NPRE 441:
Principles of Radiation Protection

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University of Illinois at Urbana-Champaign

Textbook Information

Textbook

Required textbook

[1] J. Turner, "Atoms, Radiation, and Radiation Protection”, Third Edition, Wiley-VCH, 2007.

References:

[1] H. Cember - "Introduction to Health Physics", 4th Edition, McGraw-Hill (2020).

[2] J. K. Shultis and R. E. Faw, "Radiation Shielding," American Nuclear Society (2000).

[3] R. E. Faw and J. K. Shultis, "Radiological Assessment: Sources and Doses, American Nuclear Society (1999).

[4] E. L. Alpen, "Radiation Biophysics," Academic Press (1998).

[5] Radiation Detection and Measurements, Third Edition, G. F. Knoll, John Wiley & Sons, 1999.

General Information

Instructor: Dr. Ling-Jian Meng

Course website: <http://courses.engr.illinois.edu/npre441/>

6-8 Homeworks: 25%,

Mid-term exam: 15%,

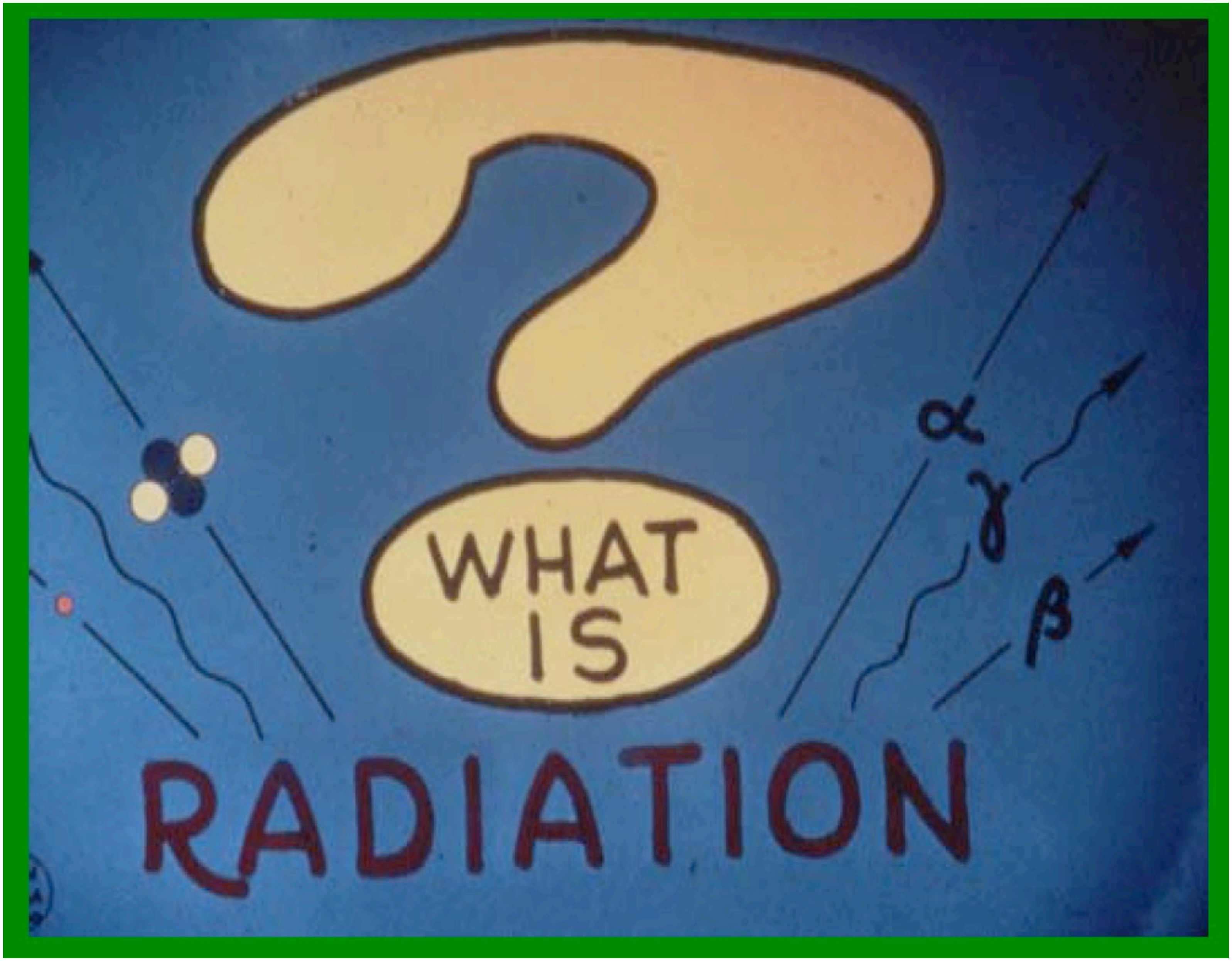
6 in-class quizzes: 30%,

Final exam: 20%,

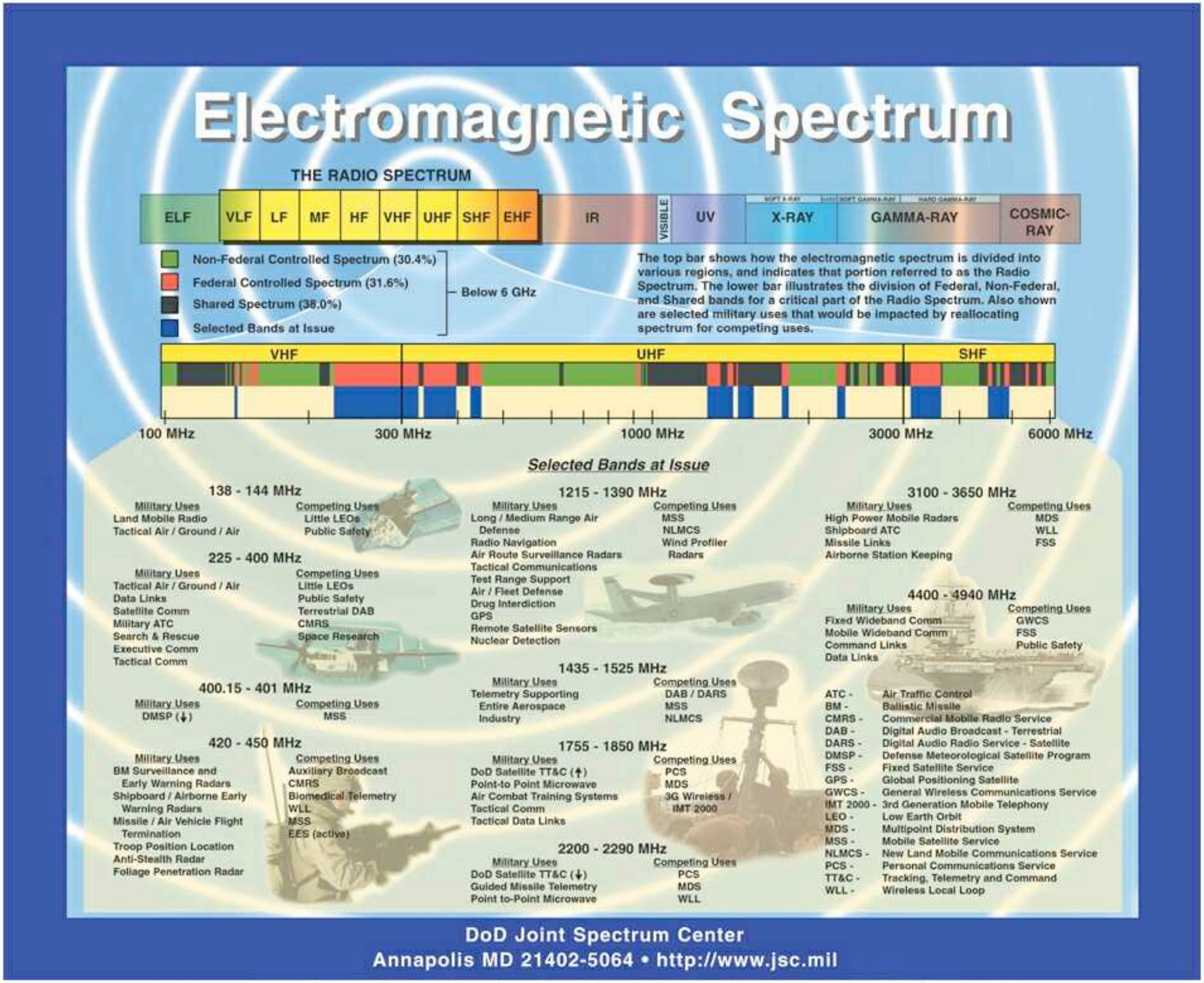
Term-project: 10%.

TA:

An Initial Overview



?
WHAT IS
α
γ
β
RADIATION


Electromagnetic Spectrum
THE RADIO SPECTRUM
ELF
VLF
LF
MF
HF
VHF
UHF
SHF
EHF
IR
VISIBLE
UV
X-RAY
GAMMA-RAY
COSMIC-RAY
Non-Federal Controlled Spectrum (30.4%)
Federal Controlled Spectrum (31.6%)
Shared Spectrum (38.0%)
Selected Bands at Issue
Below 6 GHz
The top bar shows how the electromagnetic spectrum is divided into various regions, and indicates that portion referred to as the Radio Spectrum. The lower bar illustrates the division of Federal, Non-Federal, and Shared bands for a critical part of the Radio Spectrum. Also shown are selected military uses that would be impacted by reallocating spectrum for competing uses.
VHF
UHF
SHF
100 MHz
300 MHz
1000 MHz
3000 MHz
6000 MHz
Selected Bands at Issue
138 - 144 MHz
Military Uses
Land Mobile Radio
Tactical Air / Ground / Air
Competing Uses
Little LEOs
Public Safety
225 - 400 MHz
Military Uses
Tactical Air / Ground / Air
Data Links
Satellite Comm
Military ATC
Search & Rescue
Executive Comm
Tactical Comm
Competing Uses
Little LEOs
Public Safety
Terrestrial DAB
CMRS
Space Research
400.15 - 401 MHz
Military Uses
DMSP (↓)
Competing Uses
MSS
420 - 450 MHz
Military Uses
BM Surveillance and Early Warning Radars
Shipboard / Airborne Early Warning Radars
Missile / Air Vehicle Flight Termination
Troop Position Location
Anti-Stealth Radar
Foliage Penetration Radar
Competing Uses
Auxiliary Broadcast
CMRS
Biomedical Telemetry
WLL
MSS
EES (active)
1215 - 1390 MHz
Military Uses
Long / Medium Range Air Defense
Radio Navigation
Air Route Surveillance Radars
Tactical Communications
Test Range Support
Air / Fleet Defense
Drug Interdiction
GPS
Remote Satellite Sensors
Nuclear Detection
Competing Uses
MSS
NLMCS
Wind Profiler Radars
1435 - 1525 MHz
Military Uses
Telemetry Supporting Entire Aerospace Industry
Competing Uses
DAB / DARS
MSS
NLMCS
1755 - 1850 MHz
Military Uses
DoD Satellite TT&C (↑)
Point-to Point Microwave
Air Combat Training Systems
Tactical Comm
Tactical Data Links
Competing Uses
PCS
MDS
3G Wireless / IMT 2000
2200 - 2290 MHz
Military Uses
DoD Satellite TT&C (↓)
Guided Missile Telemetry
Point to-Point Microwave
Competing Uses
PCS
MDS
WLL
3100 - 3650 MHz
Military Uses
High Power Mobile Radars
Shipboard ATC
Missile Links
Airborne Station Keeping
Competing Uses
MDS
WLL
FSS
4400 - 4940 MHz
Military Uses
Fixed Wideband Comm
Mobile Wideband Comm
Command Links
Data Links
Competing Uses
GWCS
FSS
Public Safety
ATC - Air Traffic Control
BM - Ballistic Missile
CMRS - Commercial Mobile Radio Service
DAB - Digital Audio Broadcast - Terrestrial
DARS - Digital Audio Radio Service - Satellite
DMSP - Defense Meteorological Satellite Program
FSS - Fixed Satellite Service
GPS - Global Positioning Satellite
GWCS - General Wireless Communications Service
IMT 2000 - 3rd Generation Mobile Telephony
LEO - Low Earth Orbit
MDS - Multipoint Distribution System
MSS - Mobile Satellite Service
NLMCS - New Land Mobile Communications Service
PCS - Personal Communications Service
TT&C - Tracking, Telemetry and Command
WLL - Wireless Local Loop
DoD Joint Spectrum Center
Annapolis MD 21402-5064 • http://www.jsc.mil

Electromagnetic Radiation

1. *γ-rays:* Electromagnetic radiation emitted from a nucleus or in annihilation reactions between matter and antimatter. The quantum energy of any electromagnetic photon is given in keV by

$$E_\gamma = h\nu = \frac{hc}{\lambda} = \frac{12.398 \text{ keV-Å}}{\lambda}$$

$$= \frac{1.2398 \text{ keV-nm}}{\lambda} \qquad (1.1)$$

where 1 Å (Angstrom) = 10^{-10} m, Planck's constant is

$$h = 6.626 \times 10^{-34} \text{ J s}$$
$$= 4.136 \times 10^{-18} \text{ keV s}$$

(note that 1.6022×10^{-16} J = 1 keV), and the velocity of light *in vacuo* is

$$c = 2.998 \times 10^{8} \text{ m/s}$$
$$= 2.998 \times 10^{18} \text{ Å/s}$$
$$= 2.998 \times 10^{17} \text{ nm/s}$$

Evidently, by Eq. (1.1) the quantum energy of a photon of 0.1-nm wavelength is 12.4 keV, within one part in 6000.

