (or conversely, the precision) of dose estimates and never assume that doses are known with absolute (or even high) certainty.

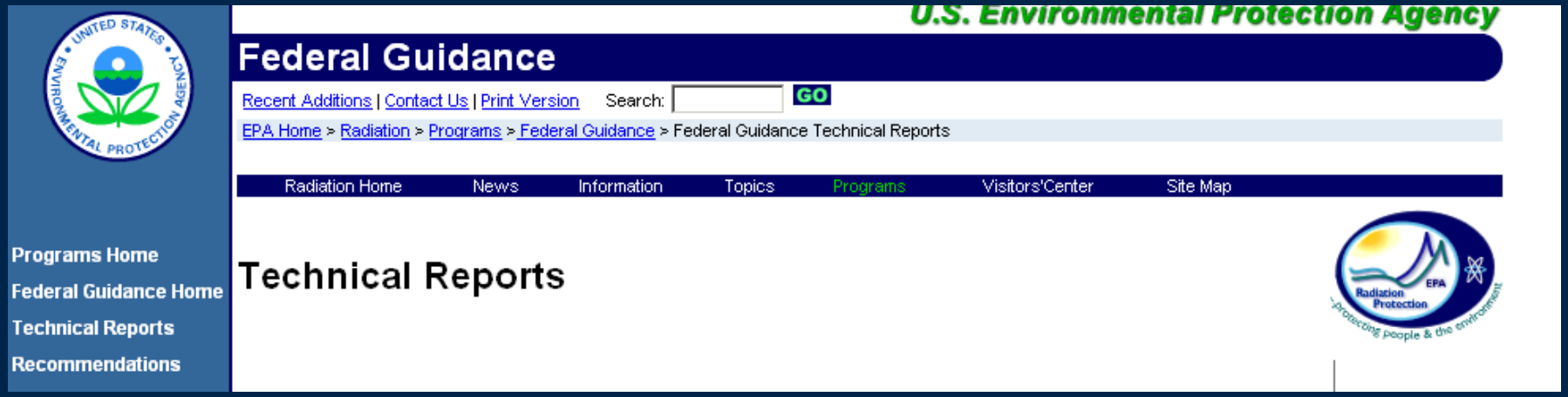
I mean it this time...

Part VI.

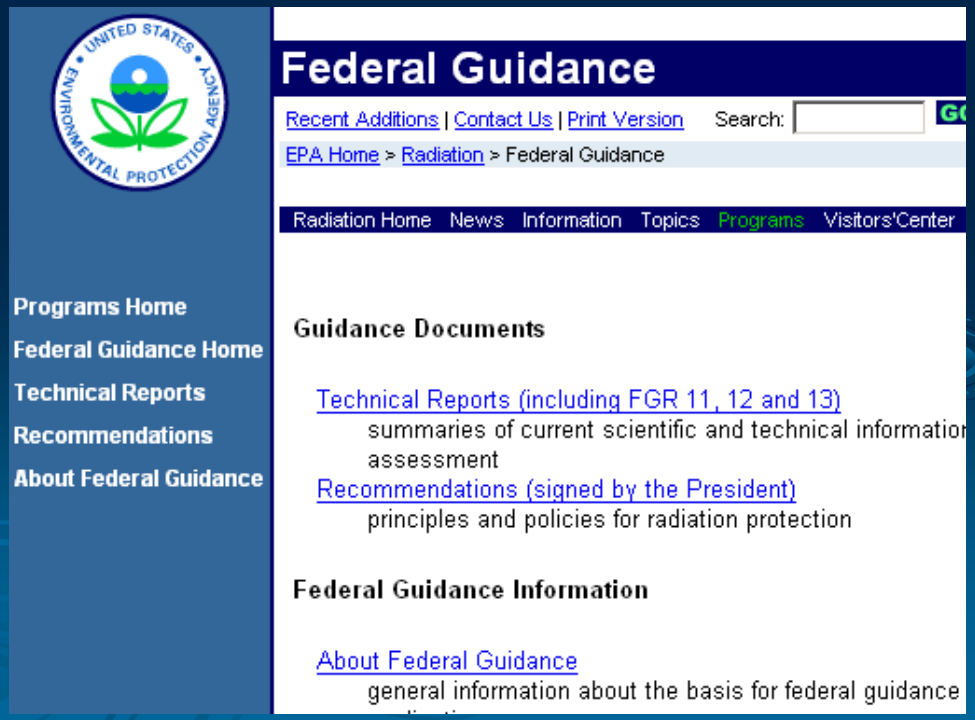
Where can you go for reliable information on dosimetry, dose estimation, dose limitation guidelines, etc. ?