Gamma Ray Emission through Beta Decay

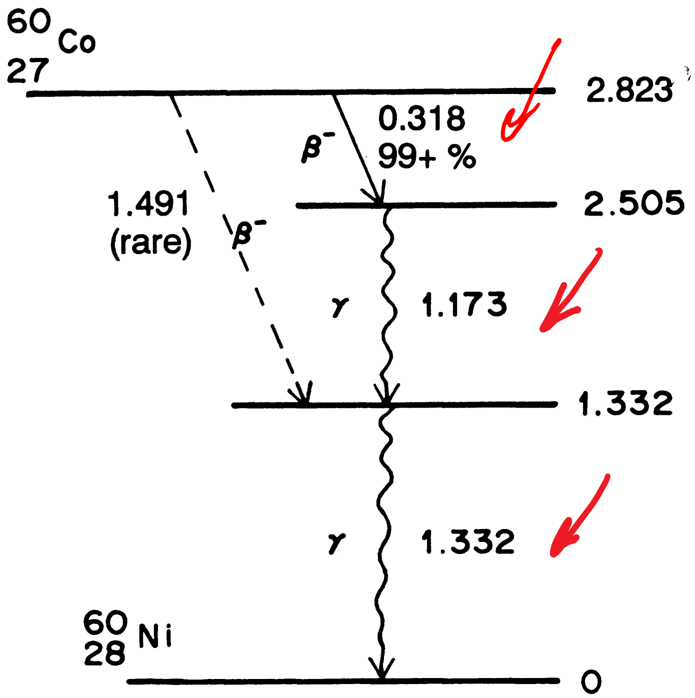


FIGURE 3.6. Decay scheme of $^{60}_{27}$Co.

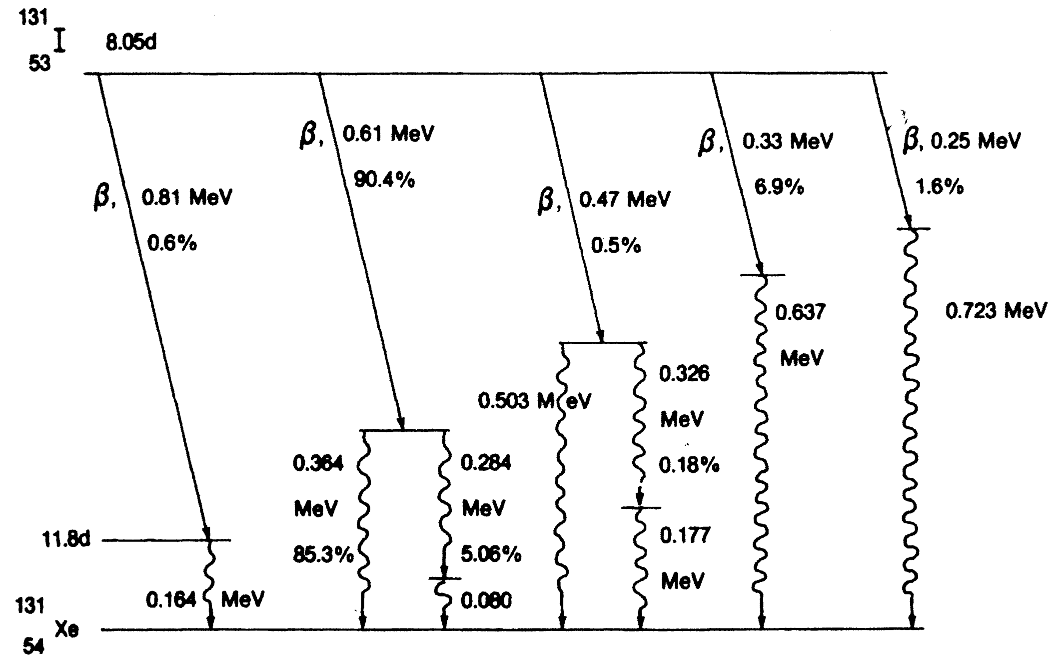


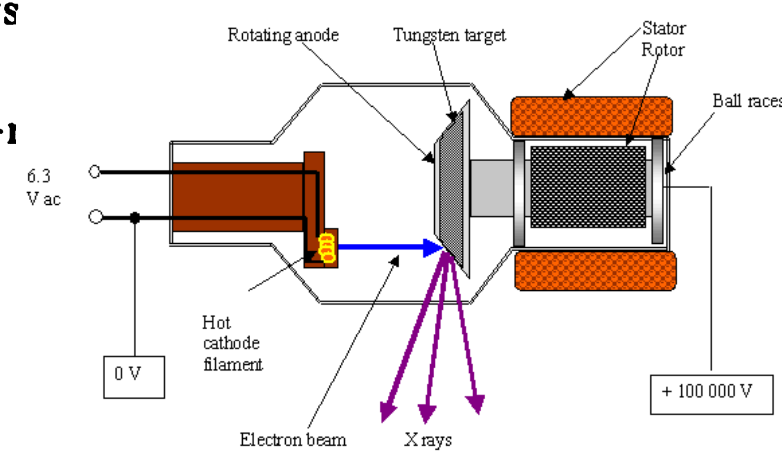
FIGURE 4.7. Iodine-131 transformation (decay) scheme.

- Beta emissions are normally associated with complicated decay schemes and the emission of other particles such as gamma rays.
- There exist the so called "pure beta emitters", such as ^{3}H, ^{14}C, ^{32}P and ^{90}Sr, which have no accompanying gamma rays.

Electromagnetic Radiation – X-rays

2. *X-rays:* Electromagnetic radiation emitted by charged particles (usually electrons) in changing atomic energy levels (called *characteristic* or *fluorescence* x-rays) or in slowing down in a Coulomb force field (*continuous* or *bremsstrahlung* x-rays). Note that an x-ray and a γ-ray photon of a given quantum energy have identical properties, differing only in mode of origin. Older texts sometimes referred to all lower-energy photons as x-rays and higher energy photons as γ-rays, but this basis for the distinction is now obsolete. Most commonly, the energy ranges of x-rays are now referred to as follows, in terms of the generating voltage:

0.1–20 kV	Low-energy or "soft" x-rays, or "Grenz rays"
20–120 kV	Diagnostic-range x-rays
120–300 kV	Orthovoltage x-rays
300 kV–1 MV	Intermediate-energy x-
1 MV upward	Megavoltage x-rays



http://www.antonine-education.com/Pages/Physics_5_Options/Medical_Physics/MED_07/med_phys_7.htm

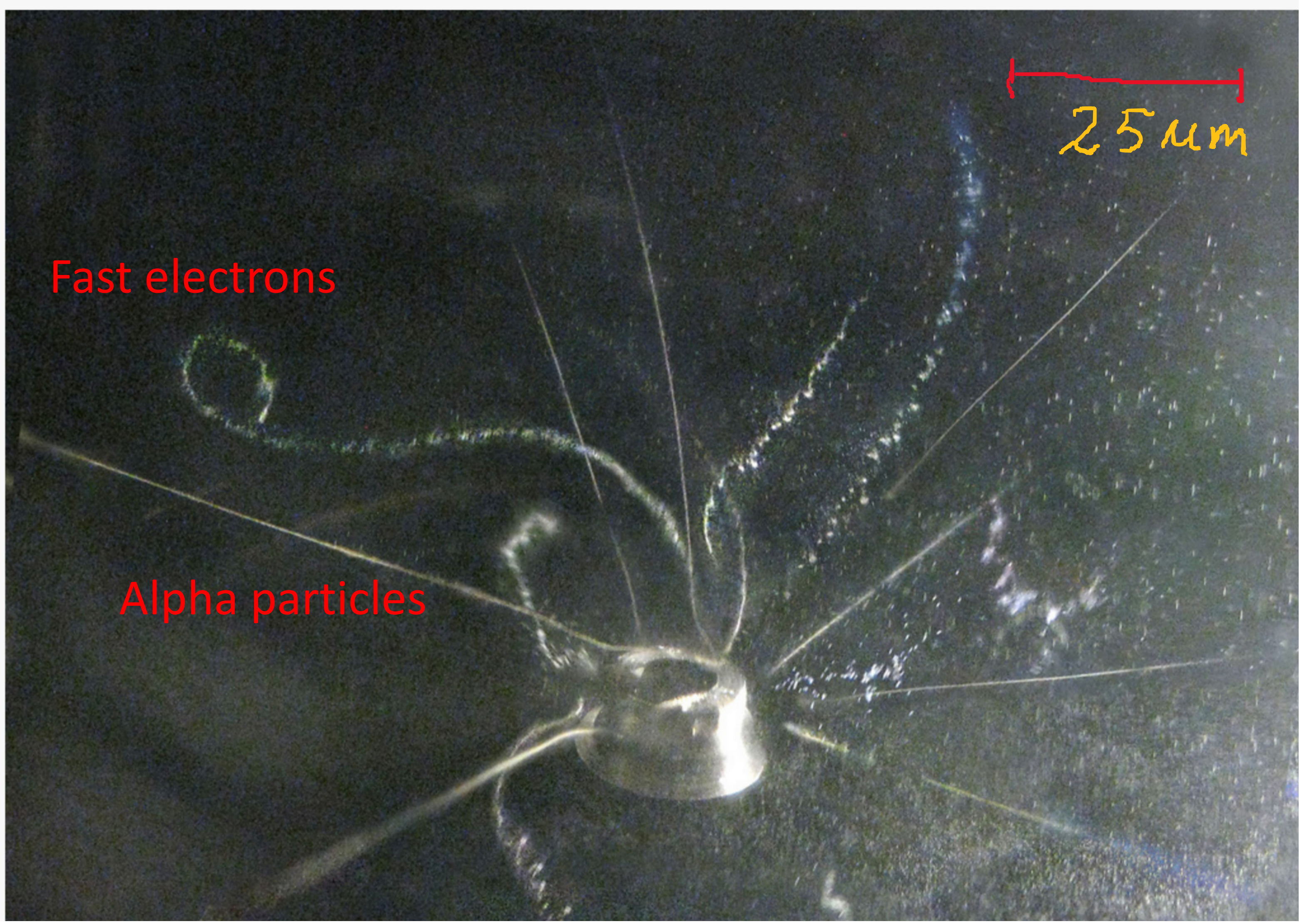
Charged Particles

3. *Fast Electrons:* If positive in charge, they are called positrons. If they are emitted from a nucleus they are usually referred to as β-rays (positive or negative). If they result from a charged-particle collision they are referred to as "δ-rays". Intense continuous beams of electrons up to 12 MeV are available from Van de Graaff generators, and pulsed electron beams of much higher energies are available from linear accelerators ("linacs"), betatrons, and microtrons. Descriptions of such accelerators, as encountered in medical applications, have been given by Johns and Cunningham (1974) and Hendee (1970).

4. *Heavy Charged Particles:* Usually obtained from acceleration by a Coulomb force field in a Van de Graaff, cyclotron, or heavy-particle linear accelerator. Alpha particles are also emitted by some radioactive nuclei. Types include:

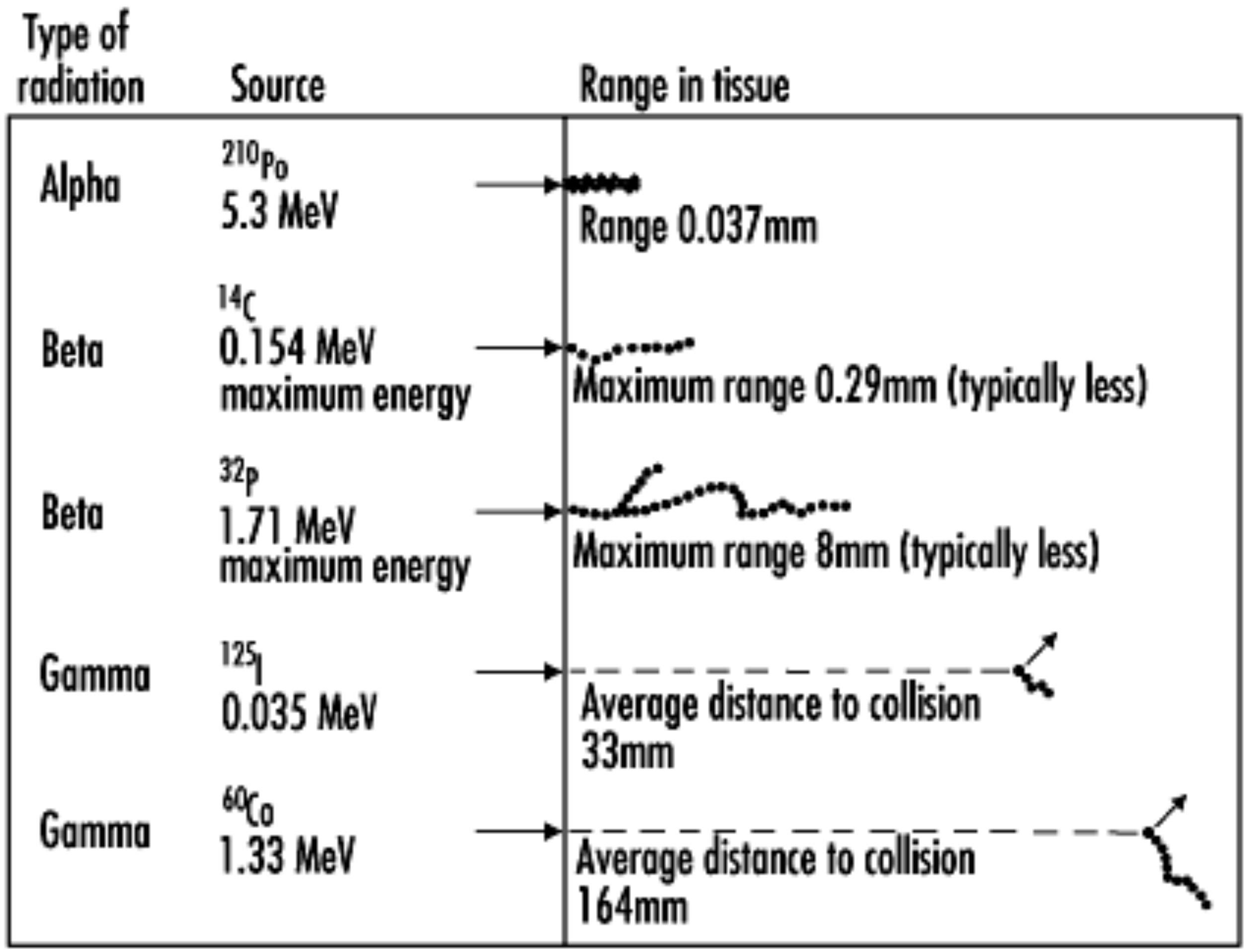
- Proton—the hydrogen nucleus.
- Deuteron—the deuterium nucleus, consisting of a proton and neutron bound together by nuclear force.
- Triton—a proton and two neutrons similarly bound.
- Alpha particle—the helium nucleus, i.e., two protons and two neutrons. ^3He particles have one less neutron.
- Other heavy charged particles consisting of the nuclei of heavier atoms, either fully stripped of electrons or in any case having a different number of electrons than necessary to produce a neutral atom.
- Pions—negative π-mesons produced by interaction of fast electrons or protons with target nuclei.

Trajectories of Beta and Alpha Particles in Air



https://www.thenakedscientists.com/forum/index.php?topic=47630.0

Trajectories of Beta and Alpha Particles in Air



Source: Shapiro 1972.

https://www.thenakedscientists.com/forum/index.php?topic=47630.0

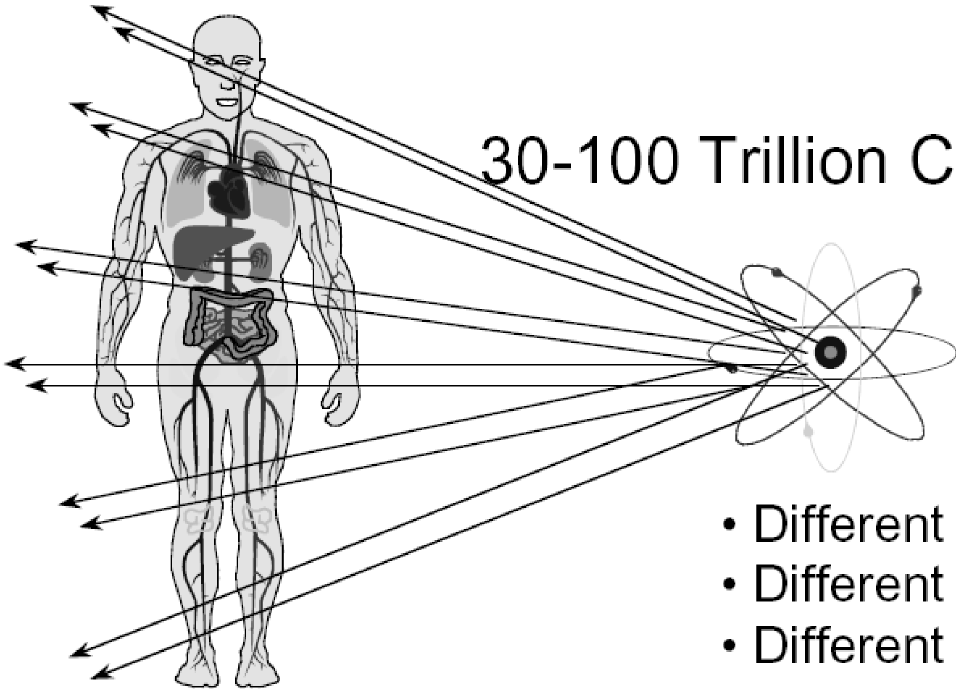
Directly and Indirectly Ionizing Radiation

The ICRU (International Commision on Radiation Units and Measurements, 1971) has recommended certain terminology in referring to ionizing radiations which emphasizes the gross differences between the interactions of charged and uncharged radiations with matter:

1. *Directly Ionizing Radiation.* Fast charged particles, which deliver their energy to matter directly, through many small Coulomb-force interactions along the particle's track.
2. *Indirectly Ionizing Radiation.* X- or γ-ray photons or neutrons (i.e., uncharged particles), which first transfer their energy to charged particles in the matter through which they pass in a relatively few large interactions. The resulting fast charged particles then in turn deliver the energy to the matter as above.

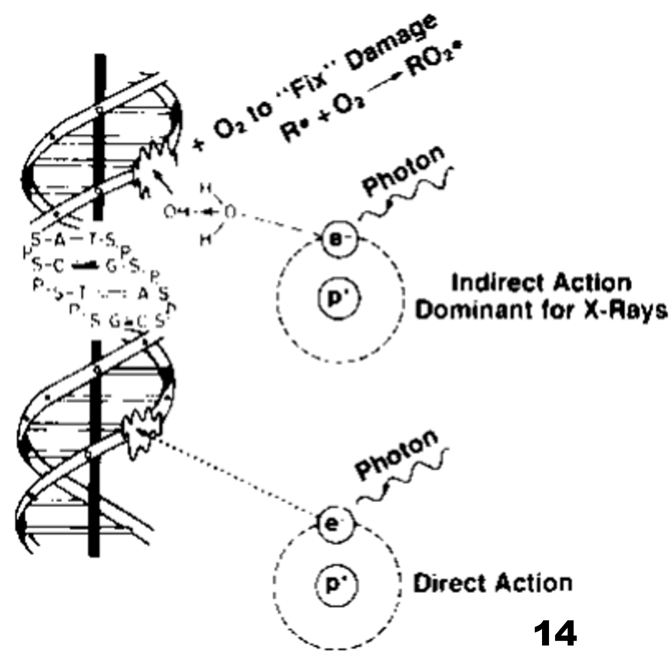
It will be seen that the deposition of energy in matter by indirectly ionizing radiation is thus a *two-step process*. In developing the concepts of radiological physics the importance of this fact will become evident.

Targets for Radiation Damage



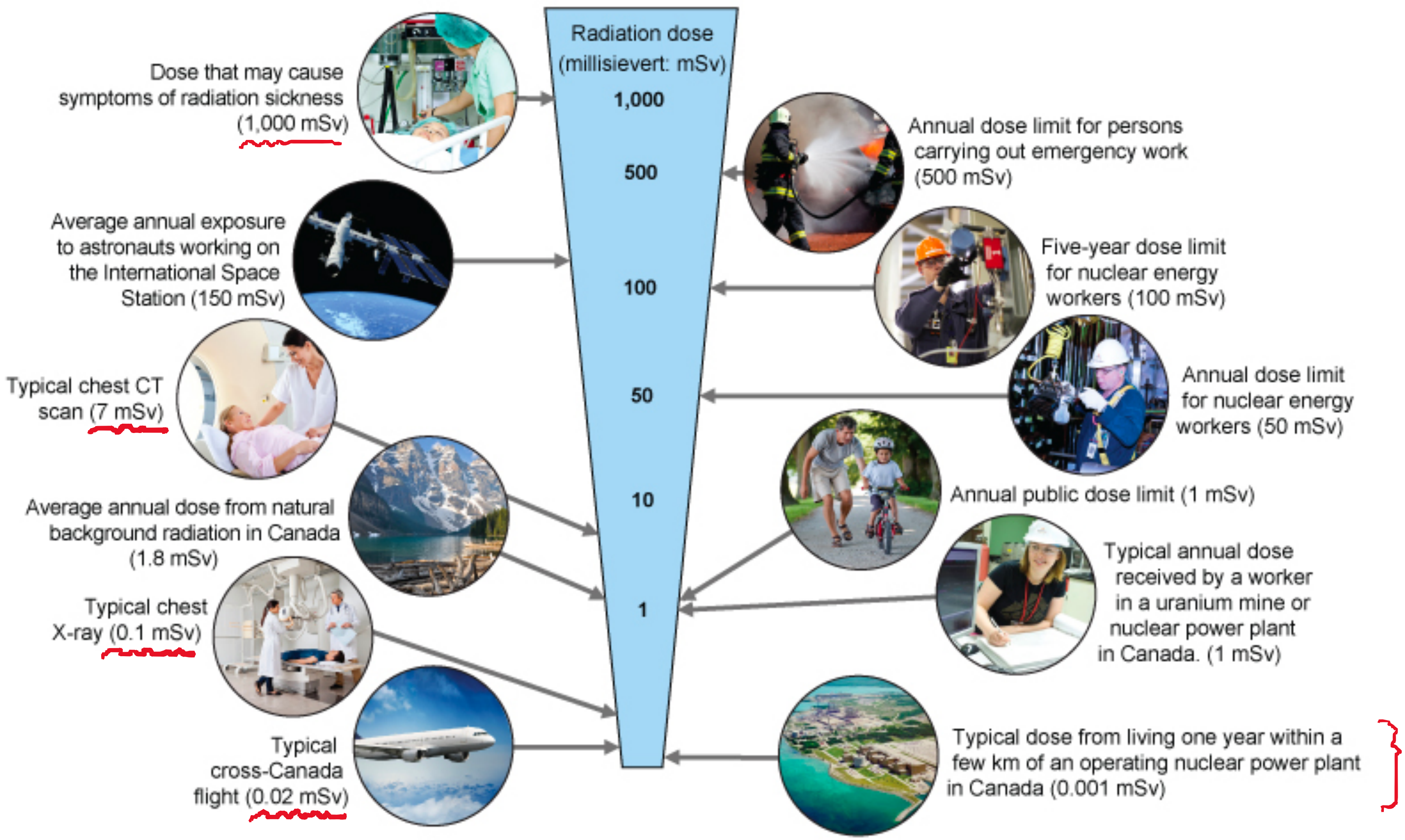
30-100 Trillion Cells at Risk

- Different Cell Types
- Different Cell Cycle
- Different Cell Targets



An Overview of Radiation Dose to General Public

Radiation dose examples



Canadian Nuclear Safety Commission, http://nuclearsafety.gc.ca/eng/resources/radiation/introduction-to-radiation/radiation-doses.cfm