Sources of information (1): EPA (e.g., Federal Guidance, Dose Coefficients, Limiting Values of Exposure)



http://www.epa.gov/radiation/federal/



Sources of information (2): NCI website for links to useful organizations, http://dceg.cancer.gov/reb/tools/useful-links

Radiation Epidemiology Branch

Understanding the link between radiation exposure and cancer

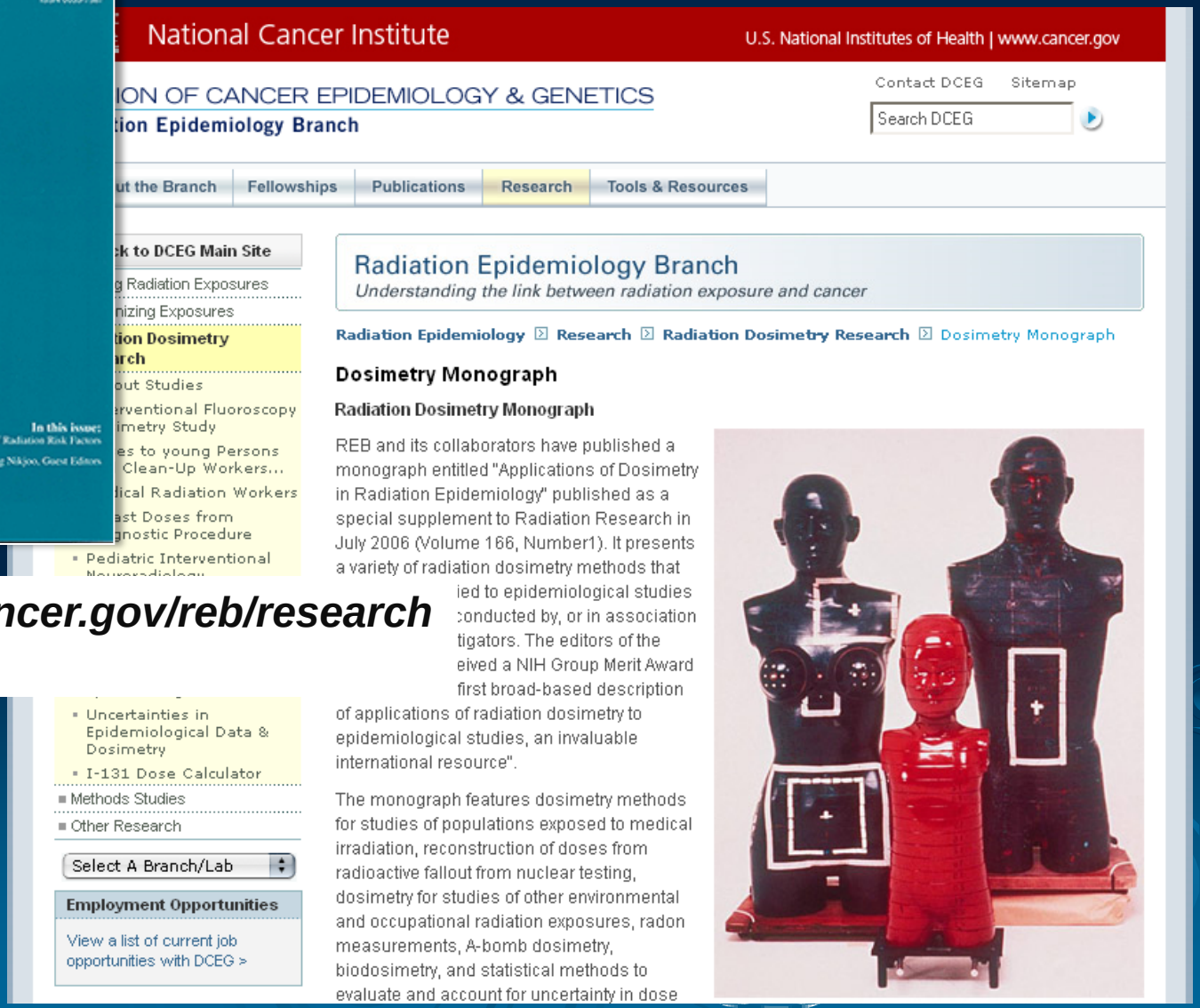
Radiation Epidemiology ▷ Tools & Resources ▷ Useful Links

Tools & Resources

Useful Links

- ICRP: International Commission on Radiological Protection
- NIAID: Medical Countermeasures Against Radiological and Nuclear Threats
- HPA: Health Protection Agency (UK)
- IAEA: International Atomic Energy Agency
- ICRU: International Commission on Radiation Units and Measurements
- International Agency for Research on Cancer
- International Commission on Non-Ionizing Radiation Protection
- NRSB: Nuclear and Radiation Studies Board
- NCRP: National Council on Radiation Protection and Measurements
- RERF Publications: Radiation Effects Research Foundation
- UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation
- WHO, Ionizing Radiation Section: World Health Organization
- Radiation Research Society
- Health Physics Society
- The Radiation Information Network
- Late Health Effects of Ionizing Radiation Conference May 4-6 2009

Sources of information (3): Applications of Dosimetry to Epidemiology – Radiation Research (July, 2006)



http://dceg.cancer.gov/reb/research/dosimetry/7

That's all Folks!