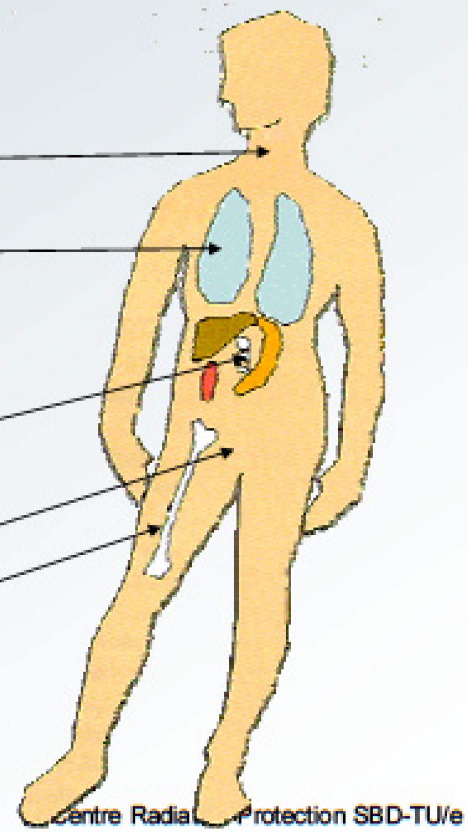
Effective Dose Equivalent (EDE)

$$\text{Effective dose} = \sum_{organ} w_{organ}\left(w_R \times D_{organ}\right) \quad (S_v)$$

$D_{organ} \leftarrow \frac{E}{m}$ (J/kg)

For calculation of effective dose:

0.05	thyroid
0.05	breast tissue
0.12	lungs
0.05	esophagus
0.12	stomach
0.05	liver
0.12	colon
0.05	urinary bladder
0.20	reproductive organs
0.01	skin
0.12	red bone marrow
0.01	bone surface
0.05	rest of body
1.00	total



Centre Radiation Protection SBD-TU/e

An Overview of General Radiation Exposure

Table 1.1 MAJOR SOURCES OF IONIZING RADIATION

Source Category	Subcategory and Description	Effective Dose (mSv) to US Population	Effective Dose (mrem) to US Population
Natural Background	Radon and thoron (inhalation)	2.28	228
	Cosmic radiation	0.33	33
	Radioactive materials in the body (ingestion)	0.29	29
	Terrestrial radiation (external to the body)	0.21	21
Healing Arts	*Medical diagnosis and therapy*		
	Medical diagnosis (computed tomography and conventional radiography and fluoroscopy)	1.80	180
	Interventional fluoroscopy	0.43	43
	Radiotherapy (excluded from dose)		
	Radiopharmaceuticals		
	Nuclear medicine (diagnosis, therapy, research)	0.77	77
Consumer	Combustion of fossil fuels, road construction materials, consumer products	0.13	13
Industrial Activities	Industrial radiography, gauges, static eliminators, sterilizers, security, medical research and exposure to patients, education and research (particle accelerators, x-ray diffraction units, electron microscopes, neutron generators, tracers), nuclear power generation, government facilities, waste handling	0.003	0.3
Occupational	Health care workers (physicians, nurses, staff)	0.0018	0.18
	Aviation (pilots, flight attendants)	0.0018	0.18
	Commercial nuclear power (plant workers)	0.0004	0.04
	Industry and commerce	0.0004	0.04
	Education and research	0.0002	0.02
	Government, Department of Energy (DOE), military personnel	0.0001	0.01
Total	—	6.248	625

Examples of Annual Dose Limits

Occupational Dose Limits for Adults

- An annual limit of 5 rem (0.05 Sv) total effective dose equivalent (TEDE).
- An annual limit of 50 rem (0.50 Sv) to an individual organ or tissue other than the lens of the eye, as determined by the deep-dose equivalent and the committed dose equivalent.
- An annual limit of 15 rem (0.15 Sv) to the lens of the eye.
- An annual limit of 50 rem (0.50) Sv) to the skin.
- An annual limit of 50 rem (0.50 Sv) to each of the extremities.

Dose Limits for Individual Members of the Public

- An annual limit of 0.1 rem (1 mSv) total effective dose equivalent (TEDE)
- An hourly limit from external sources of 0.002 rem (0.02 mSv) in unrestricted areas.

http://oregonstate.edu/ehs/book/export/html/88

An Overview of Radiation Exposure to US Population

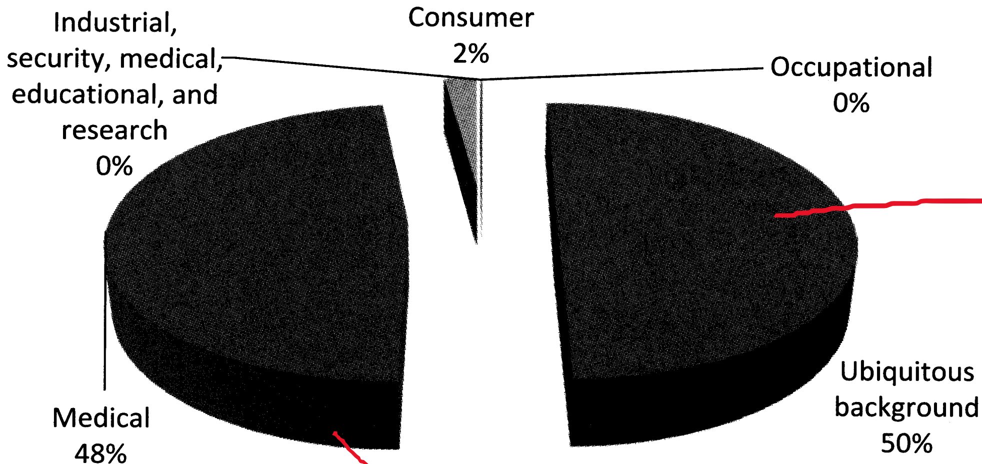


FIGURE 1.1 ◈ Exposure by Major Categories

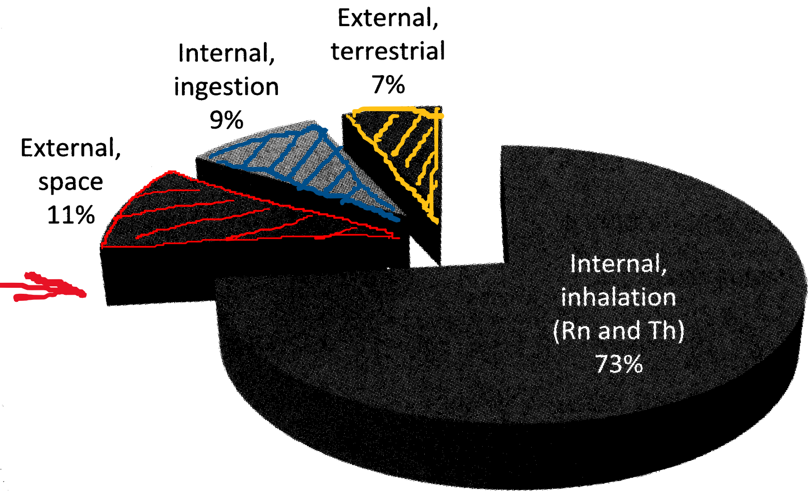


FIGURE 1.2 ◈ Ubiquitous Background

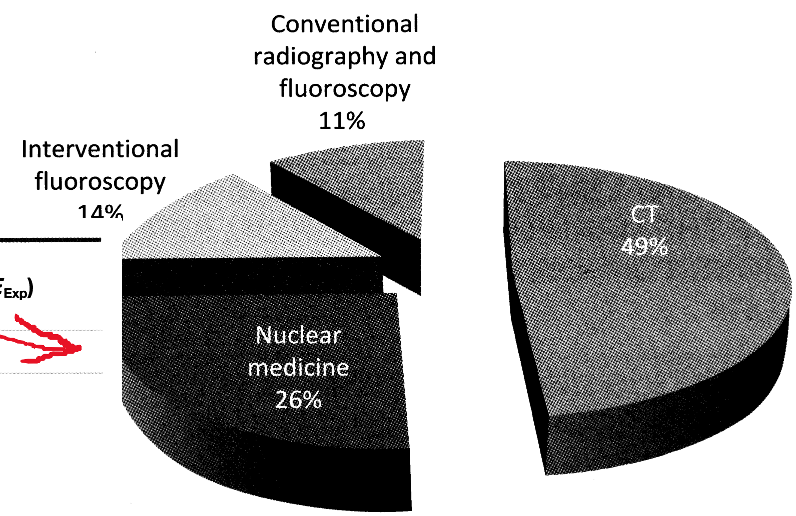


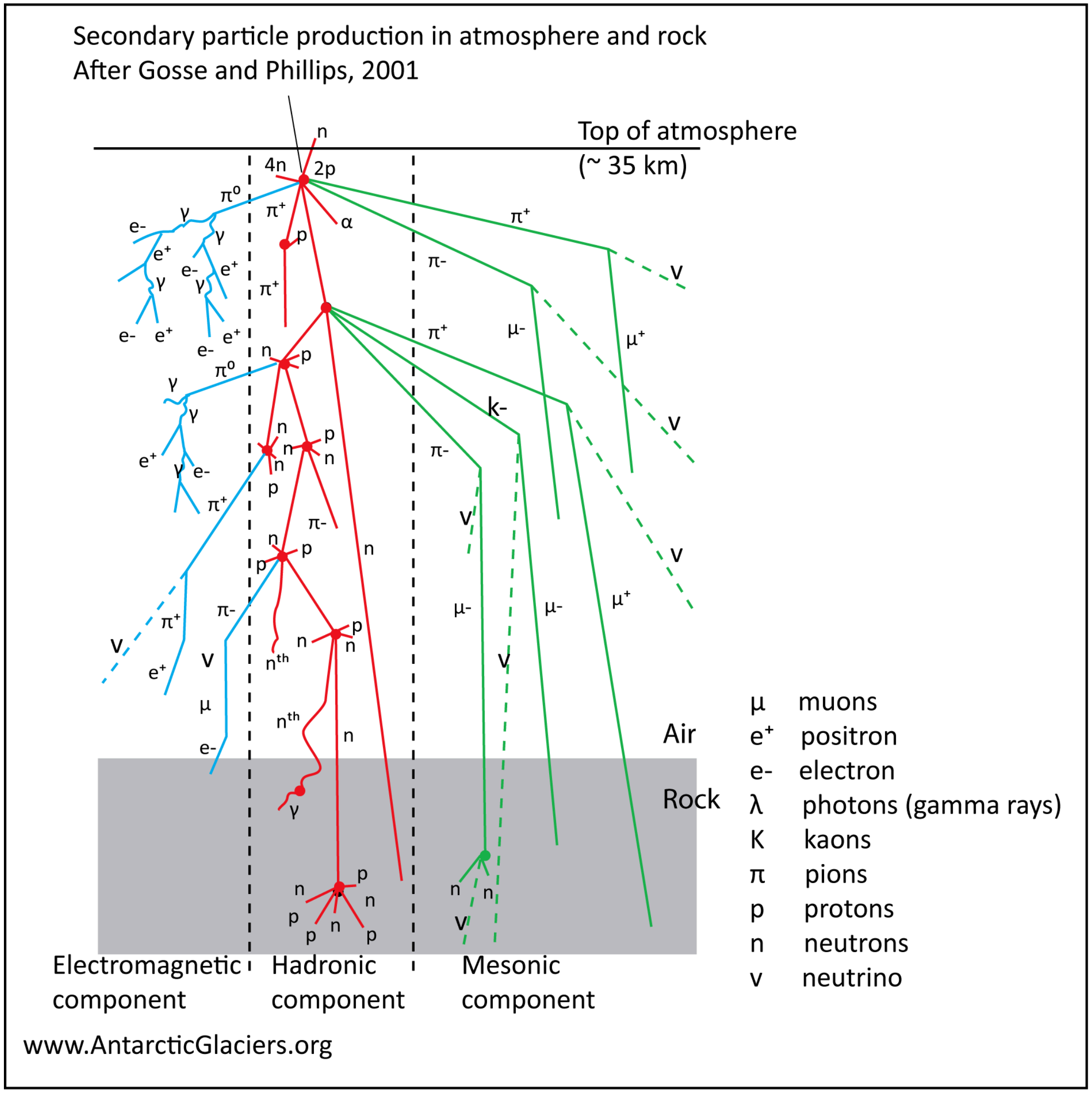
FIGURE 1.3 ◈ Medical

TABLE 1.4 **COLLECTIVE EFFECTIVE DOSE (S), EFFECTIVE DOSE PER INDIVIDUAL IN THE US POPULATION (E_{US}), AND AVERAGE EFFECTIVE DOSE FOR THE EXPOSED GROUP (E_{Exp}) FROM MEDICAL PROCEDURES FOR 2006** (After NCRP Report No. 160, 2009)

Exposure Category	S (person-Sv)	E_{US} (mSv)	E_{Exp} (mSv)
Medical			
CT	440,000	1.47	[a]
Nuclear medicine	231,000	0.77	[a]
Interventional fluoroscopy	128,000	0.43	[a]
Conventional radiography and fluoroscopy	100,000	0.33	[a]
Total	899,000	3	[a]

[a] Not determined for the medical category because the number of patients exposed is not known, only the number of procedures.

Cosmic Rays Radiation



Secondary particle production in atmosphere and rock
After Gosse and Phillips, 2001

The cosmic ray shower

It is now known that most cosmic rays are atomic nuclei. Most are hydrogen nuclei, some are helium nuclei, and the rest heavier elements. The relative abundance changes with cosmic ray energy — the highest energy cosmic rays tend to be heavier nuclei. Although many of the low energy cosmic rays come from our Sun, the origins of the highest energy cosmic rays remains unknown and a topic of much research. This drawing illustrates air showers from very high energy cosmic rays.

Formation of Cosmogenic Nuclides

Formation of cosmogenic nuclides

As the cascade of reactions propagates down through the atmosphere, the nuclear particle flux becomes dominated by neutrons + minor mesonic flux. These secondary fast nucleons continue to produce cosmogenic nuclides in the atmosphere, hydrosphere & lithosphere by breaking apart target atoms through spallation interactions. Eventually, the particles have insufficient energy to cause spallation.

Isotopes formed by the action of cosmic rays

Isotope	Mode of formation	half life
^{3}H (tritium)	$^{14}N(n,^{12}C)T$	12.3 y
^{7}Be	Spallation (N and O)	53.2 d
^{10}Be	Spallation (N and O)	1,387,000 y
^{11}C	Spallation (N and O)	20.3 m
^{14}C	$^{14}N(n,p)^{14}C$	5,700 y
^{18}F	$^{18}O(p,n)^{18}F$ and Spallation (Ar)	110 m
^{22}Na	Spallation (Ar)	2.6 y
^{24}Na	Spallation (Ar)	15 h
^{28}Mg	Spallation (Ar)	20.9 h
^{26}Al	Spallation (Ar)	717,000 y
^{31}Si	Spallation (Ar)	157 m
^{32}Si	Spallation (Ar)	153 y
^{32}P	Spallation (Ar)	14.3 d
^{34m}Cl	Spallation (Ar)	34 m
^{35}S	Spallation (Ar)	87.5 d
^{36}Cl	$^{35}Cl\ (n,\gamma)^{36}Cl$	301,000 y
^{37}Ar	$^{37}Cl\ (p,n)^{37}Ar$	35 d
^{38}Cl	Spallation (Ar)	37 m
^{39}Ar	$^{38}Ar\ (n,\gamma)^{39}Ar$	269 y
^{39}Cl	$^{40}Ar\ (n,np)^{39}Cl$ & spallation (Ar)	56 m
^{41}Ar	$^{40}Ar\ (n,\gamma)^{41}Ar$	110 m
^{41}Ca	$^{40}Ca\ (n,\gamma)^{41}Ca$	102,000 y
^{81}Kr	$^{80}Kr\ (n,\gamma)\ ^{81}Kr$	229,000 y
^{129}I	Spallation (Xe)	15,700,000 y

Applications in geology listed by isotope [edit]

Commonly measured long lived cosmogenic isotopes

element	mass	half-life (years)	typical application
beryllium	10	1,387,000	exposure dating of rocks, soils, ice cores
aluminium	26	720,000	exposure dating of rocks, sediment
chlorine	36	308,000	exposure dating of rocks, groundwater tracer
calcium	41	103,000	exposure dating of carbonate rocks
iodine	129	15.7 million	groundwater tracer
sulfur	35	0.24	water residence times
sodium	22	2.6	water residence times
tritium	3	12.32	water residence times
argon	39	269	groundwater tracer
krypton	81	229,000	groundwater tracer

An Overview of Radiation Exposure to US Population

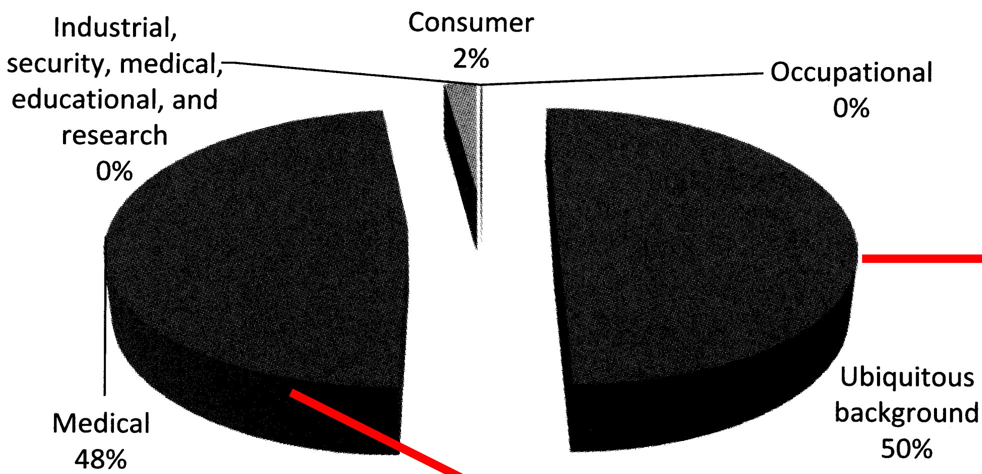


FIGURE 1.1 ◆ Exposure by Major Categories

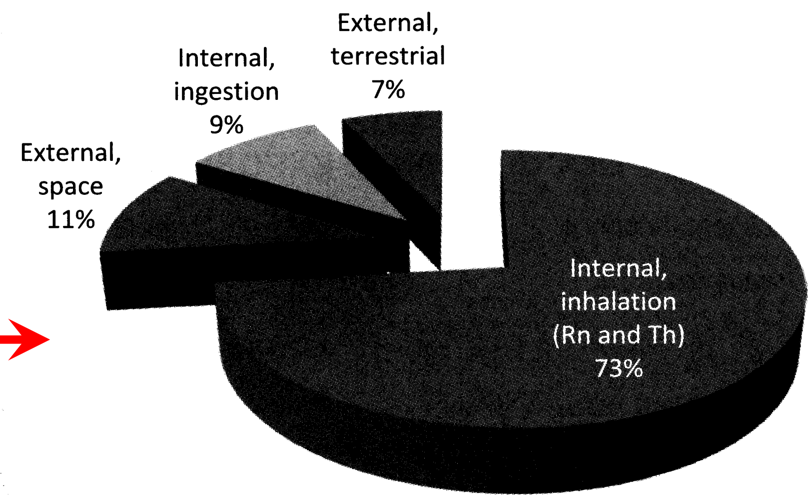


FIGURE 1.2 ◆ Ubiquitous Background

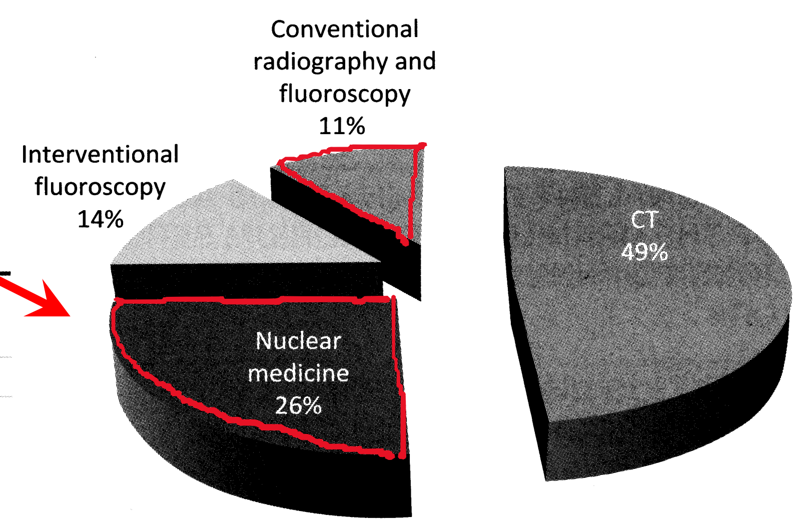


FIGURE 1.3 ◆ Medical

TABLE 1.4 COLLECTIVE EFFECTIVE DOSE (*S*), EFFECTIVE DOSE PER INDIVIDUAL IN THE US POPULATION (E_{US}), AND AVERAGE EFFECTIVE DOSE FOR THE EXPOSED GROUP (E_{Exp}) FROM MEDICAL PROCEDURES FOR 2006 (After NCRP Report No. 160, 2009)

Exposure Category	*S* (person-Sv)	E_{US} (mSv)	E_{Exp} (mSv)
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Radiation Dose from Nuclear Medicine and External Radiotherapy Procedures

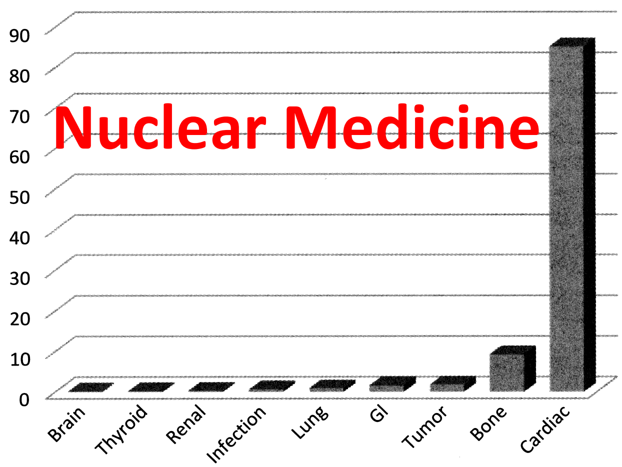

FIGURE 1.8 ◆ Percent Contributions to the Collective Effective Dose from Nuclear Medicine Procedures in the United States

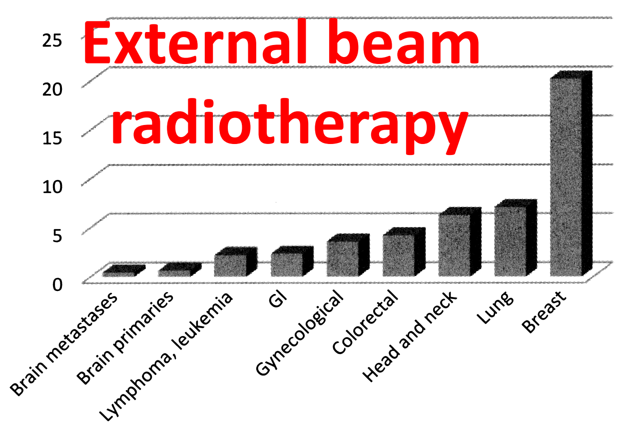

FIGURE 1.9 ◆ Percent Contributions to the Collective Effective Dose from External Beam Radiotherapy in the United States

TABLE 1.11 EFFECTIVE AND COLLECTIVE EFFECTIVE DOSES FROM EXTERNAL BEAM RADIOTHERAPY IN THE UNITED STATES IN 2006 (After NCRP Report No. 160, 2009)[a]

Treatment Site	Effective Dose (Sv)	Collective Effective Dose (Person-Sv)
Breast	0.337	71,632
Prostate	0.949	187,774
Lung	0.187	25,095
Head and neck	0.319	22,185
Colorectal	0.258	14,910
Gynecological	0.24	12,695
Brain metastases	0.031	1518
Brain primaries	0.059	2312
GI	0.233	8216
Lymphoma, leukemia	0.333	7828
Total	—	354,165

[a] E_{US} = 1.18 mSv.

An Overview of Radiation Exposure to US Population

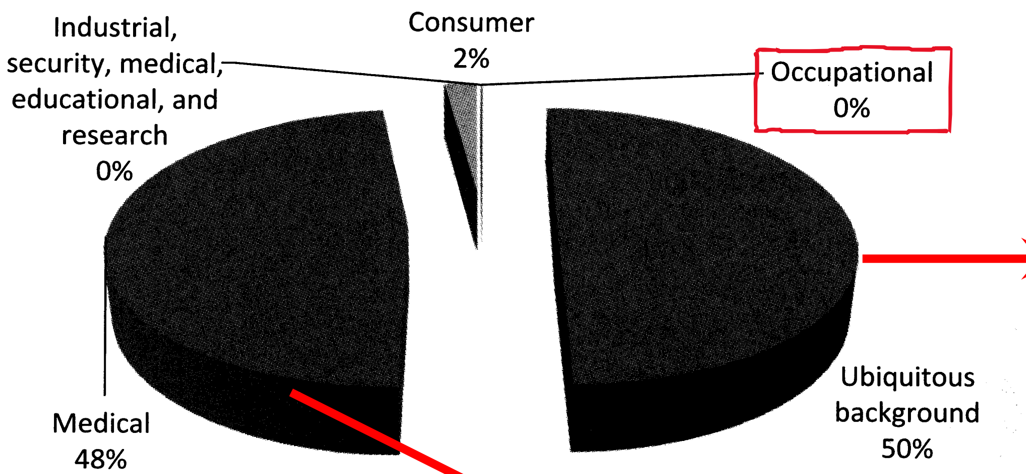

Figure 1.1 ◈ Exposure by Major Categories

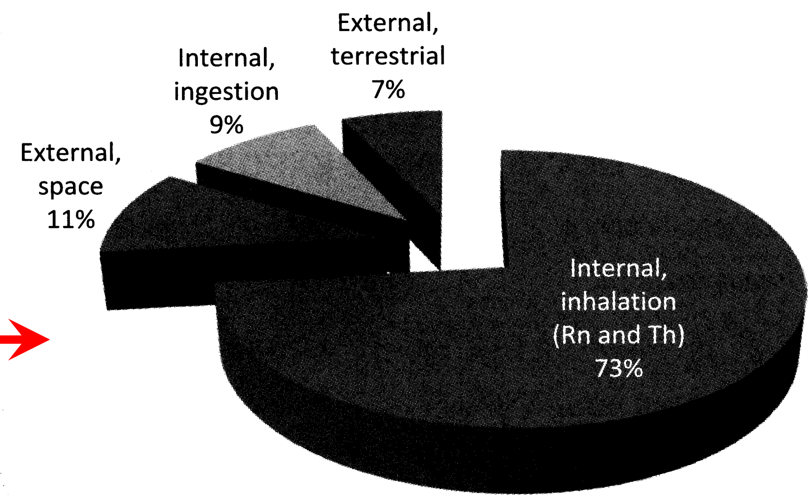

Figure 1.2 ◈ Ubiquitous Background

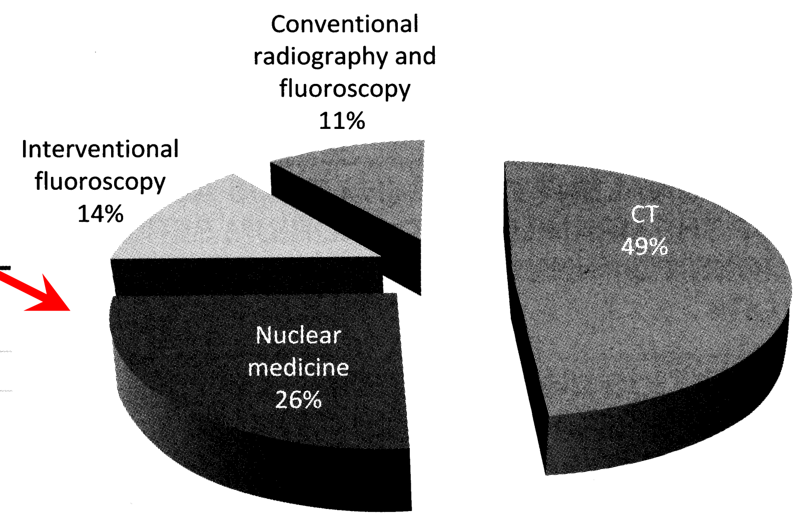

Figure 1.3 ◈ Medical

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Interventional fluoroscopy	128,000	0.43	[a]
Conventional radiography and fluoroscopy	100,000	0.33	[a]
Total	899,000	3	[a]

[a] Not determined for the medical category because the number of patients exposed is not known, only the number of procedures.

Occupational Dose for US Workers

Table 1.15 OCCUPATIONAL DOSES FOR US WORKERS IN 2006
(After NCRP Report No. 160, 2009)

Category	Description	Numbers of Workers and Doses	
Medical	Monitored workers	2,519,693	
	Workers with recordable dose	735,347	
	S (person-Sv)	549	
	Average effective dose[a] (mSv)	0.75	4
Aviation	Monitored airline crew	0	
	Number of airline crew	173,000	
	S (person-Sv)	531	
	Average effective dose[b] (mSv)	3.07	1
Commercial Nuclear Power	Monitored workers	116,354	
	Workers with recordable dose	58,788	
	S (person-Sv)	110	
	Average effective dose[a] (mSv)	1.87	2
Industry and Commerce	Monitored workers	505,369	
	Workers with recordable dose	134,105	
	S (person-Sv)	109	
	Average effective dose[a] (mSv)	0.81	3
Education and Research	Monitored workers	437,007	
	Workers with recordable dose	83,700	
	S (person-Sv)	60	
	Average effective dose[a] (mSv)	0.72	4
Government, DOE, Military[c]	Monitored workers	284,192	
	Workers with recordable dose	30,591	
	S (person-Sv)	39(18)[d]	
	Average effective dose[a] (mSv)	0.59	5
Total Monitored Workers	—	3,862,615	
Total Workers with Recordable or Estimated Dose	—	1,215,531	
Total *S* (Person-Sv)	—	1399	
Average Effective Dose[e] (mSv)	—	1.13	

[a]For those with recordable dose.
[b]Based on an estimate for 2006.
[c]Based on 2004 data.
[d]Values in parenthesis exclude the portion of the collective dose for which information on the number of workers with recordable dose is not available [for 2006: 21 (39–18) person-Sv is excluded]. The average effective dose is 18 person-Sv divided by 30,591 workers with recordable dose (= 0.59 mSv).
[e]Based on workers with recordable dose.

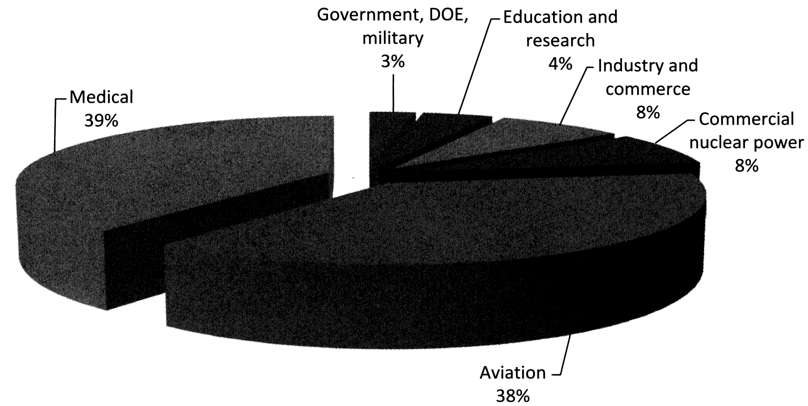

Figure 1.12 ◆ Percent Contributions to US Collective Effective Dose by Occupation

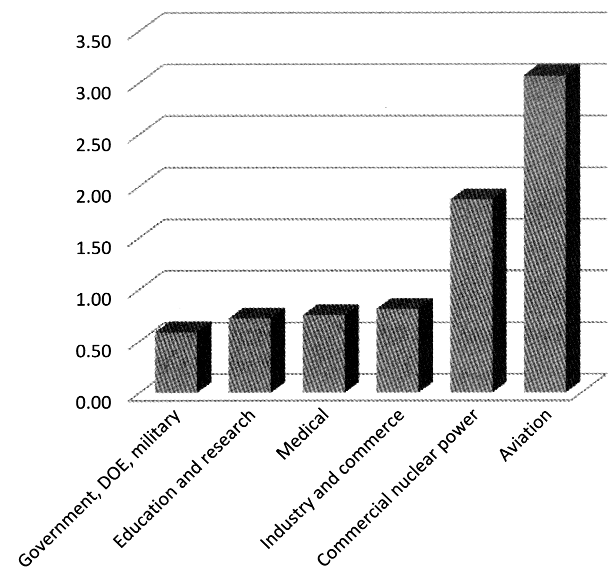

Figure 1.13 ◆ Average Effective Dose by Occupation

An Overview of Radiation Exposure to US Population

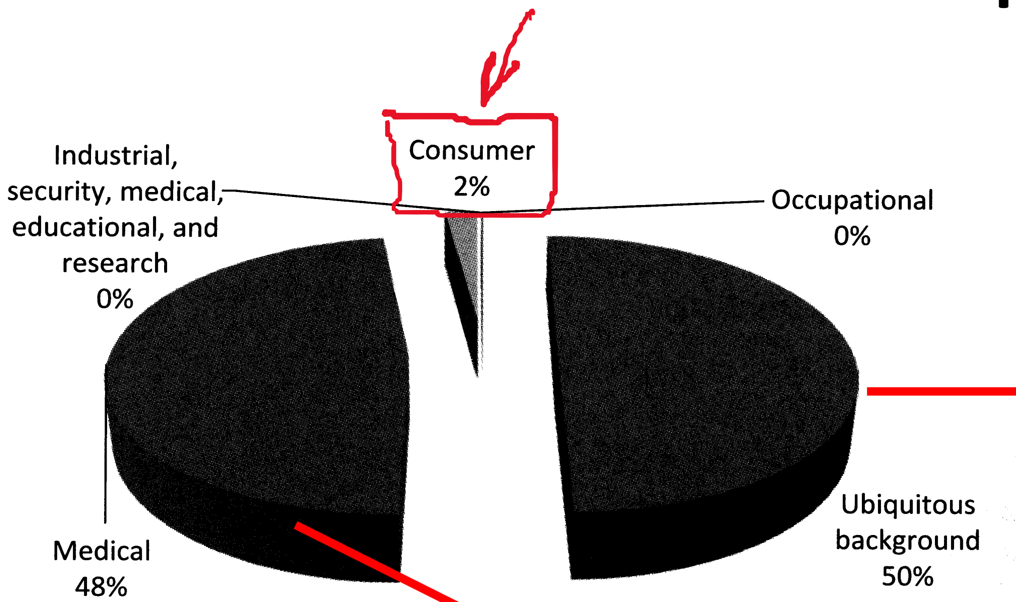

FIGURE 1.1 ◆ Exposure by Major Categories

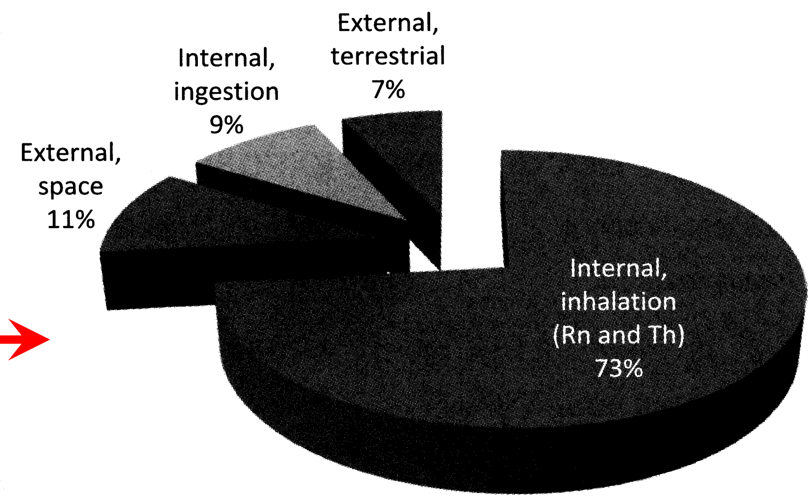

FIGURE 1.2 ◆ Ubiquitous Background

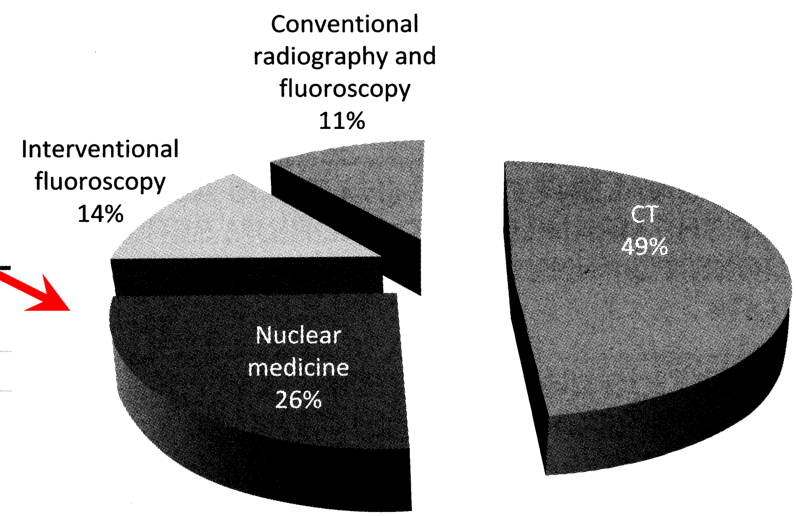

FIGURE 1.3 ◆ Medical

TABLE 1.4 **COLLECTIVE EFFECTIVE DOSE (*S*), EFFECTIVE DOSE PER INDIVIDUAL IN THE US POPULATION (E_{US}), AND AVERAGE EFFECTIVE DOSE FOR THE EXPOSED GROUP (E_{Exp}) FROM MEDICAL PROCEDURES FOR 2006** (After NCRP Report No. 160, 2009)

Exposure Category	*S* (person-Sv)	E_{US} (mSv)	E_{Exp} (mSv)
Medical			
CT	440,000	1.47	[a]
Nuclear medicine	231,000	0.77	[a]
Interventional fluoroscopy	128,000	0.43	[a]
Conventional radiography and fluoroscopy	100,000	0.33	[a]
Total	899,000	3	[a]

[a]Not determined for the medical category because the number of patients exposed is not known, only the number of procedures.

Radiation Dose from Consumer Products

TABLE 1.12 ANNUAL COLLECTIVE EFFECTIVE DOSE (S) FROM CIGARETTES (After NCRP Report No. 160, 2009)

	E per Smoker (mSv)	*S* (Person-Sv)[a]
Men	0.09–0.6	2,250–15,000
Average	0.32	8100
Women	0.08–0.5	1600–10,000
Average	0.27	5400
Total	—	13,500

[a]Based on 25 million males and 20 million females smoking 18 and 15 cigarettes per day, respectively.

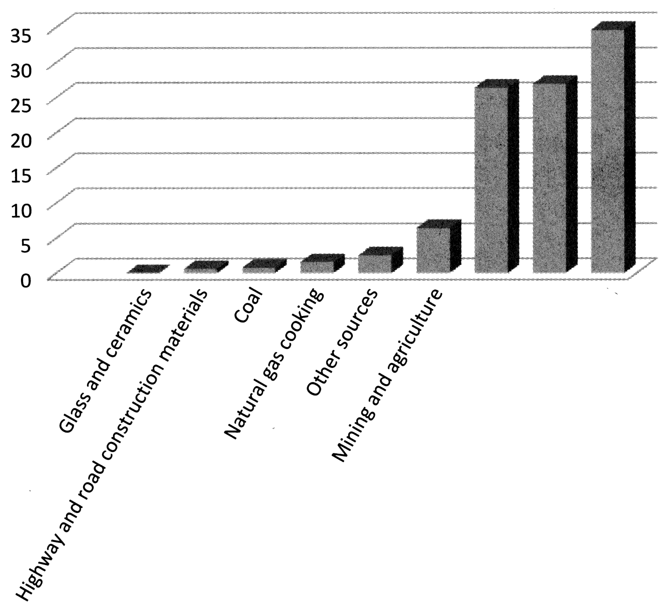

FIGURE 1.10 ◆ Percent Contributions to the Collective Effective Dose from Consumer Products and Activities in the United States

TABLE 1.13 ANNUAL EFFECTIVE DOSE TO AN EXPOSED INDIVIDUAL (E_{Exp}) AND COLLECTIVE EFFECTIVE DOSE (S) FROM CONSUMER PRODUCTS AND ACTIVITIES IN THE UNITED STATES IN 2006 (After NCRP Report No. 160, 2009)[a]

Source	E_{Exp} (μSv)	*S* (Person-Sv)
Cigarette smoking	300	13,500
Building materials	70	10,500
Commercial air travel	—	10,300
Mining and agriculture	10	2500
Other sources	—	1000
Combustion of fossil fuels	—	—
Natural gas cooking	4	620
Coal	1	300
Highway and road construction materials	40	240
Glass and ceramics	—	<10
Total	—	38,970

[a]E_{US} = 1.18 mSv.

An Overview of Radiation Exposure to US Population

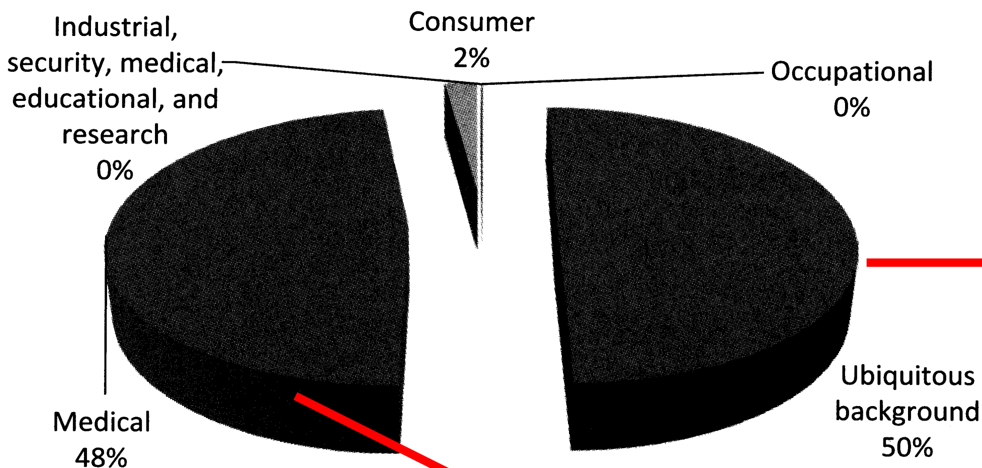

FIGURE 1.1 ◆ Exposure by Major Categories

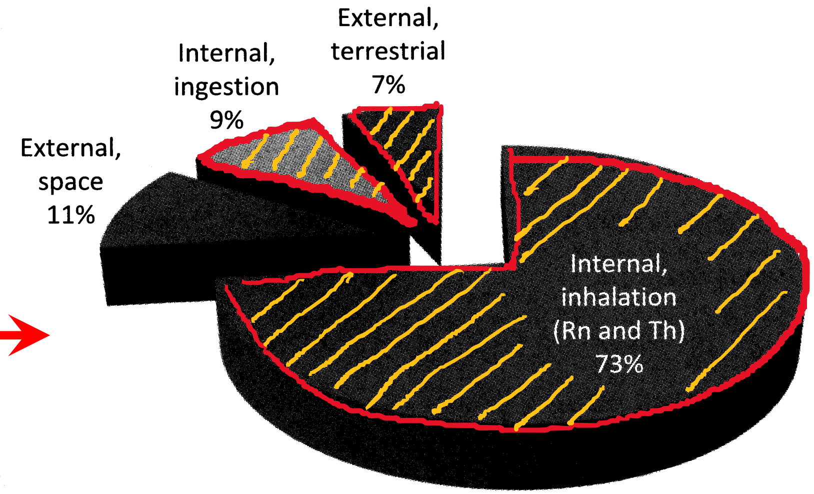

FIGURE 1.2 ◆ Ubiquitous Background

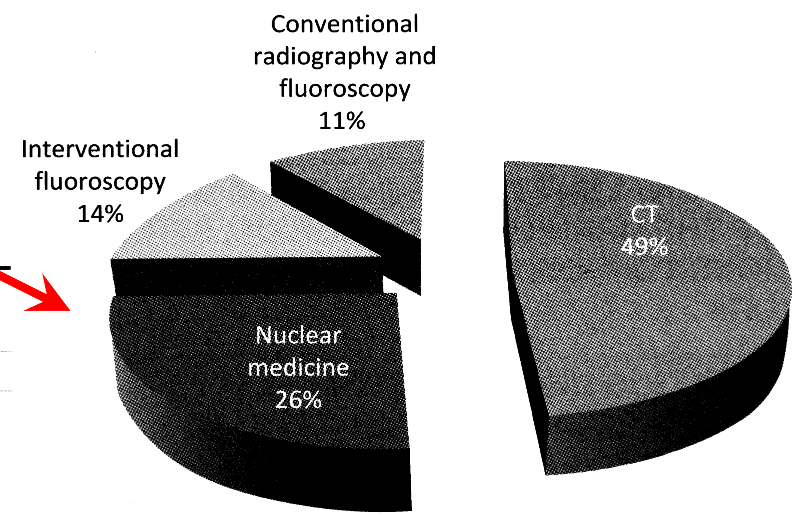

FIGURE 1.3 ◆ Medical

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Exposure Category	S (person-Sv)	E_{US} (mSv)	E_{Exp} (mSv)
Medical			
CT	440,000	1.47	[a]
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Total	899,000	3	[a]

[a]Not determined for the medical category because the number of patients exposed is not known, only the number of procedures.

Naturally Occurring Radioactive Materials (NORM)

- **All of the heavy elements (Z>83) found in nature are radioactive** and decay by alpha and beta emission. $^{209}_{83}Bi$ is the only stable nuclide with an atomic number greater than that of lead (Z=82).

- All of the naturally occurring heavy radionuclides belong to one of the **three series**, the uranium series, the thorium series and the actinium series.

- Several other elements, outside the uranium, actinium and thorium series, are also found to have radioactive isotopes, such as **^{40}K, ^{87}Rb** etc.

- Other naturally occurring radionuclides are of **cosmogenic origin**. Only those produced as a results of cosmic ray interactions with constituents of the atmosphere results in any mentionable exposure to man: ^{3}H, ^{7}Be, ^{14}C and ^{22}Na.

Formation of Cosmogenic Nuclides

Formation of cosmogenic nuclides

As the cascade of reactions propagates down through the atmosphere, the nuclear particle flux becomes dominated by neutrons + minor mesonic flux. These secondary fast nucleons continue to produce cosmogenic nuclides in the atmosphere, hydrosphere & lithosphere by breaking apart target atoms through spallation interactions. Eventually, the particles have insufficient energy to cause spallation.

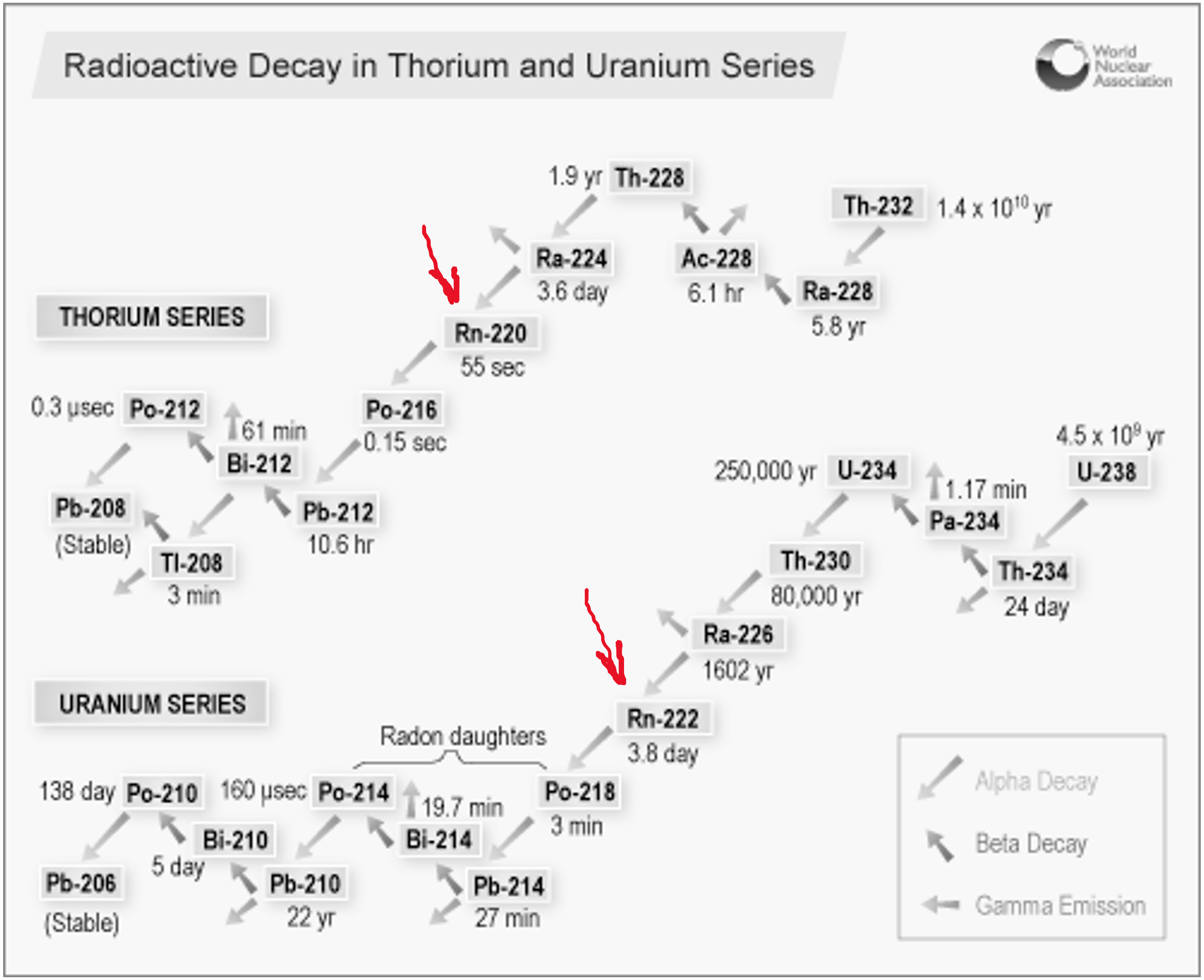
Isotopes formed by the action of cosmic rays

Isotope	Mode of formation	half life
^{3}H (tritium)	$^{14}N(n,^{12}C)T$	12.3 y
^{7}Be	Spallation (N and O)	53.2 d
^{10}Be	Spallation (N and O)	1,387,000 y
^{11}C	Spallation (N and O)	20.3 m
^{14}C	$^{14}N(n,p)^{14}C$	5,700 y
^{18}F	$^{18}O(p,n)^{18}F$ and Spallation (Ar)	110 m
^{22}Na	Spallation (Ar)	2.6 y
^{24}Na	Spallation (Ar)	15 h
^{28}Mg	Spallation (Ar)	20.9 h
^{26}Al	Spallation (Ar)	717,000 y
^{31}Si	Spallation (Ar)	157 m
^{32}Si	Spallation (Ar)	153 y
^{32}P	Spallation (Ar)	14.3 d
^{34m}Cl	Spallation (Ar)	34 m
^{35}S	Spallation (Ar)	87.5 d
^{36}Cl	$^{35}Cl(n,\gamma)^{36}Cl$	301,000 y
^{37}Ar	$^{37}Cl(p,n)^{37}Ar$	35 d
^{38}Cl	Spallation (Ar)	37 m
^{39}Ar	$^{38}Ar(n,\gamma)^{39}Ar$	269 y
^{39}Cl	$^{40}Ar(n,np)^{39}Cl$ & spallation (Ar)	56 m
^{41}Ar	$^{40}Ar(n,\gamma)^{41}Ar$	110 m
^{41}Ca	$^{40}Ca(n,\gamma)^{41}Ca$	102,000 y
^{81}Kr	$^{80}Kr(n,\gamma)^{81}Kr$	229,000 y
^{129}I	Spallation (Xe)	15,700,000 y

Applications in geology listed by isotope [edit]

Commonly measured long lived cosmogenic isotopes

element	mass	half-life (years)	typical application
beryllium	10	1,387,000	exposure dating of rocks, soils, ice cores
aluminium	26	720,000	exposure dating of rocks, sediment
chlorine	36	308,000	exposure dating of rocks, groundwater tracer
calcium	41	103,000	exposure dating of carbonate rocks
iodine	129	15.7 million	groundwater tracer
sulfur	35	0.24	water residence times
sodium	22	2.6	water residence times
tritium	3	12.32	water residence times
argon	39	269	groundwater tracer
krypton	81	229,000	groundwater tracer



http://www.world-nuclear.org/info/inf30.html

Secular Equilibrium

(more detailed discussions coming soon …)

From <<Radiation Protection and Dosimetry>>, by Michael Stabin.

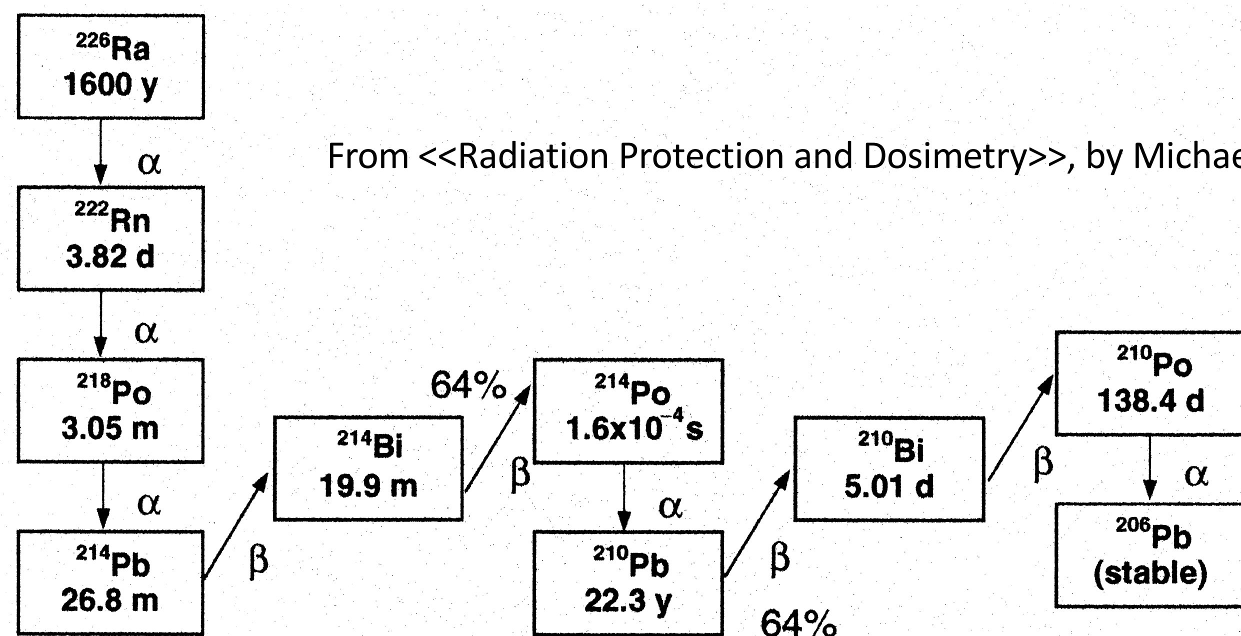
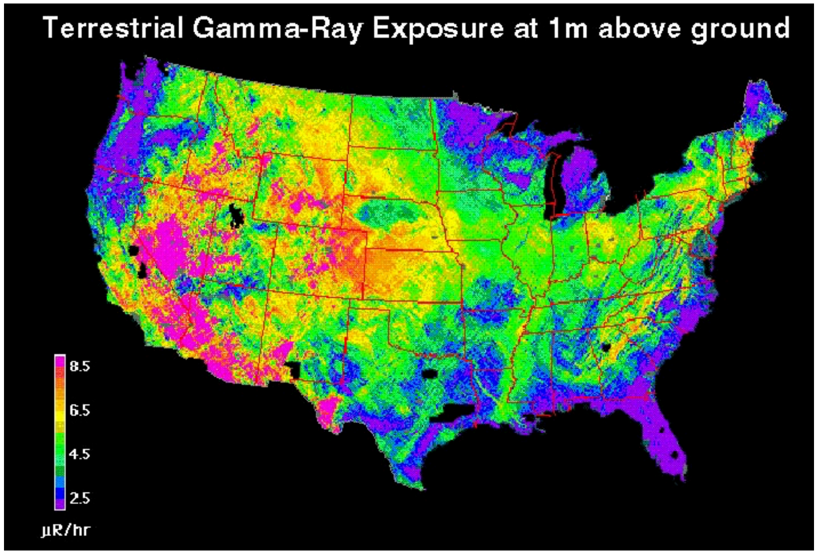
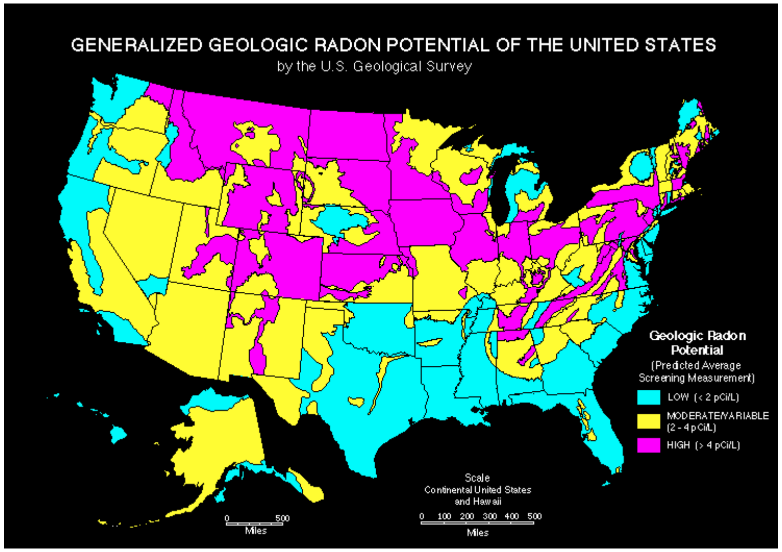


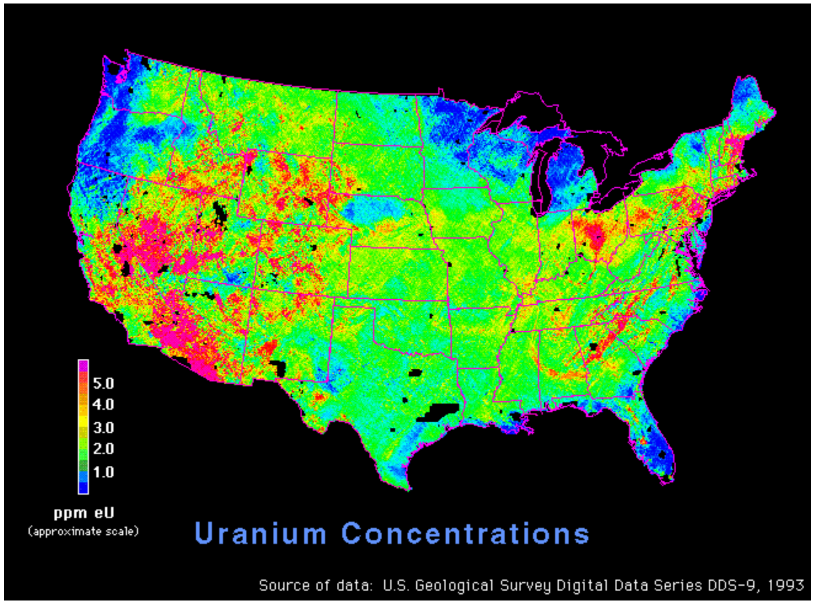
Figure 3.11 The ^{226}Ra decay series.

We can continue on with a species D, E, F, and so on, but the relationships among the species obviously become more complicated and are difficult to categorize. If Species A is very long-lived, however, relative to other members of the chain, after a long time (seven to ten half-lives of the longest-lived progeny species), all the members of the chain will be in secular equilibrium and decaying with the half-life of Species A, and all having the same activity as Species A. An important example is the ^{226}Ra decay series (Figure 3.11).

Terrestrial Naturally Occurring Radioactive Materials (NORM)







http://www.blackcatsystems.com/GM/safe_radiation.html

Topics Concerned in this Course

The scientific and engineering aspects of health physics are concerned mainly with: (1) the physical measurements of different types of radiation and radioactive materials, (2) the establishment of quantitative relationships between radiation exposure and biological damage, (3) the movement of radioactivity through the environment, and (4) the design of radiologically safe equipment, processes, and environments.

From Cember, page 1.

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